PA-1 BQ-330
Acc 85502

Advances in Soil Science

Volume 13

Dryland Agriculture: Strategies for Sustainability

Edited by R.P. Singh, J.F. Parr, and B.A. Stewart

With Contributions by
R.R. Allen, A.U. Bhatti W.R. Butcher, R.J. Cook, J.C. Day, L.F. Elliott, D.W. Fryrear, J.L. Hatfield, S.B. Hornick, D.W. Hughes, C.A. Jones, O.R. Jones, E.T. Kanemasu, R. Kunkel, D.K. McCool, R.E. Meyer, D.J. Mulla, R.I. Papendick, J.F. Parr, C.S. Potter, J.F. Power, K.G. Renard, R.P. Singh, J.L. Smith, J.L. Steiner, B.A. Stewart, J.I. Stewart, P.W. Unger, S.J. van Donk, S.M. Virmani, and C.E. Whitman

With 84 Illustrations and 70 Tables

Springer-Verlag
New York Berlin Heidelberg
London Paris Tokyo Hong Kong

R.P. Singh
Indian Council of Agricultural Research
Hyderabad 500659, India

J.F. Parr
USDA Agricultural Research Service
Beltsville, Maryland 20705, U.S.A.

B.A. Stewart
USDA Conservation & Production Laboratory
Bushland, Texas 79012, U.S.A.

ISSN: 0176-9340

Printed on acid-free paper.

© 1990 by Springer-Verlag New York Inc.
Copyright is not claimed for works by U.S. Government employees.
All rights reserved. This work may not be translated or copied in whole or in part without the written permission of the publisher (Springer-Verlag, 175 Fifth Avenue, New York, NY 10010, USA), except for brief excerpts in connection with reviews or scholarly analysis. Use in connection with any form of information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed is forbidden.
The use of general descriptive names, trade names, trademarks, etc., in this publication, even if the former are not especially identified, is not to be taken as a sign that such names, as understood by the Trade Marks and Merchandise Marks Act, may accordingly be used freely by anyone.

Typeset by Publishers Service, Bozeman, Montana.
Printed and bound by Edwards Brothers, Ann Arbor, Michigan.
Printed in the United States of America.

9 8 7 6 5 4 3 2 1

ISBN 0-387-97204-8 Springer-Verlag New York Berlin Heidelberg
ISBN 3-540-97204-8 Springer-Verlag Berlin Heidelberg New York

Advances in Soil Science

C

Advances in Soil Science

B.A. Stewart, Editor

Editorial Board

R. Lal
C.W. Rose
U. Schwertmann
B.A. Stewart
P.B. Tinker
R.J. Wagenet
B. Yaron

Preface

From the beginning of agriculture until about 1950, increased food production came almost entirely from expanding the cropland base. Since 1950, however, the yield per unit of land area for major crops has increased dramatically. Much of the increase in yields was because of increased inputs of energy. Between 1950 and 1985, the farm tractor fleet quadrupled, world irrigated area tripled, and use of fertilizer increased ninefold. Between 1950 and 1985, the total energy used in world agriculture increased 6.9 times.

Irrigation played a particularly important role in the rapid increase in food production between 1950 and 1985. The world's irrigated land in 1950 totaled 94 million hectares but increased to 140 million by 1960, to 198 million by 1970, and to 271 million hectares in 1985. However, the current rate of expansion has slowed to less than 1% per year. The world population continues to increase and agricultural production by the year 2000 will have to be 50 to 60% greater than in 1980 to meet demands. This continued demand for food and fiber, coupled with the sharp decline in the growth rate of irrigation development, means that much of the additional agricultural production in future years must come from cultivated land that is not irrigated. Agricultural production will be expanded in the arid and semiarid regions because these regions make up vast areas in developing countries where populations are rapidly rising. Expansion of agriculture in these fragile regions presents a major challenge because soil degradation can occur quickly if poor management practices are followed.

This series, *Advances in Soil Science*, was established to provide a forum for leading scientists to analyze and summarize the available scientific information on a subject, assessing its importance and identifying additional research needs. This is the second volume devoted to a single topic. Much has been learned about dryland farming, and although the technologies developed cannot be transferred directly to other regions of the world, the principles are universal. Drs. R.P. Singh and J.F. Parr served as guest editors of this volume. They have for many years been involved on a global scale with dryland agriculture. They selected authors with international experience and expertise. The authors did an outstanding job of summarizing past studies and documenting the important princi-

ples involved in dryland farming. Therefore, this volume follows the tradition of *Advances in Soil Science* in serving the international agricultural community.

It has been a stimulating and rewarding experience to work with Drs. Singh and Parr in editing this volume. I also want to thank the authors for their excellent contributions and cooperation and the Springer-Verlag staff for their kind assistance and counsel. Finally, and most important, I thank the readers for their acceptance and use of *Advances in Soil Science*.

B.A. Stewart
Series Editor

Contents

Preface v
Contributors xiii

Improving the Sustainability of Dryland Farming Systems: A Global Perspective 1
J.F. Parr, B.A. Stewart, S.B. Hornick, and R.P. Singh
I. Introduction 1
II. The Concept of Sustainability 2
III. Dynamics of Soil Productivity 4
IV. Opportunities and Limitations 5
V. Perspectives and Strategies 7
References 7

Agroclimatology of Semiarid Lands 9
J.L. Hatfield
I. Introduction 9
II. Climatic Resources 10
III. Soils 20
IV. Agroclimatic Indices 21
V. Limitations 23
VI. Research Needs 24
References 24

Conservation Tillage Systems 27
P.W. Unger
I. Introduction 28
II. Conservation Tillage Equipment 30
III. Weed Control 30
IV. Water Infiltration, Evaporation, and Conservation 32
V. Crop Growth, Yields, and Water Use 45
VI. Soil Erosion and Environmental Quality 47

VII. Insects, Plant Diseases, and Other Pests 52
VIII. Soil Properties 53
IX. Economics 57
X Summary and Conclusions 59
References 61

Tillage and Residue Management Effects on Soil Organic Matter Dynamics in Semiarid Regions 69
J.L. Smith and L.F. Elliott
I. Introduction 69
II. Characteristics of Semiarid Regions 70
III. Properties and Factors Affecting Soil Organic Matter 72
IV. The Effect of Residues on Soil Structure 76
V. Tillage and Residue Management Effects on Soil Organic Matter and Nutrients 77
VI. Tillage Strategies for Improved Management of Organic Matter and Plant Nutrients 82
VII. Cropping Methods for Maintaining Soil Organic Matter and Nutrients in Semiarid Areas 83
VIII. Summary and Conclusions 84
References 85

Tillage Systems and Equipment for Dryland Farming 89
O.R. Jones, R.R. Allen, and P.W. Unger
I. Introduction 89
II. Factors Affecting Selection of Tillage System 90
III. Tillage Systems 98
IV. Summary and Needs 124
References 125

Fertility Management and Nutrient Cycling 131
J.F. Power
I. Introduction 131
II. Principles Relating Water and Nutrient Availability 132
III. Water Deficits 135
IV. Management Practices 140
V. Conclusions 146
References 147

Water-Use Efficiency 151
B.A. Stewart and J.L. Steiner
I. Introduction 151
II. Seeding Rate and Planting Geometry 152
III. Crop Calendars 155
IV. Crop Selection and Germplasm Enhancement 164

V. Water Management 166
VI. Soil Fertility 168
VII. Research Needs for Improved Water-Use Efficiency 169
References 170

Water Erosion and Water Quality 175
D.K. McCool and K.G. Renard
I. Introduction 175
II. Impacts 177
III. Prediction 179
IV. Research Needs 182
V. Summary 183
References 183

Wind Erosion: Mechanics, Prediction, and Control 187
D.W. Fryrear
I. Introduction 187
II. Basic Wind Erosion Process 188
III. Extent of Problem 189
IV. Deposition of Eroded Material 193
V. Impact on Soil Productivity 195
VI. Wind Erosion Control 195
VII. Conclusions 197
References 198

Methods for Removing Spatial Variability from Field Research Trials 201
D.J. Mulla, A.U. Bhatti, and R. Kunkel
I. Introduction 201
II. Experimental Design 202
III. Methods of Statistical Analysis 203
IV. Explicit Trend Analysis and Removal 204
V. Comparison of Methods 206
VI. Summary 211
References 212

Diseases Caused by Root-Infecting Pathogens in Dryland Agriculture 215
R.J. Cook
I. Introduction 215
II. Etiology 216
III. Epidemiology 218
IV. Host Range and the Effects of Crop Rotations 223
V. Tillage and Crop Residue Management 225
VI. Strategies and Approaches to Economic Control 229

VII. Research Needs 231
VIII. Epilog 233
References 233

The Role of Soil Biodiversity in Sustainable Dryland Farming Systems 241
C.S. Potter and R.E. Meyer
I. Introduction 241
II. Diversity/Erodibility Relationships 242
III. Early Bioindicators of Soil Degradation 243
IV. Measurements to Characterize Biodiversity 246
V. Implications for Conservation of Marginal Lands 246
VI. Future Research Needs 247
References 248

Managing Crop Residues to Optimize Crop/Livestock Production Systems for Dryland Agriculture 253
R.I. Papendick, J.F. Parr, and R.E. Meyer
I. Introduction 253
II. Available Water and Crop Yields 254
III. Value of Crop Residues for Water Conservation 255
IV. Effect of Surface Residue Management on Crop Yields 263
V. Value of Crop Residues for Erosion Control 265
VI. Progress with Residue Management Systems 266
VII. Conservation Management and Water Quality 269
References 270

Agroclimatic Approaches for Improving Agricultural Productivity in Semiarid Tropics 273
E.T. Kanemasu, J.I. Stewart, S.J. van Donk, and S.M. Virmani
I. Introduction 273
II. Agroecological Features of the Semiarid Tropics 275
III. The Indian SAT 280
IV. The Sahelian SAT 285
V. Botswana SAT 302
VI. Summary and Conclusions 306
References 308

An Economic Analysis of Farm Management Practices and Improved Technologies in the Sahel 311
J.C. Day, W.R. Butcher, and D.W. Hughes
I. Introduction 311
II. Farming Conditions in Mali 313
III. Technological Options for Dryland Farming 318
IV. Soil, Water, and Crop Management Case Studies 319

V. Case Study Results 325
VI. Conclusions 328
Appendix 329
References 330

Use of Crop Simulation Models in Dryland Agriculture 333
C.A. Jones
I. Introduction 333
II. Evaluation of New Crops in Australia 334
III. Application of Grain Sorghum Simulation Models in Central Texas 337
IV. Future Trends in Model Use 340
References 342

Strategies for Increasing the Productivity and Stability of Dryland Farming Systems 347
C.E. Whitman and R.E. Meyer
I. Introduction 347
II. Successful Dryland Regions 349
III. Dryland Technologies 353
IV. Research and Technology Transfer 354
V. Research Needs 356
VI. A Strategy for Achieving Improved Dryland Production 356
References 357

Index 359

Contributors

R.R. Allen, U.S. Department of Agriculture, Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, Texas 79012, U.S.A.

A.U. Bhatti, Department of Agronomy and Soils, Washington State University, Pullman, Washington 99164, U.S.A.

W.R. Butcher, Department of Agricultural Economics, Washington State University, Pullman, Washington 99164, U.S.A.

R.J. Cook, U.S. Department of Agriculture, Agricultural Research Service, Washington State University, Pullman, Washington 99164, U.S.A.

J.C. Day, U.S. Department of Agriculture, Economic Research Service, Washington, D.C. 20005, U.S.A.

L.F. Elliott, U.S. Department of Agriculture, Agricultural Research Service, Shafter, California 93263, U.S.A.

D.W. Fryrear, U.S. Department of Agriculture, Agricultural Research Service, Big Spring, Texas 79721, U.S.A.

J.L. Hatfield, U.S. Department of Agriculture, Agricultural Research Service, National Soil Tilth Laboratory, Ames, Iowa 50011, U.S.A.

S.B. Hornick, U.S. Department of Agriculture, Agricultural Research Service, Soil Microbial Systems Laboratory, Beltsville, Maryland 20705, U.S.A.

D.W. Hughes, Department of Agricultural Economics, Washington State University, Pullman, Washington 99164, U.S.A.

C.A. Jones, Texas Agricultural Experiment Station, Blackland Research Center, Temple, Texas 76502, U.S.A.

O.R. Jones, U.S. Department of Agriculture, Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, Texas 79012, U.S.A.

E.T. Kanemasu, Department of Agronomy, University of Georgia, Georgia Station, Griffin, Georgia 30223, U.S.A.

R. Kunkel, Department of Horticulture and Landscape Architecture, Washington State University, Pullman, Washington 99164, U.S.A.

D.K. McCool, U.S. Department of Agriculture, Agricultural Research Service, Washington State University, Pullman, Washington 99164, U.S.A.

R.E. Meyer, Agency for International Development, Office of Agriculture, Bureau for Science and Technology, Washington, D.C. 20523, U.S.A.

D.J. Mulla, Department of Agronomy and Soils, Washington State University, Pullman, Washington 99164, U.S.A.

R.I. Papendick, U.S. Department of Agriculture, Agricultural Research Service, Washington State University, Pullman, Washington 99164, U.S.A.

J.F. Parr, U.S. Department of Agriculture, Agricultural Research Service, National Program Staff, Beltsville, Maryland 20705, U.S.A.

C.S. Potter, American Association for the Advancement of Science Fellow, Agency for International Development, Washington, D.C. 20523, U.S.A.

J.F. Power, U.S. Department of Agriculture, Agricultural Research Service, University of Nebraska, Lincoln, Nebraska 68583, U.S.A.

K.G. Renard, U.S. Department of Agriculture, Agricultural Research Service, Tucson, Arizona 85719, U.S.A

R.P. Singh, Indian Council of Agricultural Research, Central Research Institute for Dryland Agriculture, Hyderabad-500659, India

J.L. Smith, U.S. Department of Agriculture, Agricultural Research Service, Washington State University, Pullman, Washington 99164, U.S.A.

J.L. Steiner, U.S. Department of Agriculture, Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, Texas 79012, U.S.A.

B.A. Stewart, U.S. Department of Agriculture, Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, Texas 79012, U.S.A.

J.I. Stewart, World Hunger Alleviation through Response Farming, P.O. Box 1158, Davis, California 95617, U.S.A.

P.W. Unger, U.S. Department of Agriculture, Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, Texas 79102, U.S.A.

S.J. van Donk, B.P. 11011, Centre AGRHYMET, Niamey, Niger.

S.M. Virmani, International Crops Research Institute for the Semi-Arid Tropics, Pantancheru P.O., Andhra Pradesh, 502324, India

C.E. Whitman, U.S. Department of Agriculture, Agricultural Research Service, National Program Staff, Beltsville, Maryland 20705, U.S.A.

Improving the Sustainability of Dryland Farming Systems: A Global Perspective

J.F. Parr, B.A. Stewart, S.B. Hornick, and R.P. Singh

I. Introduction 1
II. The Concept of Sustainability 2
III. Dynamics of Soil Productivity 4
IV. Opportunities and Limitations 5
V. Perspectives and Strategies 7
References 7

I. Introduction

Arid and semiarid regions comprise almost 40% of the world's land area and are inhabited by some 700 million people. Approximately 60% of these drylands are in developing countries. Low rainfall areas constitute from 75–100% of the land area in more than 20 countries in the Near East, Africa, and Asia. Farmers in these regions produce more than 50% of the groundnuts, 80% of the pearl millet, 90% of the chickpeas, and 95% of the pigeon peas. These dryland areas will continue to produce most of the world's food grains for expanding populations in the years ahead. However, yields are extremely low compared with those of the humid and subhumid regions. In some countries of sub-Saharan Africa and the Near East food grain production per capita has declined significantly during the past decade. Although part of this decline can be attributed to high rates of population growth, periodic drought, and unfavorable agricultural production and marketing policies of the national governments, much of it results from the steady and continuing degradation of agricultural lands from soil erosion and nutrient depletion and the subsequent loss of soil productivity (FAO, 1986; Dregne, 1989).

Many of these dryland areas are typified by a highly fragile natural resource base. Soils are often coarse-textured, sandy, and inherently low in fertility,

1990 by Springer-Verlag New York Inc.
Advances in Soil Science, Volume 13

organic matter, and water-holding capacity and easily susceptible to wind and water erosion. Runoff losses during rainfall events commonly exceed 50%. Rainfall patterns are erratic and unpredictable, and crops can suffer from moisture deficits and drought even during normal rainfall periods.

About 75% of the crops produced in the Near East region are grown under dryland or rainfed conditions. It is estimated that more than 70% of the projected food and feed deficit by the year 2000 must come from increased yields on established croplands since very little new arable land is available for agricultural development. The situation is much the same in India, where some 45% of the total crop production now comes from drylands. By the end of this century this amount will have to increase to about 60% if India is to provide adequate food and fiber for a projected population of nearly one billion people by the year 2000 (Indo-U.S. Subcommission Report, 1987; Singh, 1989).

The development of productive, profitable, and environmentally sound farming systems for the U.S. drylands of the Great Plains and Pacific Northwest has become a high priority of U.S. agricultural research. The Agricultural Research Service of the U.S. Department of Agriculture (USDA) has committed major resources for research to improve soil, water, and crop management practices for dryland agriculture in the United States. There is a growing number of scientist-to-scientist linkages between the United States and developing countries which are fostering cooperative research on problems of mutual concern. Such research has become even more important in recent years because of the increased economic and environmental costs associated with irrigated agriculture (Steiner et al., 1988; Singh, 1989; Stewart et al., 1990).

II. The Concept of Sustainability

"Sustainable agriculture" according to Lockeretz (1988) is a loosely defined term that encompasses a range of strategies for addressing many of the problems that afflict U.S. agriculture and agriculture worldwide. Such problems include loss of soil productivity from excessive erosion and associated plant nutrient losses; surface and groundwater pollution from pesticides, fertilizers, and sediment; impending shortages of nonrenewable resources; and low farm income from depressed commodity prices and high production costs. Furthermore, "sustainable" implies a time dimension and the capacity of a farming system to endure indefinitely (Lockeretz, 1988).

Two recent initiatives by the U.S. government to further the concept and understanding of sustainable agriculture are noteworthy. One was the Research and Education Program to promote Low-Input/Sustainable Farming Systems (USDA, 1988) and the other was the widely heralded book on *Alternative Agriculture* which discusses the role of alternative farming methods in modern production agriculture (National Research Council, 1989). This concept is illustrated in Figure 1 which has been adapted from Dr. Neill Schaller, USDA-CSRS (personal communication).

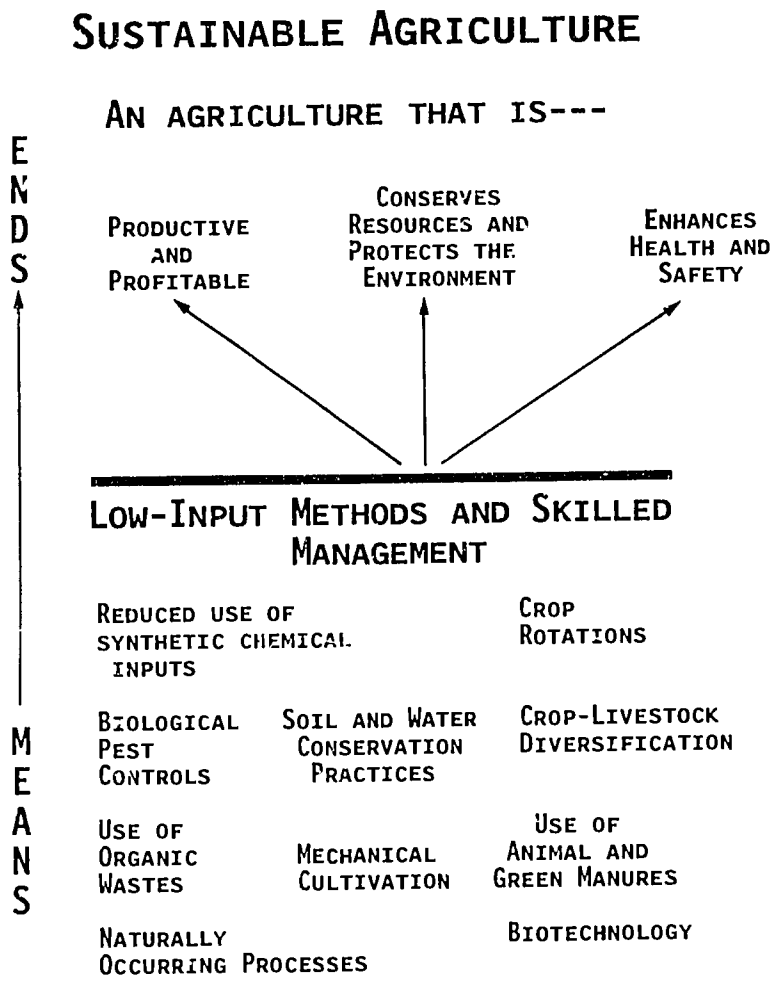


Figure 1. A current concept of sustainable agriculture in the United States showing the ends or objectives and the means of achieving them through low-input methods and skilled management.

The ultimate goal or the ends of sustainable agriculture is to develop farming systems that are productive and profitable, conserve the natural resource base, protect the environment, and enhance health and safety, and to do so over the long-term. The means of achieving this is low-input methods and skilled management, which seek to optimize the management and use of internal production inputs (i.e., on-farm resources) in ways that provide acceptable levels of sustainable crop yields and livestock production and result in economically profitable returns. This approach emphasizes such cultural and management practices as crop rotations, recycling of animal manures, and conservation tillage to control

soil erosion and nutrient losses and to maintain or enhance soil productivity. Low-input farming systems seek to minimize the use of external production inputs (i.e., off-farm resources), such as purchased fertilizers and pesticides, wherever and whenever feasible and practicable; to lower production costs; to avoid pollution of surface and groundwater; to reduce pesticide residues in food; to reduce a farmer's overall risk; and to increase both short- and long-term farm profitability (Parr et al., 1989, 1990; Parr and Hornick, 1990).

Another reason for the focus on low-input farming systems is that most high-input systems, sooner or later, would probably fail because they are not either economically or environmentally sustainable over the long-term. Thus, in the U.S., "sustainable agriculture" has settled in as the ultimate goal. How we achieve this goal depends on creative and innovative conservation and production practices that provide farmers with economically viable and environmentally sound alternatives or options in their farming systems.

III. Dynamics of Soil Productivity

The "key" to improving the sustainability of dryland farming systems is soil productivity, which has been defined as "The capability of soil for producing a specified plant or sequence of plants under a defined set of management practices. It is measured in terms of outputs or harvests in relation to the inputs of production factors for a specific kind of soil under a physically defined system of management" (USDA, 1957).

An important relationship that is often overlooked is that for most agricultural soils, degradative processes such as soil erosion, nutrient runoff losses, and organic matter depletion are going on simultaneously with the beneficial effects of conservation practices such as crop rotations, conservation tillage, and recycling of animal manures and crop residues. Hornick and Parr (1987) first illustrated this relationship, shown in Figure 2, which was modified by Stewart et al. (1990) to include the last two processes and practices shown here. As soil degradative processes proceed and intensify, soil productivity decreases concomitantly. Conversely, soil conservation practices tend to slow these degradative processes and increase soil productivity. Thus, the potential productivity of a particular soil at any point in time is the result of ongoing degradative processes and applied conservation practices. Generally, in arid and semiarid environments the most serious degradative processes are soil erosion and associated nutrient losses, and organic matter depletion.

On our best agricultural soils—that is, gently sloping, medium-textured, well-structured, and with a deep, well-drained profile—a high level of productivity can be maintained by relatively few, but essential conservation practices that readily offset most degradative processes. However, on marginal soils of limited capability, such as steeply sloping, coarse-textured, poorly structured soils depleted of nutrients and with a shallow, poorly drained profile, soil conservation practices must be maximized to counteract further degradation. Thus, a truly sus-

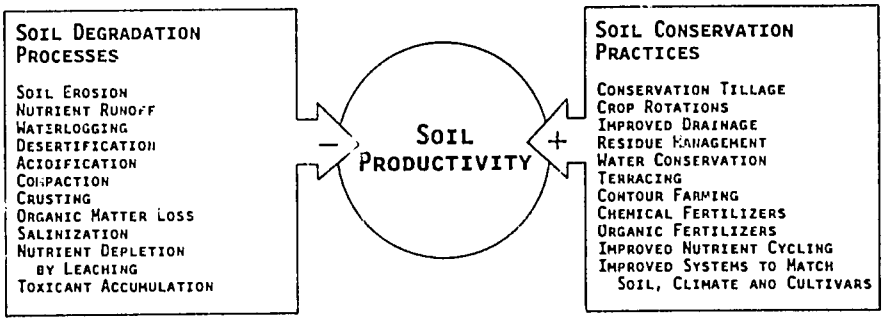


Figure 2. Relationship of soil degradative processes and soil conservation practices.

tainable farming system is one in which the beneficial effects of various conservation practices are equal to or exceed the adverse effects of degradative processes. Organic wastes and residues offer the best possible means of restoring the productivity of severely eroded agricultural soils or of reclaiming marginal soils (Hornick and Parr, 1987).

The vital component in this dynamic equilibrium (see Figure 2) is soil organic matter, which must be maintained and replenished through regular additions of organic materials such as animal manures and crop residues (Parr and Colacicco, 1987) and composted municipal wastes (Hornick et al., 1984). The proper use of organic amendments is of utmost importance in maintaining the tilth, fertility, and productivity of agricultural soils and in minimizing wind and water erosion and preventing nutrient losses through runoff and leaching.

IV. Opportunities and Limitations

Climate and soil are the two most critical factors that will determine the ultimate sustainability of agricultural systems. Figure 3 shows how varying the temperature and soil moisture regimes affects the difficulty of attaining sustainability of an agricultural system (Stewart et al., 1990). As temperature increases and precipitation decreases, the development of sustainable farming systems becomes more difficult. This happens because, under these conditions, soil erosion and organic matter depletion generally become the dominant soil degradative processes. Soil organic matter levels generally decrease as temperatures increase because of increased microbial activity. Intensive tillage also accelerates the loss of soil organic matter through oxidative processes.

The potential for erosion by water and, particularly, wind also tends to increase with increasing temperatures. Both of these degradative processes progressively accelerate with increasing aridity because of the associated decline in soil organic matter, and because there is less natural vegetation to control erosion. The rate

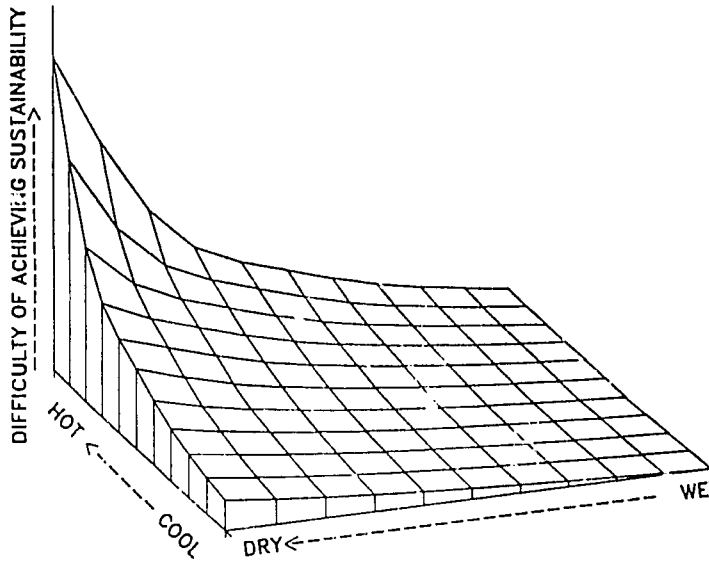


Figure 3. Generalized representation of the effects of temperature and precipitation on the difficulty of developing sustainable agricultural systems.

and extent of these degradative processes are greater for hot and dry climatic regimes. Moreover, the cost and level of inputs needed to restore the productivity of degraded lands in such a harsh environment are much greater, and the benefits to be derived from soil conservation practices are considerably lower than in the cooler and wetter areas.

The key to improving the sustainability of rainfed/dryland farming systems is to halt any further deterioration of the natural resource base, that is, agricultural land, and the associated loss of soil productivity. This can be achieved largely by implementing sound soil and water management practices. In many cases, improvements can be achieved by the application of established principles of soil and water management to crop and livestock production. In other situations, new concepts and methodologies appropriate to the unique aspects of dryland areas will be required. It should be recognized that in some cases soil and climatic factors will seriously limit the feasibility and practicability of reclaiming degraded lands for agricultural use. Obviously, government policies, land tenure arrangements, and social, cultural, and economic factors influence the way in which dryland resources are used. Achieving long-term sustained growth in the productive capacity of low-rainfall areas will require sound decisions and cooperative efforts by national governments and donor organizations based on accurate assessments of problems and potentials of the natural resources, as well as on careful analysis of alternative policies, programs, and projects (Steiner et al., 1988).

V. Perspectives and Strategies

In view of the urgent need to improve the productivity, stability, and sustainability of dryland farming systems for an expanding world population, the editors felt that a book was needed not only to address the current state of the art, including research needs and priorities, but also to present new perspectives and strategies to minimize the risks of dryland farming. The volume, *Dryland Agriculture: Strategies for Sustainability*, comprises 17 chapters written by widely recognized authorities on the most vital aspects of dryland farming.

Two chapters deal with the agroclimatic resource base and address the relationships of precipitation, temperature, and crop growth. Six chapters focus on different aspects of tillage including conservation tillage systems, crop residue management and soil organic matter dynamics, mechanization and equipment, soil fertility and nutrient cycling, control of soilborne plant diseases, and management of crop residues for water conservation and for use by livestock, especially small ruminant animals.

One chapter emphasizes ways in which water-use efficiency by crops can be enhanced while two others discuss the mechanics, prediction, and control of water erosion and wind erosion. Two rather innovative chapters deal with ways of overcoming spatial variability of soils in dryland field research trials and the role of soil biodiversity in improving the sustainability of dryland farming systems.

In assessing the sustainability of these systems the economic aspects are often neglected. Thus, a chapter has been included on an economic analysis of farm management practices and improved technologies for sub-Saharan Africa. There is also a chapter on the use of crop simulation models in dryland agriculture to provide researchers with greater capability for predicting and evaluating crop response to various management practices and technological inputs. Finally, the volume concludes with a chapter which provides examples of some successful approaches and strategies for increasing the productivity and stability of dryland farming systems in a number of developing countries.

We believe this volume fulfills a long-recognized need that will assist researchers, educators, extension workers, and administrators of national governments and donor organizations to develop practical and workable strategies for improving the sustainability of dryland farming systems worldwide. Meeting this challenge in the years ahead will require more sustainable production per unit area, conservation and rational use of natural resources, preservation and protection of the environment, development of improved management practices and appropriate/affordable technologies, and favorable government policies and incentives for farmers to increase their productivity.

References

Dregne, H.E. 1989. Desertification of Drylands. *In* Proc. Intl. Conf. on Dryland Farming, August 11-15, 1988, Amarillo/Bushland, Texas. Texas Agric. Exp. Sta., College Station.

Food and Agriculture Organization (FAO). 1986. African Agriculture: The Next 25 Years. Main Report. FAO, Rome.

Hornick, S.B. and J.F. Parr. 1987. Restoring the productivity of marginal soils with organic amendments. Am. J. Alternative Agric. 2:64-68.

Hornick, S.B., L.J. Sikora, S.B. Sterrett, J.J. Murray, P.D. Millner, W.D. Burge, D. Colacicco, J.F. Parr, R.L. Chaney, and G.B. Willson. 1984. Utilization of sewage sludge compost as a soil conditioner and fertilizer for plant growth. U.S. Department of Agriculture Information Bulletin No. 464.

Indo-U.S. Subcommission on Agriculture. 1987. Report of the U.S. Dryland Farming Team and the Economics Team Visits to India, March/April and June 1987. Published by USDA-OICD-FERRO, December 1987, New Delhi.

Lockeretz, W. 1988. Open questions in sustainable agriculture. Am. J. Alternative Agric. 3:174-181.

National Research Council. 1989. Alternative Agriculture. Committee on the Role of Alternative Farming Methods in Modern Production Agriculture. Board on Agriculture, National Academy Press, Washington, D.C.

Parr, J.F. and D. Colacicco. 1987. Organic materials as alternative nutrient sources. Chapter 4, pp. 81-89. *In* Z.R. Helsel (ed). Energy in Plant Nutrition and Pest Control. Elsevier Science Publishers, Amsterdam, The Netherlands.

Parr, J.F. and S.B. Hornick. 1990. Recent developments in alternative agriculture in the United States. *In* Proc. of Intl. Conf. on Kyusei Nature Farming, October 17-21, 1989, Khon Kaen University, Khon Kaen, Thailand (in press).

Parr, J.F., R.I. Papendick, S.B. Hornick, and R.E. Meyer. 1990. Strategies for developing low-input sustainable farming systems for rainfed agriculture. *In* Proc. Intl. Symposium for Managing Sandy Soils, February 6-11, 1989, Jodhpur, India. Indian Council of Agricultural Research, New Delhi (in press).

Parr, J.F., R.I. Papendick, I.G. Youngberg, and R.E. Meyer. 1989. Sustainable agriculture in the United States. Chap. 4, pp. 50-67. *In* Proc. Intl. Symposium on Sustainable Agricultural Systems. Soil and Water Conservation Society, Ankeny, Iowa.

Singh, R.P. 1989. Dryland/rainfed agriculture and water resources management research and development in India. *In* Proc. Intl. Colloquium on Sharing Innovation: Global Perspectives on Food, Agriculture and Rural Development, October 17-18, 1989, Washington, D.C. Smithsonian Institution (in press).

Steiner, J.L., J.C. Day, R.I. Papendick, R.E. Meyer, and A.R. Bertrand. 1988. Improving and sustaining productivity in dryland regions of developing countries. Adv. Soil Science. 8:79-122. Springer-Verlag, New York.

Stewart, B.A., R. Lal, and S.A. El-Swaify. 1990. Sustaining the resource base of an expanding world agriculture. *In* Proc. Workshop on Mechanisms for a Productive and Sustainable Resource Base, July 29-30, 1989, Edmonton, Canada. Soil and Water Conservation Society, Ankeny, Iowa (in press).

U.S. Department of Agriculture. 1957. Soil—Yearbook of Agriculture. U.S. Government Printing Office, Washington, D.C.

U.S. Department of Agriculture. 1988. Low-Input/Sustainable Agriculture: Research and Education Program. U.S. Government Printing Office, Washington, D.C.

Agroclimatology of Semiarid Lands*

J.L. Hatfield

I. Introduction 9
II. Climatic Resources 10
A. Precipitation 10
B. Radiation 13
C. Temperature 15
D. Humidity 17
E. Wind 18
F. Evaporation 19
III. Soils 20
IV. Agroclimatic Indices 21
V. Limitations 23
VI. Research Needs 24
References 24

I. Introduction

The mention of agroclimatology of semiarid lands immediately draws to mind rainfall and its seasonal distribution. Rainfall, both in amount and distribution, often means the difference between adequate or scarce food supplies in subsistence agriculture. Individuals, who depend entirely on what they produce for survival, completely understand the implications of rainfall variability. Even though they may not be able to express the meaning of these resources quantitatively, they fully comprehend the impact of minor changes and the interactions of the various climatic variables. To advance our understanding of the climatic resources in dryland areas, a more comprehensive treatment of these variables than was available in the past must be developed.

*Contribution from the USDA-ARS.

1990 by Springer-Verlag New York Inc.
Advances in Soil Science, Volume 13

The term *dryland agriculture* suggests a lack of available water, thus, a deficient amount of rainfall. Assessment of exactly what constitutes limiting rainfall depends on the interactions between the amount of rainfall and crop growth at different stages of crop development and the different management practices. In this chapter the climatic resources of dryland agricultural regions is discussed.

II. Climatic Resources

A. Precipitation

No one particular rainfall distribution pattern is associated with dryland or semi-arid regions. Dregne (1982) described four patterns of rainfall distribution in dryland areas – winter, summer, continental, and multimodal. The four types of rainfall distribution for northern latitudes are shown in Figure 1. These general patterns are inclusive of all the dryland areas.

In the winter rainfall patterns or Mediterranean climate, the rainfall occurs during the cooler months of the winter and summers are typically rain free. Areas along the west coast of North and South America, western Australia, and the eastern side of the Mediterranean Sea exhibit this pattern. Annual precipitation in these areas ranges between 250 and 500 mm, with the largest monthly variation at the beginning and end of the rainy season. Rainfall during the winter months can be considered more effective because of the low evaporative demand and the increased opportunity for soil storage before, evaporation losses can occur. Also rainfall intensities are generally low, with rains occurring for a long period over large areas.

Summer rainfall is often more intense, but the storms are generally widespread. The summer rainfall pattern is generally a result of monsoon activity during the warm summer months with the remainder of the year being dry (see Fig. 1; Dregne, 1982). The length of the rainy season increases as one approaches the equator, and the largest variation, in both the length of the rainy season and the amount of rainfall, occurs at the outer extremities of this precipitation pattern. Stations in the summer rainfall pattern typically exhibit variations between 10 and 150% of the annual mean. The departures from the mean are generally more negative than positive.

The areas that have this type of rainfall pattern are those locations influenced by the intertropical convergence zone. Since this synoptic pattern is a wide-scale phenomenon, major shifts in this pattern will have large effects on the precipitation patterns over wide areas. The geographical areas which represent this rainfall pattern are areas south of the Sahara and in India between 0 and 10°N and in northern Australia between 15 and 20°S (Dregne, 1982).

Continental rainfall is characterized by localized, intense storms, commonly referred to as thunderstorms which are the result of convective storm activity resulting from intense surface heating. Although there is a pronounced summer rainfall pattern with lesser amounts of rain falling during the remainder of the year, some precipitation occurs in every month. This pattern of precipitation

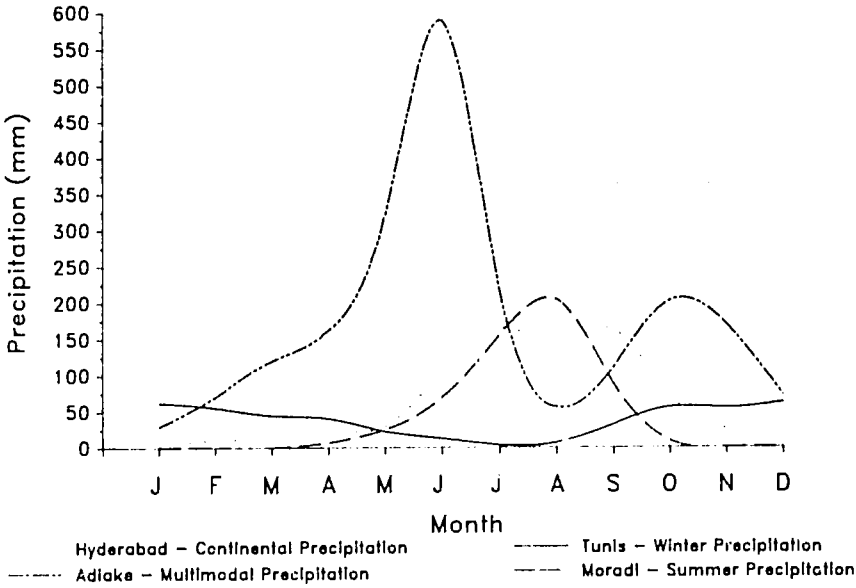


Figure 1. Rainfall distribution patterns prevalent in the semiarid regions of the world.

occurs in the inland areas of continents and is typically found in central North America, central China, the Soviet Union, and Argentina (Dregne, 1982). The storms triggered by the low pressure systems tend to be more generalized in both area and amounts while the convective storms are localized in area and amount. The convective summer storms are often accompanied by severe weather leading to hailstorms which can destroy crops.

Annual and monthly rainfalls under the continental pattern are quite variable. This variation in the monthly rainfall is illustrated by the 75-year statistics from Lubbock, Texas (Fig. 2). Figure 2 shows the maximum, minimum, mean, and standard deviation about the monthly mean; in every month there is a minimum of zero precipitation and a large standard deviation. This type of statistical representation provides a clearer picture of the precipitation resource for an area. The continental pattern like the summer pattern shows large variation from year to year, with a tendency toward a more frequent occurrence below the mean than above, as in Lubbock, Texas (Fig. 3).

The fourth precipitation pattern, the multimodal distribution, two alternating rainy and dry seasons occur. The intensity and duration of the rainy season vary greatly from year to year, and the two dry periods are not of the same length. This pattern of precipitation is confined to Africa and South America (Niewolt, 1977). These areas are located near the equator and are a result of the interaction between the intertropical convergence zone and the subtropical high pressure systems (Niewolt, 1977). Any shifts in these two major meteorological factors have a significant impact on when precipitation begins and how long it lasts. Thus, the year-to-year

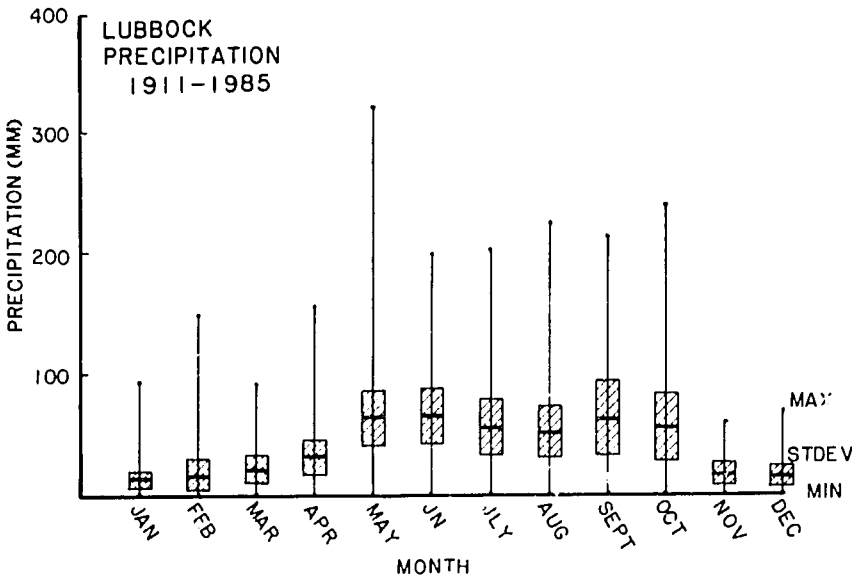


Figure 2. Monthly precipitation, maximum, minimum mean, and standard deviation about the mean for 75-year record at Lubbock, Texas.

rainfall variability is very large. The storms in this region tend to be more intense than in the summer pattern but less intense than the continental pattern.

Precipitation in all dryland areas is extremely variable and unreliable. Thus, one often does not separate the cause from the effect. There is no reliable method of predicting the amount of precipitation within a season, or the onset of the rainy season, both of which are extremely valuable to guide management practices in dryland regions. Stewart (1986) discussed the impact of developing management strategies to cope with the negative impacts of the rainfall variability. Stewart (1987) found that both the amount of rainfall and the duration of the rainy period were significantly correlated with the date of the onset of the monsoon. He found the 1954–1983 precipitation record of Niamey, Niger, divided into two groups; early and late onset of rains. Three features were characteristic of each group. In the early season, median rainfall amounted to 602 mm compared to 400 mm in the late onset seasons. The median duration of the rainy season was 113 days versus 83 days for the early and late seasons, respectively. Average rainfall per day in the early season was 5.3 mm compared to a late onset season average of 4.7 mm (Stewart, 1987). These characteristics are important in terms of planning and quantifying the precipitation resource in the dryland regions. Sivakumar (1989) described the agronomic implications of managing cropping practices to rainfall for Niger.

For many dryland areas in developing countries an increasing amount of climatic analyses are being completed relative to agroclimatology. An example of

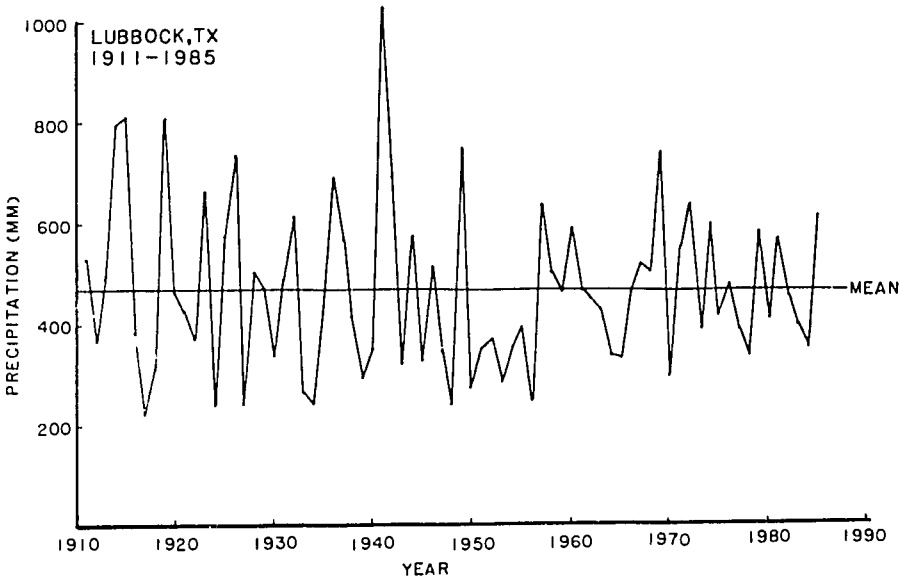


Figure 3. Yearly totals of rainfall for a 75-year period at Lubbock, Texas.

this type of compilation is given in the recent study in Mali reported by Sivakumar et al. (1984). This bulletin reports the mean monthly and yearly rainfalls with the probability estimates of the frequency of occurrence of particular rainfall amounts. Hargreaves (1982) has also prepared similar analyses for Senegal in which he computed the 75% probability of precipitation as the primary variable. The compilation of these data will provide a clearer understanding of the precipitation resource in dryland regions.

B. Radiation

Solar radiation for the dryland regions is not very well-defined, primarily because of the lack of measurement sites. Some general statements can be made about the potential solar radiation available for various regions. The amount of radiation available at the top of the atmosphere can be easily calculated using the relationship between the earth's position relative to the sun (Temps and Coulson, 1977). The energy which reaches the earth's surface depends on the time of year, cloudiness, elevation, water vapor content of the atmosphere, and exposure of the site (Niewolt, 1977). We can use the equations describing the penetration of solar radiation through the atmosphere to estimate an amount of the earth's surface; however, local conditions dictate the total energy received.

Some models such as those described by Davé et al. (1975) and Davé and Braslau (1975), could be employed to estimate incident solar radiation under clear skies. Decrease in solar radiation due to clouds could be accounted for by an

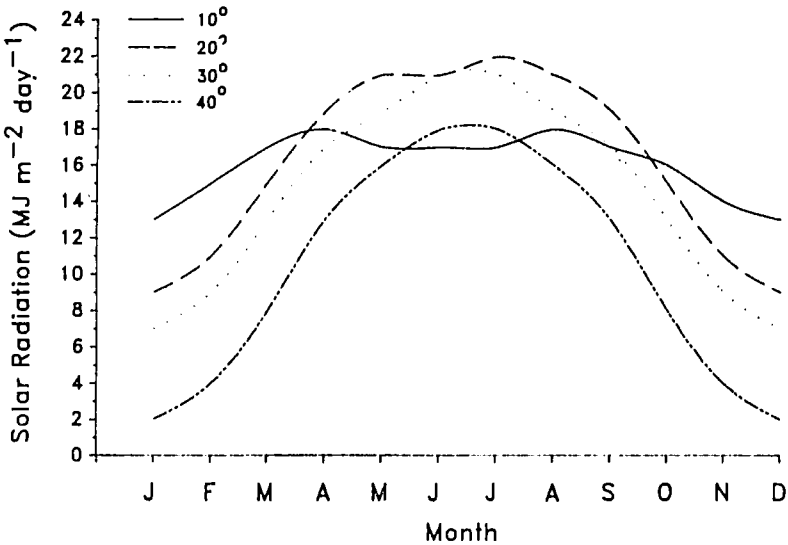


Figure 4. Radiation totals received on a horizontal surface for 10, 20, 30, and 40°N latitude.

adjustment for the percentage of cloud cover, which is observed as part of the meteorological observation schedule. However, accounting for the cloud type effect on global solar radiation is more difficult. Some models, such as those described by Davé and Braslau (1975), could be employed to account for various slopes and aspects of the surface. Modifications can be made for direct and diffuse solar radiation using the methods described by Temps and Coulson (1977).

Under clear sky conditions the amount of radiation at the surface varies largely with latitude in the Northern Hemisphere, as shown in Figure 4. The pattern changes in the Southern Hemisphere because of the sun's position. Lof et al. (1966) present charts of the world distribution of solar radiation. Unfortunately, an extensive record of solar radiation measurements around the world is not available for a comprehensive analysis. However, based on observations available for selected sites, variation in solar radiation with precipitation patterns could be analyzed as shown in Figure 5. The largest variation occurs during the season with the largest amount of precipitation because of the variation in cloudiness. The extreme variation in the precipitation in semiarid areas also leads to large deviations in the solar radiation resources about the mean.

Solar radiation resources are important for planning purposes and crop modeling efforts. There have been many successful uses of the percentage of possible sunshine as a means of estimating solar radiation. These are described by Jensen (1973) and by Dorenbos and Pruitt (1974). The form of these relationships is

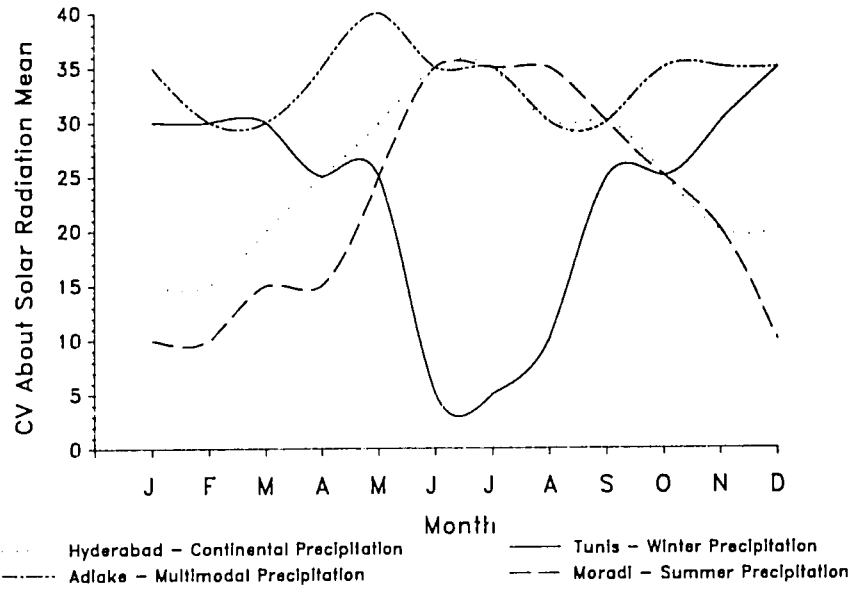


Figure 5. Coefficient of variation about the radiation mean for the four rainfall distribution patterns.

$$S_t = \left(a + b\,\frac{n}{N}\right)S$$

where S_t is the solar radiation, n/N the ratio of actual to potential sunshine hours, and S the extraterrestrial radiation for the particular latitude. This form of the relationship must be calibrated for each particular location and contains large errors because of the difficulty in estimating cloud cover. Solar radiation data obtained from reliable and calibrated instrumentation remain the best alternative.

For many applications, for example, evapotranspiration or soil water balance models, an estimate of net radiation is needed. Net radiation can be estimated empirically as a function of solar radiation with linear equations of the form

$$Rn = a + b\,S_t$$

with the typical values of a ranging from 0.6 to 1.0 and for b between −240 and −440. These coefficients have been summarized by Jensen (1973).

C. Temperature

Temperature within semiarid areas is not as variable as precipitation. However, in the context of influencing plant growth, it remains a controlling factor. The seasonal and diurnal variations of temperature must be considered if we are to develop

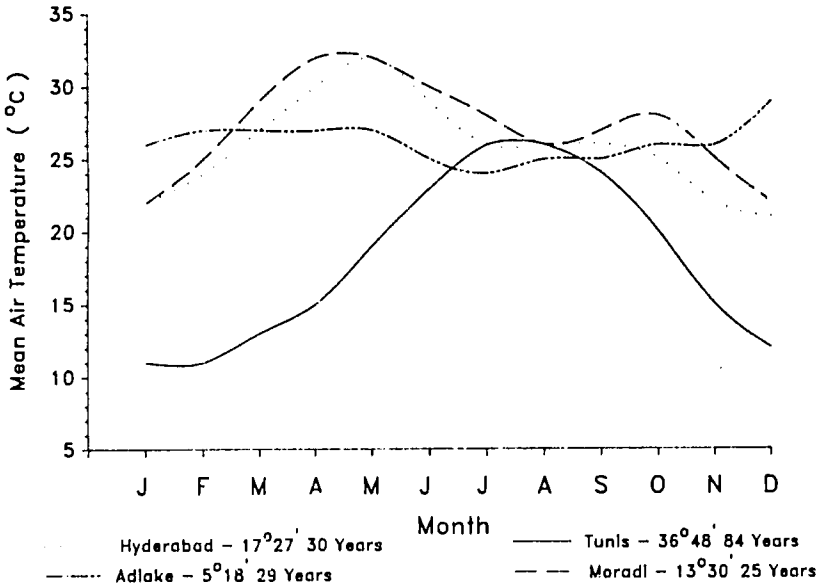


Figure 6. Seasonal variation in air temperature as a function of the station latitude and precipitation pattern.

a realistic understanding of an area's agroclimate. Initially, we consider only air temperature data, which are commonly collected at the height of standard 2 m.

Seasonal variation in temperature increases with the distance from the equator (Fig. 6). Near the equator in the tropics is a zone with near constant seasonal temperature, and seasonal variation increases as the position of the sun changes. Niewolt (1977) discusses these features in detail. The seasonal patterns are complicated by the rainfall pattern, as shown in Figure 6.

Seasonal variations in temperature are not controlled solely by the position of the sun, but rather by a myriad of local factors including elevation, prevailing winds, clouds, humidity, distance from large bodies of water, and natural ground cover. To illustrate the effect of cloudiness, Figure 6 compares the seasonal temperatures from monsoon and from continent rainfall areas for Hyderabad, India; Adiake, Ivory Coast; Tunis, Tunisia; and Maradi, Niger. Areas with monsoon rainfall show a reduced average temperature during the rainy season compared with the warmer temperature prevalent in the continental patterns.

Mean maximum and minimum air temperatures vary among stations, however, some representative semiarid locations are shown in Table 1. Temperatures from these stations are quite variable with the diurnal range depending on the precipitation patterns. Locations from the continental climate (e.g., Hyderabad) have the largest diurnal range during the summer while the monsoon season (e.g., Maradi) exhibits a reduced diurnal variation. Temperature patterns depend on the exact location, however, these data serve as a guide for general discussion. Some of the recent reports like that prepared by Sivakumar et al. (1984) for Mali and

Table 1. Mean monthly maximum and minimum air temperature (°C) for selected semiarid stations.[a]

Station		Temperature, °C											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Niamey, Niger (40), Summer	max	33	36	39	41	40	37	34	32	33	37	37	34
	min	16	18	22	26	27	25	24	23	23	23	19	16
Khortoum, Sudan (82), Summer	max	32	33	37	40	42	41	38	36	38	39	35	32
	min	16	17	20	23	26	27	26	25	25	25	21	17
Dakar, Senegal (30), Summer	max	25	25	25	25	26	29	30	30	30	30	29	27
	min	17	17	17	18	20	23	25	25	24	24	23	20
Lubbock, TX (30), Continental	max	12	14	18	24	28	33	33	33	29	24	17	13
	min	−7	−2	1	7	12	17	19	19	14	8	1	−3
Bismarck, ND (30), Continental	max	−7	−4	2	13	19	24	29	29	22	16	4	−3
	min	−19	−16	−9	0	6	11	14	13	7	1	−8	−15

[a] Length of record shown in parentheses by the station name and the type (years) is of precipitation pattern.

Sivakumar and Gnoumou (1987) for Burkina Faso serve as a model guide for presentation of data. In their report they included probability values for given maximum and minimum temperature levels. Another report that provides a data source is Wallen and Perrin de Brichambaut (1962), who collected available data for the Near East countries. Data are available from a number of sources for each country.

Temperature data are needed for crop models, evapotranspiration models and evaluation of planning models. These data are generally reliable and have a length of record sufficient for climatic analyses. Soil temperature data, however, are more difficult to obtain because few observations are made. Soil temperature data are often needed for planting and cropping decisions and often are not available. It is possible to estimate soil temperature from air temperature and radiation using some of the empirical and theoretical models. Examples of the combination of empirical and theoretical approaches are those described by Persaud and Chang (1983), Gupta et al. (1982), and Hasfurhter and Burman (1974). These models have produced acceptable results in predicting soil temperatures for a variety of conditions and are relatively simple to use.

D. Humidity

Measurements and maps of the atmospheric water content are of value for evapotranspiration, insect, and disease models. The most common expression of atmospheric water content is relative humidity; however, vapor pressure deficit

Table 2. Midday relative humidity values for selected stations from the semiarid areas.[a]

Station	Relative humidity, %											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Teheran, Iran, Winter	50	40	30	30	20	20	15	20	20	30	45	50
Damascus, Syria, Winter	59	47	41	31	27	19	18	19	24	31	41	58
Shlifa, Lebanon, Winter	73	69	67	57	53	48	51	52	58	58	68	75
Lubbock, TX, Continental	48	48	40	41	43	43	48	48	51	48	45	46
Bismarck, ND, Continental	67	67	62	54	50	54	47	44	49	50	63	69

[a] Rainfall pattern is shown for each station.

is of more practical application. Vapor pressure deficit conveys more of an expression of the drying power of the atmosphere and is related to evapotranspiration and crop harvest. The mean water vapor pressure could be obtained from the air temperature and relative humidity. Generally, mean humidity values given in most climatic summaries are adequate for most applications. An example of this type of report is that of Griffiths (1972) for Africa. These data, however, are still sparse except for first-order meteorological stations. Relative humidity varies with the time of year and precipitation patterns and is generally higher during the rainy seasons. Wallen and Perrin de Brichambaut (1962) reported humidity values for various stations in the Near East, and selected data from these sites and additional Great Plains locations are shown in Table 2.

E. Wind

Wind speed and wind direction data are even more difficult to obtain at local sites than humidity data. General patterns of wind flow are dictated by the general circulation patterns and prevailing storm tracks (Niewolt, 1977). This is primarily an effect of the low pressure systems which accompany these storms. For example, storm systems responsible for monsoon activity cause a change in the wind-flow patterns.

Local wind speeds are a function of the position of the pressure system and local topography. Data would be available from first-order or airport stations but should be extrapolated into agricultural areas with caution. Windspeed data available for semiarid areas show that these areas often have higher wind speeds than the more humid regions. The higher wind speeds are due to generally sparse vegetation which has lesser of an effect on the mean flow than dense vegetation in humid areas. Dorenbos and Pruitt (1974) discuss the need for windspeed data

in the evaporation models. These data need to be collected routinely with reliable, accurate instrumentation. Extrapolation of windspeed data must take into consideration the height of observation.

Wind in many semiarid areas is responsible for plant damage from either blowing sand or mechanical damage (Grace, 1977). The lack of ground cover, often found in semiarid regions makes the sandy soils particularly susceptible to strong winds. Protection of plants by wind barriers is necessary to ensure establishment of seedlings. Understanding wind effects on plants will improve plant production systems in semiarid areas.

F. Evaporation

The water balance of an area, which is a balance of precipitation and evaporation, is often a major factor in agricultural production in the semiarid regions, and agroclimatic indices are based on this precipitation/evaporation balance.

Water loss from a vegetated surface has been described by a number of reports and the factors influencing the evaporation losses are well understood. Dorenbos and Pruitt (1974) and Jensen (1973) provide a comprehensive treatment of potential evaporation models and the input data needed for each particular method. Hatfield (1989) discussed the current limitations in the ET methods more commonly used in semiarid areas. The more common models currently used for assessing evaporation are those of Thornthwaite, Blaney-Criddle, Jensen- Haise, Priestly-Taylor, Penman-Monteith, and the evaporation pan model (Jensen, 1973). Each of these models has particular limitations with which the user should be aware. The primary limitation of any of the models is the availability of data. Dugas and Ainsworth (1983) compared the Penman-Monteith, Priestley-Taylor, and evaporation pan techniques over the state of Texas. They found that all of these methods were comparable, but in the more humid areas of east Texas the Priestley-Taylor was less reliable. Over Texas for the complete year, the Penman-Monteith model provided the most consistent estimates. Use of this model is recommended, with an understanding of the limitations. Allen (1986) discussed some of the refinements that help improve the Penman model to make it more applicable to a wide range of conditions. Sivakumar and Gnoumou (1987) used the Penman model to evaluate the potential evapotranspiration for Burkina Faso. Potential evapotranspiration amounts vary greatly with the season and the rainfall pattern, as shown in Figure 7.

Any evaporation model will provide an estimate of the potential evaporation rate or amount integrated over some time interval. Water use by a crop under nonlimiting water conditions can be estimated from reference evapotranspiration using a K_c factor or crop coefficients. Dorenbos and Pruitt (1974), compiled K_c factors for several crops and stages of development. As a word of caution about the use of these K_c values, they can be used for nonlimiting water conditions but may not be applicable to the limited soil water conditions of the semiarid regions. This aspect needs considerable refinement and is an area of future research which needs to be addressed. Dancette (1980) found that the water requirements of several millet

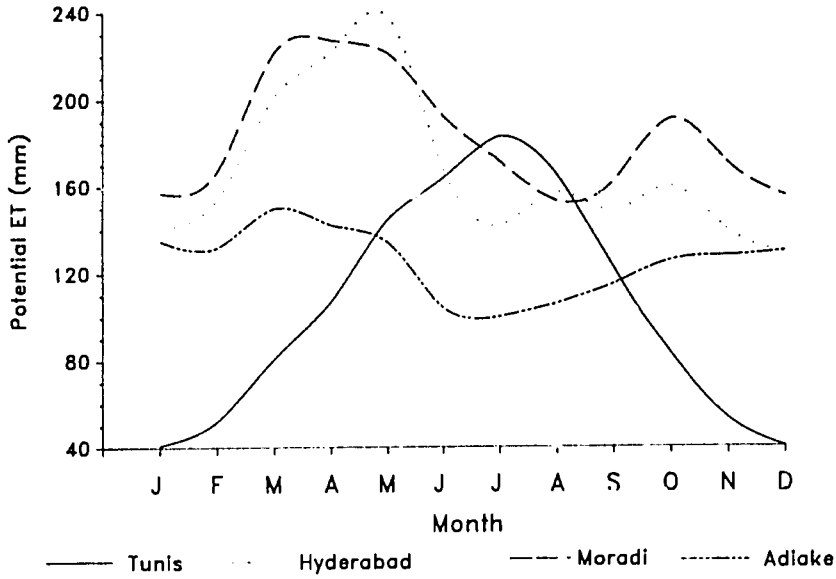


Figure 7. Seasonal variation in potential evapotranspiration for the four rainfall pattern types shown in Figure 1.

varieties were in direct proportion to the length of the growing season. A unique feature of this study was that water requirements were measured under situations of limited soil water. He stated that improvements in millet production will require the interdisciplinary research efforts to address breeding, management, economics of millet production and animal utilization.

III. Soils

In any agroclimatological analysis, the soils resource of an area cannot be overlooked. Soils information needs to be placed on a reference scale similar to the climatological data. From the interfaces between soils and climate, extensive use of models that assess the agroclimatic potential of an area can be made and the economic implications of a management practice can be evaluated. With the development of more sophisticated geographic information systems this will become an achievable reality.

Soils in semiarid regions vary considerably, and other chapters provide an overview of the soil types. From an agroclimatological viewpoint several aspects of the soils are important: the water holding capacity, infiltration rate, and available depth for rooting. It is obvious that these parameters will have an impact on the effectiveness of the soil profile in capturing rainfall and water supply to the growing plant.

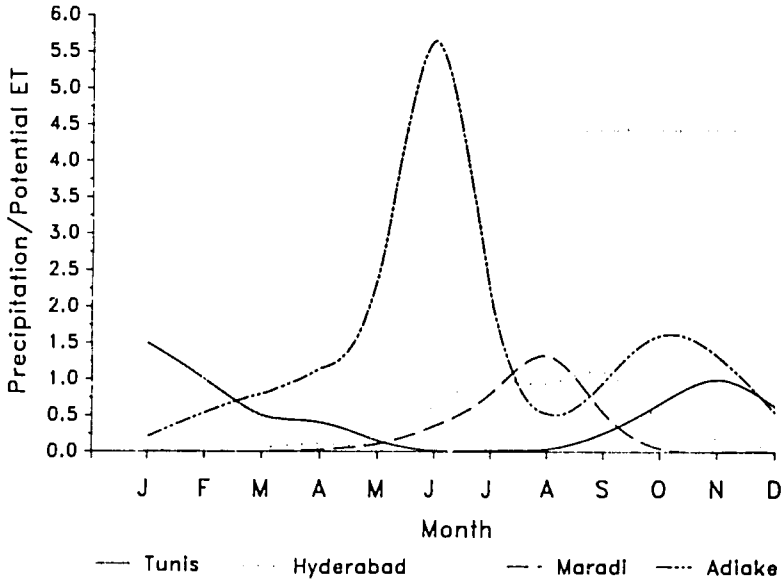


Figure 8. Seasonal variation in precipitation/potential evapotranspiration ratio for the four rainfall patterns shown in Figure 1.

IV. Agroclimatic Indices

The utility of climatic data for the semiarid area lies in the incorporation of these data into agroclimatic indices. These indices may range from the simple precipitation/potential evaporation (P/E_p) ratios to more complicated soil–plant–atmosphere models. It is only through the incorporation of several pieces of data that a comprehensive understanding of the agroclimatic resources of an area can be made. Several of these indices are discussed to show the utility and limitations of some of these approaches.

One of the most used approaches is the precipitation/potential evaporation ratio. The 1977 UNESCO conference on desertification defined a climatic aridity index based on precipitation (P) and potential evaporation (E_p) from the Penman ET model (UNESCO, 1977). The committee defined four classes of arid zones:

hyperarid zone ($P/E_p < 0.03$)
arid zone ($0.03 > P/E_p < 0.20$)
semiarid zone ($0.20 > P/E_p < 0.50$)
subhumid zone ($0.50 > P/E_p < 0.75$)

This delineation of the zones is not precise, and large errors can occur in the classification of a given location. The computed P/E_p ratio is for the four rainfall patterns of Figure 1, and Figure 8 shows that a given station can be classified in many different categories over a year. FAO (1978), in an attempt to refine these

indices, suggested that the growing period be used to evaluate the climatic zones. The committee defined a potential growing period as the number of continuous days in a year when the precipitation exceeded 0.5 E_p plus a period over which 100 mm of stored soil water could be used from the soil profile. Use of this procedure resulted in three classes of growing periods: normal, intermediate, and dry. A normal growing period would include a time when precipitation exceeded evaporation, for example, a humid period, while an intermediate growing period would not. In a dry growing period, precipitation would not exceed half the potential evaporation. Using this system, an area with a growing period between 1 and 74 days is arid while those with growing periods between 75 and 119 days are classified as semiarid regions.

Martonne (1962) had suggested that an aridity index (I) could be expressed as

$$I = \frac{nP}{T + 10}$$

where n is the number of rainy days, P the mean precipitation per day (millimeters day^{-1}), and T the temperature in a selected period (degrees Celsius). He suggested that this method would provide an effective classification method for developing countries. Krishnan et al. (1980) defined an aridity index (AI) as

$$\mathrm{AI} = \frac{(E_p - E_a) * 100}{E_p}$$

Where E_a is the actual evaporation and E_p is calculated from a Penman model. This model requires detailed measurements of the actual evaporation and thus, would not be a general model useful for large-scale analyses. Also, it is difficult to obtain the actual evaporation data for a number of crops.

Walton (1969) cautioned that the highly variable rainfall in arid regions makes nonsense of mean annual rainfall statistics, and thus would affect the interpretation of any climatic index. Subramaniam and Sastri (1969) found the definition of a climatic zone would vary from year-to-year because of the variation in yearly rainfall. They found in a 75-year record that 39 years were on the dry side and 37 on the wet side. This pattern is evident in all rainfall records from semiarid stations. Russell (1978) stated that most of the climatic classification similar to those just described are applicable to mesoscale analysis. However, a more microapproach is necessary for planning and evaluation purposes. He proposed that pattern analysis could be used successfully in agroclimatological studies. He suggested that pattern analysis techniques could be used for five purposes in agroclimatological research: classification of climates, detection of homoclimates, grouping of experimental areas and locations, geographic extrapolation of experimental results, and domain definition. He used this procedure to identify similar areas in Australia and India, and stated that lack of quantitative definition of the climate–crop interaction was a major limitation.

An approach which is based on the climate–crop interaction was proposed by de Jager (1971) and used by Scotney and de Jager (1971). In their methodology

the climatic requirements of the crop were assessed and the inability of the climate to satisfy the requirements reduced the potential crop yield. Their examples used soil water and maize yield but could easily be extended to any number of variables. Approaches such as those shown by Brown et al. (1983) on genetic material may be useful in developing more quantitative approaches to climate-plant interactions. The refinement of the multivariate methods suggested by Ayoade (1977) may provide an improved quantitative description which other groups have desired. The recent advances in mathematics called fuzzy sets have not been extensively applied to agroclimatology, although McBratney and Moore (1985) have shown some preliminary data which are encouraging. This procedure may be a refinement of the pattern analysis techniques.

One of the more complete examples of agroclimatic classification is that given by Reddy (1983a,b,c,d) based on rainfall and potential evapotranspiration. He applied his classification scheme to India, Senegal, and Burkina Faso. He defined an available effective rainy period as the number of consecutive weeks in which the 14-week moving average of $P/E_p \geq 0.75$ with the initial week having a $P/E_p \geq 0.5$. This procedure allows an identification of the wet and dry spells and an estimate of potential years of crop failure (Reddy, 1983a,b). He found that in the semiarid tropics cropping patterns are influenced not only by the effective rainy period but also by the variability in this period and the times at which the sowing rains commence (Reddy, 1983c). In this study it was found that crop varieties which were suited also varied, but their response was more closely correlated with the soil type and the occurrence of wet and dry spells. In extending this procedure to large areas or countries he used the same methodology, Euclidean matrix, as Russell (1980) to stratify the stations (Reddy, 1983d). This study provides a framework on which further analyses of this research topic can be conducted.

Climatic analysis for the semiarid regions requires integration of climatic, soils, and crop information. The methods shown here are not complete and require further refinement. These refinements are in the area of improved understanding of the crop-climate interaction, particularly when this information is used to evaluate alternative crop selection or management practices. There are no set guidelines or fully successful studies that allow for a complete analysis of the agroclimatological resources of an area. These studies are beginning to emerge as the ease in data base manipulation becomes more advanced.

V. Limitations

It is often assumed that the primary limitation to agroclimatological research is data, however, the limit is high-quality data. In this chapter several climatic parameters have been shown and the confidence level we can place in those numbers and the derived climatic indices is implicitly assumed to be 100 percent. However, each number should be treated with scrutiny. Advances in agroclimatological analysis will come with greater reliability in the available data rather than a large increase in the amount of data. Developing countries may lack data from the

agriculture areas, but, a few well-placed and maintained agroclimatological stations will be of greater benefit than a large number of poorly maintained stations.

With the development of computer resources to blend soils, climate, and agricultural data, it will be possible to develop more comprehensive studies of the agroclimatological resources. This will allow the primary limitation of data availability to be overcome, resulting in an advance in the understanding of the agroclimatological resources for small areas.

VI. Research Needs

The emergence of computer technology and simulation models affords the opportunity to advance the knowledge base in agroclimatology. The largest need for research documentation is in the area of the stress response of crops to limited soil water supplies. There is little comprehensive information on the varietal response of any of the crops commonly grown in semiarid areas. This information is needed to develop a more complete understanding of the impacts of reduced rainfall.

Interfacing the climatic probabilities of a number of parameters, such as rainfall, temperature, and evaporation, with crop growth models will provide a more complete description of the total agricultural system. This approach allows a framework into which the impacts of insects, diseases, and weeds can be incorporated. This approach will require refinement in the available soil water models to interface more accurately with the crop growth patterns.

The primary research need for agroclimatology is to assemble multidisciplinary research teams whose members have the capabilities to address a broad spectrum of problems. Given this approach the development of a broader spectrum of answers can be obtained. The reports cited in this report address the available data base but have not moved toward integrating this knowledge. This integration of knowledge to stabilize production in a semiarid region is the challenge for the remainder of this century.

References

Allen, R.G. 1986. A Penman for all seasons. J. Irrig. Drainage. 112:348-368.

Ayoade, J.O. 1977. On the use of multivariate techniques in climatic classification and regionalization. Arch. Meterol. Geophys. Bioclimatol. 24:257-267.

Brown, D.K , M.F. Sorrels, and W.R. Coffman. 1983. A method for classification and evaluation of testing environments. Crop. Sci. 23:889-893.

Dancette, C. 1980. Water requirements and adaptations to the rainy season of millet in Senegal. In R.H. Shaw, M.V.K. Sivakumar, and S.M. Virmani (eds.). Proc. of the International on Agroclimatological Research Needs of the Semi-arid Tropics. ICRISAT. Hyderbad, India. pp. 106-120.

Davé, J.V., P. Halpern, and N. Braslau. 1975. Spectral distribution of the direct and diffuse solar energy received at sea-level of a model atmosphere. Rep. G320-3332 IBM Palo Alto Scientific Center.

Davé, J.V., and N. Braslau. 1975. Effect of cloudiness on the solar energy through a realistic model atmosphere. J. Appl. Meteorol. 14:388-395.

de Jager, J.M. 1971. Theory for the assessment of environmental potential. Agrochemophysica. 3:67-70.

Dorenbos, J., and W.O. Pruitt. 1974. Crop water requirements. Irrigation and Drainage paper No. 24. FAO, Rome.

Dregne, H.E. 1982. Dryland soil resources. Science and Technology Agriculture Report. Agency for International Development, Washington, D.C.

Dugas, W.A., and C.G. Ainsworth. 1983. Agroclimatic atlas of Texas. VI. Potential evapotranspiration. Texas Agric. Expt. Station. MP-1543. College Station, TX.

FAO. 1978. Report on the agro-ecological zones project. I. Methodology and results for Africa. World Soils Resources Project #48. Rome.

Grace, J. 1977. Plant response to wind. New York. Academic Press.

Griffiths, J. 1972. Climates of Africa. In World Survey of Climatology, Vol. 10. Elsevier Publ. Co., Amsterdam.

Gupta, S.C., J.K. Radke, W.E. Larson, and M.J. Shaffer. 1982. Predicting temperatures of bare- and residue-covered soils from daily maximum and minimum air temperatures. Soil Sci. Soc. Am. J. 46:372-376.

Hargreaves, G.H. 1982. Dependable precipitation and potential yields for Senegal. A practical guide for rainfed agriculture. International Irrigation Center. Utah State Univ. Logan, Utah.

Hasfurhter, V.R., and R.D. Burman. 1974. Soil temperature modeling using air temperature as a driving mechanism. Trans ASAE 17:78-81.

Hatfield, J.L. 1990. Methods of estimating evapotranspiration. In B.A. Stewart and D.R. Nielson (eds.). Irrigation of Agricultural Lands. American Soc. of Agronomy, Madison, WI.

Jensen, M.E. 1973. Consumptive use of water and irrigation water requirements. Techn. Comm. on Irrig. Water Requirements. Irrigation and Drainage Div. ASAE.

Krishnan, A., Y.S. Rama Krishnam, aad G.G.S.N. Rao. 1980. Is the incidence of droughts increasing in the arid zone of north-west India. In Manu, H.S. (ed.). Arid zone research and development. Central Arid Zone Res. Institute. Scientific Publishers. Jodhpur, India. pp. 47-51.

Lof, G.O.G., J.A. Duffie, C.O. Smith. 1966. World distribution of solar radiation. Univ. of Wisconsin. Report No. 21.

Martonne, E. de. 1962. Une nouvelle fonction climatologigue l'indice d'aridite. La Meteorologie Nouvelle 2:449-458.

McBratney, A.B., and A.W. Moore. 1985. Application of fuzzy sets to climate classification. Agric. For. Meteorol. 35:165-187.

Niewolt, S. 1977. Tropical Climatology. New York: John Wiley & Sons.

Persaud, N., and A.C. Chang. 1983. Estimating soil temperature by linear filtering of measured air temperature. Soil Sci. Soc. Am. J. 47:841-846.

Reddy, S.J. 1983a. Agroclimatic classification of the semi-arid tropics. I. A method for the computation of classificatory variables. Agric. Meteorol. 30:185-200.

Reddy, S.J. 1983b. Agroclimatic classification of the semi-arid tropics. II. Identification of classificatory variables. Agric. Meteorol. 30:201-219.

Reddy, S.J. 1983c. Agroclimatic classification of the semi-arid tropics. III. Characteristics of variables relevant to crop production impotential. Agric. Meteorol. 30:269-292.

Reddy, S.J. 1983d. Agroclimatic classification of the semi-arid tropics. IV. Classification of India, Senegal, and Upper Volta. Agric. Meteorol. 30:293-325.

Russell, J.S. 1978. Classification of climate and the potential usefulness of pattern-analysis techniques in agroclimatological research. In Shaw, R.H., M.V.K. Sivakumar, and S.M. Virmani (eds.). Proc. of the International Workshop on the Agroclimatological Research Needs of the Semi-Arid Trops. ICRISAT, Hyderbad, India, pp. 47-58.

Scotney, D.M., and J.M. de Jager. 1971. The assessment of environmental potential. Agrochemophysica. 3:71-74.

Sivakumar, M.V.K. 1989. Integrating soil and crop models for agroclimatological analyses. International Conference on Dryland Farming. Amarillo/Bushland, Texas, Aug. 15-19, 1988.

Sivakumar, M.V.K., M. Konate, and S.M. Virmani. 1984. Agroclimatology of West Africa: Mali. Information Bulletin No. 19. ICRISAT.

Sivakumar, M.V.K., and F. Gnoumou. 1987. Agroclimatology of West Africa: Burkina Faso. Info. Bull. No. 23. ICRISAT.

Stewart, J.I. 1986. Development of management strategies for minimizing the impact of seasonal variation in rainfall. International Consultants Meeting on Research on Drought Problems in the Arid and Semi-Arid Tropics (ICRISAT).

Stewart, J.I. 1987. Potential for response farming in sub-Saharan Africa. Workshop on Soil and Water Management Systems for Rainfed Agriculture in the Sudano-Sahelian Zone. ICRISAT, Niamey, Niger.

Subramaniam, V.P., and C.V.S. Sastri. 1969. A study of aridity and droughts at Visakhapatnam. Annals of the Arid Zone. 8:18-22.

Temps, R.C., and K.L. Coulson. 1977. Solar radiation incident upon slopes of different orientations. Solar Energy. 19:179.

UNESCO. 1977. World map of desertification. United Nations Conference on Desertification. A/Conf. 74/2.

Wallen, C.C., and G. Perrin de Brichambaut. 1962. A study of agroclimatology in semi-arid and arid zones of the near east. FAO/UNESCO/WMO Interagency report on Agroclimatology.

Walton, K. 1969. The Arid Zones. Chicago: Aldine Pub. Co.

Conservation Tillage Systems*

P.W. Unger*

I. Introduction 28
A. Definitions 28
B. Type of Conservation Tillage Systems 28
C. Purpose of This Review 29
II. Conservation Tillage Equipment 30
III. Weed Control 30
A. Weed Control with Tillage 30
B. Weed Control with Herbicides 31
C. Weed Control with Crop Rotations 31
IV. Water Infiltration, Evaporation, and Conservation 32
A. Infiltration and Runoff 32
B. Evaporation 35
C. Water Conservation 37
V. Crop Growth, Yields, and Water Use 45
A. Growth and Yields 45
B. Water Use and Use Efficiency 46
VI. Soil Erosion and Environmental Quality 47
A. Wind Erosion 47
B. Water Erosion 49
C. Environmental Quality 51
VII. Insects, Plant Diseases, and Other Pests 52
VIII. Soil Properties 53
A. Temperature 53
B. Soil Aggregation 55
C. Soil Density and Porosity 55
D. Other Physical Properties 56
IX. Economics 57

*Contribution from USDA, Agricultural Research Service, Conservation and Production Research Laboratory, P.O. Drawer 10, Bushland, TX 79012.

1990 by Springer-Verlag New York Inc.
Advances in Soil Science, Volume 13

X. Summary and Conclusions 59
A. Accomplishments 59
B. Needs 60
References 61

I. Introduction

"Conservation tillage is not a panacea, but it is one of the best ways yet found to meet our national priorities of soil and water conservation" (Meyers, 1983). These words by the former chief of the U.S. Department of Agriculture's (USDA's) Soil Conservation Service corroborate the attitude of many persons regarding the potentials of this practice for conserving soil and water resources, not only in the United States, but also in many other countries throughout the world.

A. Definitions

A commonly accepted definition of conservation tillage is any tillage system that leaves at least 30% of the soil surface covered with residues after a crop is planted. It implies that a similar or greater amount of residues would be present at all times during the interval between crops. Another definition is "any tillage sequence that reduces loss of soil or water relative to conventional tillage; often a form of noninversion tillage that retains protective amounts of residue on the surface" (SCSA, 1982). Conventional tillage has been defined as "the combined primary and secondary tillage operations performed in preparing a seedbed for a given crop in a given geographical area" (SCSA, 1982). Conventional tillage may reduce soil and water losses, but reduction in losses compared with conventional tillage is a requirement of conservation tillage (Mannering and Fenster, 1983).

The importance of surface residues for reducing soil and water losses is recognized by both definitions of conservation tillage. However, crop residues are sometimes limited under dryland conditions and may be removed (harvested) for other purposes in other cases. Consequently, conservation tillage in this chapter involves not only residue management systems (adequate residues available), but also tillage practices that conserve soil and water under low- or no-residue conditions compared with more traditional clean tillage methods.

B. Type of Conservation Tillage Systems

Conservation tillage is an umbrella term covering a wide range of tillage practices that provide soil and water conservation benefits. Practices used for row crops [maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L. Moench), etc.] generally are different from those used for small grain crops [wheat (*Triticum aestivum* L.),

Table 1. Conservation tillage methods[a]

Rowcrop agriculture	Small grain agriculture
Narrow strip tillage	Stubble mulch farming
No-till, zero-till, slot plant	Stirring or mixing machines
Strip rotary tillage	Disk-type implements
	• Oneway disk
Ridge planting	• Offset disk
Till plant	• tandem disk
Plant conventionally on ridge	Chisel plows
	Field cultivators
Full width – no plow tillage	Mulch treaders
Fall and/or spring disk	
Fall or spring chisel, field cultivate	Subsurface tillage
	Sweep plows
Full width – plow tillage	Rotary rodweeder
Plow plant	Rodweeder with semichisels
Spring plow-wheel-track plant	
	Ecofallow
	Direct drill

[a] From Mannering and Fenster (1983).

barley (*Hordeum vulgare* L.), rice (*Oryza sativa*), etc.]. Major types for row crops are narrow strip; ridge planting; full-width, no-plow; and full-width, plow. The types for small grains are stubble-mulch, ecofallow, and direct drilling. Mannering and Fenster (1983) discussed various subtypes of these practices which are listed in Table 1. Additional information regarding these practices is given in the chapter by Jones et al. on Tillage Systems and Equipment for Dryland Farming.

The practices listed in Table 1 were developed primarily for mechanized crop production, as in the United States, Canada, Australia, and other countries. Although mechanized equipment for such practices may not be available in less developed countries, the underlying principles of these practices for conserving soil and water are applicable, regardless of the type of equipment used (hand, animal-drawn, or tractor-drawn).

C. Purpose of This Review

The agricultural literature for the last several decades contains many reports pertaining to conservation tillage. A review of all such literature, even only that which pertains to dryland, is beyond the scope of this chapter. For this chapter, selected references are used to illustrate actual and potential benefits and problems of using conservation tillage for conserving soil and water resources under dryland crop production conditions.

II. Conservation Tillage Equipment

The equipment requirements for conservation tillage vary, depending on which type of system is used. Some systems depend primarily on mechanized equipment, while others are also adaptable to animal-drawn or hand-operated equipment. A detailed discussion regarding the types of equipment frequently used for the various conservation tillage systems is given by Jones et al. in the chapter on Tillage Systems and Equipment for Dryland Farming.

III. Weed Control

Weeds (including volunteer crop plants) compete with crops for water, nutrients, and light under all cropping conditions. However, under dryland conditions, competition for water is generally considered the most important. Consequently, effective weed control before and after crop planting is essential if crops are to produce at their potential under the prevailing environmental conditions. Weed control before planting increases the potential for higher soil water contents at planting, thus providing additional water for the subsequent crop. Weed control during the crop's growing season reduces direct competition for water.

Weeds can be controlled by cultural methods or with herbicides, either singly or in various combinations, to prevent weed seed germination or seedling establishment or to eliminate seedlings or plants that escaped the initial control measures. Best control is achieved when differences in crop and weed biological characteristics are exploited (Wiese and Staniforth, 1973).

Weeds may be annuals (cool or warm season), biennials, or perennials, with each type often requiring a different control method in a given crop production system. Because weed species differ greatly in different regions, general control measures involving tillage, herbicides, and crop rotations will be given rather than specific control measures for specific weed species.

A. Weed Control with Tillage

Controlling weeds is one of the major reasons for performing tillage. Tillage aids weed control by (1) killing emerging seedlings, (2) burying seeds, (3) delaying growth of perennials, (4) providing a rough surface, which hinders seed germination, (5) providing loose surface soil, which permits effective cultivation, (6) providing a clean uniform surface for efficient action of herbicides, and (7) incorporating herbicides when necessary (Richey et al., 1977). Different tillage methods affect soils differently. Consequently, different degrees of weed control may be achieved depending on which tillage method is used on a given soil.

Clean tillage methods such as moldboard plowing and repeated disking (oneway, tandem, offset) effectively control some weeds; but these methods mix or bury crop residues, thus leaving the soil highly susceptible to erosion. These tillage methods also bury weed seeds which may germinate when they are returned to the

surface by subsequent tillage, often one or more years after being buried initially. Alternative tillage methods that retain some or all residues on the surface include chisel, sweep or blade, till-plant, and no-tillage. Cultivation during the growing season may be required unless herbicides are used, as in the no-tillage system.

B. Weed Control with Herbicides

Herbicides are frequently used to control some weeds in many cropping systems involving tillage and for controlling all weeds in no-tillage systems. The herbicide used in a given situation depends on its mode of action and the type of plants to be controlled. Herbicides must be compatible with the current, as well as subsequent, crops to avoid damage.

Some herbicides require incorporation with soil to be effective. Tillage is used for this purpose. Soil mixing implements such as disks, rotary tillers, and rolling cultivators are more effective than stirring (chisels, sweeps) or inverting (moldboard plows) implements for herbicide incorporation.

The effectiveness of surface-applied herbicides also may be strongly influenced by the tillage system used because of the amount of residues retained on the surface with different implements. The surface residues may intercept herbicides, thus leaving some areas of soil untreated. Uniform distribution of residues on the surface minimizes herbicide interception problems and maximizes surface coverage with the residues.

Use of herbicides in no-tillage systems, and in other tillage systems as well, may cause a shift in weed species that predominate in a given situation. Richey et al. (1977) reported an increase in herbicide-resistant weeds (*Asclepias syriaca* L., *Panicum dichotomiflorum* Michx., and briars) with continuous no-tillage. In a wheat–sorghum–fallow system, the weed population shifted from broadleaf species that were susceptible to atrazine [2-chloro-4-(ethylamino)-6-(isopropylamino)-*s*-triazine] to a grassy species (*Cenchrus* sp.) that was resistant (Phillips, 1969).

C. Weed Control with Crop Rotations

Some weeds in some crops are difficult to control with tillage or with herbicides because of the similar biological characteristics and growth periods of the weeds and crops and because of the vigorous growth habits of some weeds (especially perennials). Weed control in continuous cropping systems may be especially difficult in such cases.

Where difficult-to-control weeds are present, rotations involving two or more dissimilar crop species may be the most effective and economical control method available. The rotations may involve warm-season crops, cool-season crops, or a combination of the two. Use of dissimilar warm-season crops [for example, sorghum and cotton (*Gossypium hirsutum* L.)] permits use of different herbicides, planting dates, and/or tillage methods, resulting in greater opportunity to control the troublesome weeds. Similar opportunities exist for cool-season crops. Even greater opportunities exist when warm- and cool-season crops are rotated. In

such cases, the problem weed can be controlled with tillage and/or herbicides during the interval between crops. Use of crop rotation also permits selecting crops that are most competitive against the troublesome weeds (Wiese and Staniforth, 1973). Crop rotation, or even skipping a crop, and using intensive weed control practices during the noncropped period may be necessary to reduce heavy infestations of troublesome weeds (Unger and McCalla, 1980).

IV. Water Infiltration, Evaporation, and Conservation

Yields of dryland crops are heavily dependent on the amount of water available for use by the crop. Consequently, water conservation is an important component of a dryland cropping system. Water conservation involves enhancing water infiltration into the soil (reducing runoff), suppressing soil water evaporation, and minimizing soil water use by noncrop plants (weeds, volunteer crop plants, etc.). Weed control was discussed in Section III and will not be discussed further. Also, it is assumed that the water storage capacity of soils under consideration is fixed; thus, altering the storage capacity is not discussed.

A. Infiltration and Runoff

Infiltration and runoff are closely related in that water that infiltrates a soil cannot be lost as runoff. However, runoff prevention does not ensure infiltration because some of the water temporarily stored on the surface may evaporate before it can infiltrate the soil.

Surface residues, as with conservation tillage systems, reduce runoff and increase infiltration by dissipating the energy of falling raindrops, thereby reducing soil aggregate dispersion that results in surface sealing, and retarding the flow rate of water across the surface, thus providing more time for water infiltration.

Table 2. Effect of tillage on runoff and soil losses from land cropped to maize in Nigeria[a,b]

	Bare fallow		Ploughed		No-tillage	
Slope (%)	Runoff (%)	Soil loss (Mg ha^{-1})	Runoff (%)	Soil loss (Mg ha^{-1})	Runoff (%)	Soil loss (Mg ha^{-1})
1	18.8	0.2	8.3	0.04	1.2	0.0007
5	20.2	3.6	8.8	2.16	1.8	0.0007
10	17.5	12.5	9.2	0.39 [sic][c]	2.1	0.0047
15	21.5	16.0	13.3	3.92	2.2	0.0015

[a] From Rockwood and Lal (1974).
[b] Rainfall was 44.2 mm.
[c] Probably an error.

Table 3. Average rainfall, runoff, and soil loss on tillage plots at Madison, South Dakota[a]

Tillage practice	Average values (1965 to 1970) Rainfall (mm)	Runoff (mm)	Soil loss (Mg ha^{-1})
Fallow	420	50 a[b]	17.5 a[b]
Conventional (plow and disk)	420	29 b	6.0 b
Mulch	420	24 c	3.7 c
Till-plant (with slope)	420	21 c	3.5 c
Till-plant (on contour)	420	10 d	0.9 d

[a] From Onstad (1972).
[b] Values within a column followed by the same letter are not significantly different (Duncan's multiple range test, 5% level).

Duley and Kelly (1939) measured infiltration of simulated rainfall into six soils ranging in surface texture from sandy loam to clay loam and subsoil textures from sand to clay. The surfaces were either bare or covered with 5.6 Mg ha^{-1} of wheat straw. Total water infiltration and infiltration rate averaged about five and three times greater, respectively, with the straw cover than with the bare surface. The differences in infiltration were attributed to a thin, dense layer that formed on the bare soil but not on the protected soil. The authors concluded that surface conditions had a greater effect on infiltration than soil type, slope, antecedent water content, and rainfall intensity. Soil water contents were not reported, but the study suggested that water storage for a subsequent crop would be greater in straw-covered than in bare soils.

Water infiltration increases with increasing amounts of residue on the surface (Berry et al., 1985; Lang and Mallett, 1984). Therefore, a complete cover of residues affords maximum protection of surfaces against raindrop impact and the potential for maintaining maximum infiltration rates. Land slope and soil permeability, however, also affect runoff and infiltration. Data in Tables 2, 3, and 4 illustrate the effects of tillage practice and/or slope of several soils on runoff and soil loss.

Table 4. Runoff and sediment yield from corn watersheds at Coshocton, Ohio, during a severe rainstorm on 5 July 1969[a]

Tillage	Slope (%)	Rainfall (mm)	Runoff (mm)	Sediment yield (Mg ha^{-1})
Plowed, clean-tilled sloping rows	6.6	140	112	50.7
Plowed, clean-tilled contour rows	5.8	140	58	7.2
No-tillage, contour rows	20.7	129	64	0.07

[a] From Harrold and Edwards (1972).

For the study in Nigeria (Table 2), runoff for a given practice (bare fallow, plowed, or no-tillage) was relatively little affected by soil slope but averaged 19.5, 9.9, and 1.8% on bare fallow, plowed, and no-tillage areas, respectively. Soil loss was affected by slope, and the reduction in soil loss on plowed and no-tillage areas was greater than the reduction in runoff from those areas.

The study in South Dakota (Table 3) was conducted on silty clay loam soils having about 6% slopes. All tillage methods reduced runoff as compared with the fallow treatments, but less runoff occurred with conservation tillage treatments (mulch or till-plant) than with conventional tillage. The value of contour tillage is also demonstrated by data in Table 3.

Rainfall was identical and slopes were similar for clean-tilled watersheds with sloping and contour rows for the study in Ohio (Table 4) but runoff and soil loss from the contoured watershed were only 52 and 14%, respectively, of that from the sloping-row watershed. No-tillage with corn planted in sod on contour rows resulted in 57% runoff and 0.1% soil loss compared with that from the sloping-row watershed, even though the slope was much greater on the no-tillage watershed.

The foregoing examples illustrate that residues retained on the surface with various tillage methods usually reduced runoff and soil losses. Unfortunately, amounts of residue are often low under dryland conditions or the residues are removed for other purposes. In such cases, other measures must be relied on to reduce runoff if water conservation is an important aspect of the cropping system. Reduction of runoff is possible with tillage, even where little or no residues are present, as Tables 2, 3, and 4 illustrate. Such reductions resulted from disrupting the dense, crusted surface layer, performing tillage on the contour, and/or increasing the surface roughness and plow-layer pore space. Similar results were reported by Black and Siddoway (1979), Muchiri and Gichuki (1983), Rawitz et al. (1983), Sherif et al. (1982), Stroosnijder and Hoogmoed (1984), and Willcocks (1981, 1984). Infiltration also can be increased by disrupting compact soil layers, if they are present.

The effect of surface roughness (retention volumes) and plow-layer pore space resulting from various tillage methods on infiltration of simulated rainfall is shown in Table 5. Cumulative infiltration approached plow-layer total pore space and surface retention volumes for the plow treatment before runoff started and exceeded those volumes before 25 mm of runoff occurred. For other treatments, storage volumes were not filled, even though 50 mm of runoff occurred. Smoother surfaces with treatments other than plowing apparently resulted in more rapid soil dispersion and surface sealing, which rapidly reduced infiltration and resulted in considerably more runoff.

Besides contouring and the retention storage afforded by surface roughness and plow-layer pore space, reduced amounts and/or rates of runoff also result from strip cropping (Wischmeier and Smith, 1978), various types of terraces (ASAE, 1982; Hauser, 1968; Jones, 1981), graded furrows (Pathak et al., 1985; Richardson, 1973), and furrow dikes (tied ridges) (Clark and Jones, 1981; Gerard et al., 1983, 1984), thus providing a potential for greater water infiltration and higher crop yields.

Table 5. Effect of tillage-induced plow layer porosity and surface roughness on cumulative infiltration of simulated rainfall[a]

Tillage treatment[c]	Potential water storage volume (mm) due to		Cumulative infiltration[b] (mm) to		
	Pore space[d]	Surface roughness	Initial runoff	25 mm runoff	50 mm runoff
Untilled	81	8	9	21	24
Plow	137	50	171	217	230
Plow-disk-harrow	124	25	53	73	84
Cultivated	97	29	57	83	91
Rotovated	117	15	24	38	41

[a] From Burwell et al. (1966).
[b] Water applied at a 127-mm hour^{-1} rate.
[c] Plowing and rotovating performed to a 15-cm depth; cultivating to a 7.5-cm depth on untilled soil.
[d] Measured to tillage depth.

B. Evaporation

In many dryland regions, as in the U.S. Great Plains, about 60% of the 500 mm of average annual precipitation may be lost directly from the soil by evaporation (Bertrand, 1966). The water may evaporate from the soil surface before it infiltrates, as the surface dries, or from within the soil, especially before a plant canopy completely covers the surface. As plant canopies develop, evaporation decreases and transpiration increases (Ritchie and Burnett, 1971).

Soil water evaporation occurs in three stages, with the greatest potential for reducing evaporation occurring during the first two stages (Lemon, 1956). During the first stage, evaporation is rapid and steady and depends on the net effects of water transmission to the surface and above-ground conditions such as wind speed, temperature, relative humidity, and radiant energy. Evaporation decreases rapidly as the soil water supply decreases in the second stage, during which soil factors control the rate of water movement to the surface and evaporation is little influenced by above-ground factors. Evaporation during the third stage is controlled by adsorptive forces at the solid-liquid interface and is extremely slow. Potential methods for decreasing evaporation include decreasing the turbulent transfer of water vapor to the atmosphere, decreasing capillary continuity, and decreasing capillary flow and water-holding capacity of surface soil layers.

Crop residue mulches have been studied extensively for decreasing evaporation. They mainly affect first-stage evaporation (Bond and Willis, 1969; Unger, 1976; Unger and Parker, 1976); but the long-term effect of mulches on evaporation is difficult to establish because of the interacting effects of the mulches on water infiltration, distribution in soil, deep percolation, and subsequent evaporation. Consequently, higher soil water contents resulting from surface mulches are attributable to the combined effects of the different

Table 6. Average daily soil surface temperature as affected by bare soil and wheat straw position during 5-week, August–September, period Akron, Colorado[a]

Straw position[b]	Soil surface temperature[c,d] (C)
Bare soil	47.8 c
Flat straw	41.7 b
3/4 flat, 1/4 standing	39.6 b
1/2 flat, 1/2 standing	32.2 a

[a] From Smika (1983).
[b] All straw amounts were 4.6 Mg ha^{-1}.
[c] Average of measurements at 1000, 1200, and 1500 hr with a radiation thermometer.
[d] Values accompanied by different letters are significantly different at $P = 0.01$ (Duncan's multiple range test).

processes, especially under field conditions where little or no control over soil wetting by precipitation exists.

Laboratory studies by Bond and Willis (1969), Hanks and Woodruff (1958), Unger and Parker (1976), and others have shown that evaporation decreases with increases in mulch thickness. Because mulch material density affects the thickness and surface coverage obtained with a given weight of material, a low-density material such as wheat straw reduces evaporation more effectively than higher-density materials such as sorghum stubble or cotton stalks. About two and more than four times as much sorghum stubble and cotton stalks, respectively, were needed to obtain a reduction in evaporation similar to that obtained with a like amount of wheat straw on a weight basis (Unger and Parker, 1976).

Other characteristics of residues that affect evaporation are residue orientation (flat or matted versus standing), which affects porosity and thickness of the layer; uniformity of the surface residue layer; rainfall interception by the residues; reflectivity, which affects the radiant energy balance at the soil surface; and aerodynamic roughness resulting from the residues (Van Doren and Allmaras, 1978).

Although measurement of evaporation under field conditions is difficult because of the interacting factors mentioned previously, some studies have clearly shown that surface residues decrease evaporation under field conditions. Smika (1983) showed that the same amount of residue on the soil surface, but in different positions, resulted in different rates of water loss by evaporation. As the amount of standing residue increased, greater wind speed was needed to initiate water loss. In addition, the water loss rate at a given wind speed decreased with increased amounts of standing residue. Residue position also affected soil temperature (Table 6), which in turn affected the evaporation rate through its influence on vapor pressure of the soil water (Smika, 1983).

The amount and position of surface residue strongly affect initial evaporation from a soil, but the water flow to the surface and the porosity or air permeability of the surface soil become more important in the evaporation process after the soil surface is dry. This was illustrated by Smika (1976a), who compared the

effects of conventional-, minimum-, and no-tillage treatments on soil water loss during a 34-day period following 165 mm of rainfall, during which no additional rainfall occurred. On the day after the rainfall, soil water contents to the 15-cm depth were similar for all treatments. At 34 days, soil with the conventional-tillage treatment had dried to less than 0.1 cm cm^{-1} to a 12-cm depth and the minimum-tillage soil had dried to that water content to a 9-cm depth. These depths corresponded to the depths at which a blade tillage operation was performed 8 days before the rain. In contrast, soil with the no-tillage treatment dried to the 0.1 cm cm^{-1} water content only to a 5-cm depth. Some soil water loss to depths greater than those mentioned occurred with each treatment, but water contents remained highest with the no-tillage treatment. Residue amounts on the surface during the 34-day drying cycle were 1.20, 2.20, and 2.70 Mg ha^{-1} with conventional-, minimum-, and no-tillage treatments, respectively.

C. Water Conservation

Water conservation (or storage in soil) is the net result of the interactions of a series of complex factors and processes. These include the amount, distribution, and type of precipitation; water infiltration, runoff, evaporation, distribution in the profile, and deep percolation; the soil itself (namely, texture, depth, density, organic matter content, etc.); and management practices used on the land (residue management, tillage system, cropping system, weed control, etc.).

Under dryland conditions, especially where growing-season precipitation is limited, the amount of plant-available water stored in soil at planting time has a major effect on growth and yield of the crop. For example, grain yields of dryland wheat, grain sorghum, and sunflower (*Helianthus annuus* L.) on a clay loam soil at Bushland, Texas, increased an average of 7.2, 17.0, and 7.0 kg ha^{-1}, respectively, for each additional millimeter of plant-available water in the soil at planting time (Johnson, 1964; Jones and Hauser, 1975; O.R. Jones, Bushland, Texas, personal communication).

Although many factors are involved, the emphasis in this section is on the effects of crop residue management practices on soil water storage under field conditions. In the following examples based on field studies, water conservation is the net result of the prevailing conditions, including weed control, infiltration and runoff, and evaporation, which were discussed individually in Sections III, IVA, and IVB, respectively, and are not repeated in this section.

An early study by Duley and Russel (1939) involved straw management, type of tillage, and basin listing (furrow diking or tied ridges) treatments (Table 7). Water storage with the surface straw treatment was much greater than with any other treatment and about two times greater than for the basin listing treatment that prevented runoff. This indicated the importance of surface residues for enhancing water conservation and that preventing runoff alone was not the total solution to water conservation. This was substantiated further in a study by Russel (1939) involving some of the early research with subsurface (stubble-mulch) tillage (Table 8). The preceding studies also showed that although runoff

Table 7. Effect of straw and tillage treatments on soil water storage 23 April to 9 September 1938 in Lincoln, Nebraska[a]

Treatment	Precipitation[b] stored (mm)	(%)	Depth of water penetration (m)
Straw, 4.5 Mg ha^{-1}, on surface	247	54.3	1.8
Straw, 4.5 Mg ha^{-1}, disked in	176	38.7	1.5
Straw, 4.5 Mg ha^{-1}, plowed in	155	34.1	1.5
No straw, disked	89	19.6	1.2
No straw, plowed	94	20.7	1.2
Decayed straw, 2 Mg ha^{-1}, plowed in	79	17.4	1.2
Basin listed	126	27.7	1.5

[a] Adapted from Duley and Russel (1939).
[b] Precipitation totaled 455 mm.

prevention with basin listing does not result in the greatest water conservation, it is an important practice for conserving water when crop residues are not available.

Stubble-mulch tillage (subtillage) was developed primarily for controlling wind erosion in the U.S. Great Plains; but its value for controlling water erosion and increasing water conservation, although limited, was soon recognized (McCalla and Army, 1961). The limited effectiveness of stubble-mulch tillage for controlling water erosion is attributed to the relatively low amounts of residue produced by dryland crops, which also contributed to the small increases in water storage compared with clean tillage. For example, differences in soil water contents averaged only 0.7% to a 1.5-m depth among stubble-mulch, plow, and one-way disk treatments from 1941 to 1947 in Montana and only 0.3% to a 1.8-m depth for similar treatments in Idaho. In Kansas, available water contents were 135, 152, and 180 mm to a 1.8-m depth with one-way disk, plow, and stubble-mulch tillage treatments, respectively. Wheat grain yields averaged 0.61, 0.45, and 0.93 Mg ha^{-1} with the respective treatments (McCalla and Army, 1961). At Bushland, Texas, soil water content to a 1.8-m depth at planting was 12 mm greater and grain yields were 0.11 Mg ha^{-1} greater with stubble-mulch than with one-way disk tillage in a continuous wheat system. In a wheat–fallow system, the increase in water content was 27 mm and the increase in yield was 0.13 Mg ha^{-1} (Johnson and Davis, 1972). The average increase in soil water content with stubble-mulch over clean tillage was 25 mm at seven locations in the central Great Plains (U.S.) (Smika, 1976b). Factors other than low residue production that contributed to the small increases in water storage with stubble-mulch tillage were the need for frequent tillage to control weeds, which exposed moist soil to the atmosphere and thereby increased evaporation, and the failure of stubble-mulch tillage to control all weeds, which resulted in some water loss by transpiration.

Although stubble-mulch (sweep or blade) tillage resulted in water storage and/or yields as great as or greater than with clean tillage in the preceding studies, such

Table 8. Water storage, runoff, and evaporation from field plots in Lincoln, Nebraska, 10 April to 27 September 1939[a]

Treatment	Storage (mm)	Runoff (mm)	Evaporation (mm)	Evaporative loss (%)[b]
Straw, 2.2 Mg ha^{-1}, normal subtillage	30	26	265	83
Straw, 4.5 Mg ha^{-1}, normal subtillage	29	10	282	88
Straw, 4.5 Mg ha^{-1}, extra loose subtillage	54	5	262	82
Straw, 9.0 Mg ha^{-1}, normal subtillage	87	Trace	234	73
Straw, 17.9 Mg ha^{-1}, no tillage	139	0	182	57
Straw, 4.5 Mg ha^{-1}, disked in	27	28	266	83
No straw, disked	7	60	254	79
Contour basin listing	34	0	287	89

[a] Adapted from Russel (1939).
[b] Based on total precipitation, which was 321 mm for the period.

tillage may not be the most effective under all conditions. For example, sweep tillage (about 0.1 m deep) resulted in generally poor water infiltration rates and sorghum grain yields on ferruginous sandy loam soils in Botswana (Willcocks, 1981). The poor response to sweep tillage was attributed to limited loosening of the clod-forming soil. Tillage methods that loosened the soil to about 0.2 m and provided for surface retention of water resulted in more reliable yields.

When suitable chemicals (herbicides) became available, interest developed in using them rather than tillage to control weeds and, thereby, maintain more residues on the soil surface for a longer time, which could improve erosion control and water conservation under dryland conditions. The practice, called chemical fallow, was the forerunner of present-day no-tillage crop production systems. Although chemical fallow aids erosion control (especially wind erosion), it generally did not improve water conservation because all weeds were not controlled by the herbicides during the fallow period (Wiese and Staniforth, 1973). In addition, weed control with herbicides was generally more expensive than with tillage.

The low amount of residues produced by dryland crops was not recognized as a factor contributing to the poor results in the initial studies. This limitation became apparent from studies by Greb et al. (1967) and Unger (1978a), which showed that soil water storage during fallow progressively increased with increasing amounts of crop residues on the soil surface (Tables 9 and 10). Results from several other studies involving herbicides and tillage for weed control are given in Tables 11, 12, 13, and 14.

For the studies by Greb (1974, 1978) (Table 11), limited-tillage treatments reduced weed growth, increased water storage, and increased yields compared with those of the spring disk (check) treatment. However, differences among limited-tillage treatments were small, which indicates the importance of early weed control for conserving water and increasing yields. Data in Tables 12, 13, and 14 show that the gain in soil water was lower for tillage treatments (plowing or disking) that incorporated residues than for treatments that maintained surface

Table 9. Straw mulch effects on soil water storage efficiency in Sidney, Montana; Akron, Colorado; and North Platte, Nebraska 1962 to 1965[a]

Mulch rate (Mg ha^{-1})	Fallow period precipitation (mm)	Water storage efficiency (%)
0	355	16
1.7	355-549	19-26
3.4	355-648	22-30
6.7	355-648	28-33
10.1	648	34

[a] From Greb et al. (1967).

residues (stubble-mulch, or limited-tillage, or herbicides only). The greatest gain resulted from herbicide-only treatments that permitted maximum retention of surface residues.

The foregoing examples illustrate the influence of various residue management practices on soil water conservation and crop yields. The progressive improvement in water conservation and wheat yields at Akron, Colorado, with changing management practices during fallow is illustrated in Table 15. The gain in water storage and yields is attributed to better weed control and to surface-residue maintenance, which enhanced infiltration and suppressed evaporation. The yield increases, however, are greater than would be predicted, based on the gain in yield per unit of soil water at planting time (Johnson, 1964). This suggests that improved varieties, fertility and weed control, and improved use of growing-season precipitation also contributed to the yield increases. Unger et al. (1986) have shown a positive influence of surface residues on growing-season precipitation use by sorghum for grain production.

Table 10. Straw mulch effects on soil water storage during fallow,[a] water storage efficiency, and dryland grain sorghum yield in Bushland, Texas, 1973-1976[b]

Mulch rate (Mg ha^{-1})	Water storage[c] (mm)	Storage efficiency[c] (%)	Grain yield (Mg ha^{-1})	Total water use (mm)	WUE[d] (kg m^{-3})
0	72 c[e]	22.6 c	1.78 c	320	0.56
1	99 b	31.1 b	2.41 b	330	0.73
2	100 b	31.4 b	2.60 b	353	0.74
4	116 b	36.5 b	2.98 b	357	0.84
8	139 a	43.7 a	3.68 a	365	1.01
12	147 a	46.2 a	3.99 a	347	1.15

[a] Fallow duration of 10 to 11 months.
[b] From Unger (1978a).
[c] Water storage determined to 1.8-m depth. Precipitation averaged 318 mm.
[d] Water use efficiency based on grain produced, growing season precipitation, and soil water changes.
[e] Column values followed by the same letter are not significantly different at the 5% level (Duncan's multiple range test).

Table 11. Effect of fall weed-control treatments in new wheat stubble on soil water storage and grain yields in dryland rotations[a]

Rotation and fall weed-control treatments	Fall weed growth (Mg ha^{-1})	Soil water storage at Fall dormancy[b] (mm)	Wheat or millet planting[c] (mm)	Grain yield (Mg ha^{-1})	WUE[d] (kg m^{-3})
Wheat-fallow					
Akron, Colo., 1969–1972 (Greb, 1974)			Winter wheat		
Check, spring disk	1.14	28	89	2.42	1.71
Fall sweep, single	0.65	53	112	2.69	1.79
Fall sweep, double	0.37	64	127	2.94	1.87
Atrazine + fall sweep	0.33	64	127	2.90	1.85
Fallow-wheat-millet					
Akron, Colo., 1973–1977 (Greb, 1978)			Millet		
Check, spring disk	1.18	1	114	1.99	–
Fall sweep, double	0.51	19	133	2.26	–
Contact herbicides + fall sweep	0.56	13	127	2.21	–
Fall sweep + atrazine	0.39	17	135	2.41	–

[a] From Greb (1974, 1978).
[b] From 25 October to 10 November.
[c] From 1 to 10 September for wheat and 1 to 10 June for millet.
[d] Water use efficiency based on grain yields, growing-season precipitation, and soil water changes.

Table 12. Effect of tillage and herbicide treatments on soil water contents at the end of the fallow period[a] and on wheat and sorghum yields in a 3-year wheat-fallow-sorghum-fallow rotation[b]

Treatment from wheat harvest to sorghum planting: Fall	Spring	Treatment from sorghum harvest to wheat planting[c]	Soil water gain[d] (mm)	Grain yields: Wheat (Mg ha^{-1})	Sorghum (kg ha^{-1})
Subtillage	Disk	Subtillage (5)	186 b[e]	3.49 a	4.08 b
Subtillage	Atrazine	Subtillage (4)	213 ab	3.76 a	4.20 b
Atrazine	Atrazine	Subtillage (4)	211 ab	3.63 a	4.58 ab
Atrazine	Atrazine	Contact herbicide (4–6)	223 a	3.49 a	4.89 a
Subtillage	Atrazine	Contact herbicide (4–6)	216 ab	5.02 a	5.02a

[a] Fallow duration of about 11 months.
[b] From Smika and Wicks (1968).
[c] Values in parentheses denote number of operations.
[d] Determined to a 3-m depth.
[e] Average values in a column followed by the same letter or letters are not significantly different at the 5% level (Duncan's multiple range test).

Table 13. Effect of tillage and herbicide treatments on soil water contents at the end of the fallow period and on wheat yields in a 2-year wheat-fallow rotation[a]

Operations during fallow[b]			
Initial operation following wheat harvest	Subsequent operations[c]	Soil water gain[d] (mm)	Grain yield (kg ha^{-1})
Plow	Subtillage (5)[d]	186 c[e]	3.09 b
Subtillage	Subtillage (5)	238 b	3.36 ab
Atrazine followed by subtillage	Subtillage (5)	272 b	3.29 ab
Atrazine	Subtillage (4)	275 b	3.36 ab
Atrazine	Contact herbicides (4–6)	325 a	3.56 a

[a] From Smika and Wicks (1968).
[b] Fallow duration of about 14 months.
[c] Values in parentheses denote number of operations.
[d] Determined to a 3-m depth.
[e] Average values in a column followed by the same letter or letters are not significantly different at the 5% level (Duncan's multiple range test).

In the U.S. southern Great Plains, dryland crops often do not produce enough residues to markedly increase soil water storage, even when most residues are maintained on the soil surface. In contrast, an irrigated crop such as winter wheat generally produces more than 7 Mg ha^{-1} of residues, and up to 11 Mg ha^{-1} have been measured. In the late 1960s, limited- and no-tillage studies involving

Table 14. Effect of tillage and herbicide treatments on number of operations needed for weed control, residues maintained on the surface, soil water storage during fallow, and wheat yields in a 2-year wheat-fallow rotation[a]

	Operations during fallow[b]				
Treatment	Tillage[c] (No.)	Herbicide application (No.)	Residues maintained[d] (%)	Soil water gain[e] (mm)	Grain yield (Mg ha^{-1})
Plow	8.5	0.0	0	146	2.69
Stubble mulch	8.7	0.0	21	203	2.88
Atrazine + stubble mulch	7.6	1.4	21	215	2.91
Atrazine + contact herbicide + stubble mulch	5.1	2.8	25	237	3.04
Atrazine + contact herbicide	0.0	6.0	46	274	3.17

[a] From Wicks and Smika (1973).
[b] Fallow duration of about 14 months.
[c] The plow treatment included one moldboard plowing in the spring. Other tillage was with sweep implement.
[d] Average amount of residues at start of fallow was 6.6 ha^{-1}.
[e] Determined to a 3-m depth.

Table 15. Progress in fallow systems with respect to water storage and wheat yields in Akron, Colorado[a]

Years	Tillage during fallow[b]	Fallow water storage (mm)	Fallow water storage (% of precipitation)	Wheat yield (Mg ha^{-1})
1916-30	Maximum tillage; plow, harrow (dust mulch)	102	19	1.07
1931-45	Conventional tillage; shallow disk, rod weeder	118	24	1.16
1946-60	Improved conventional tillage; begin stubble mulch in 1957	137	27	1.73
1961-75	Stubble mulch; begin minimum tillage with herbicides in 1969	157	33	2.16
1975-90	Projected estimate; minimum tillage; begin no-tillage in 1983	183	40	2.69

[a] Adapted from Greb (1979).
[b] Based on 14-month fallow, from mid-July to second mid-September.

residues from irrigated winter wheat were initiated at Bushland, Texas (Unger et al., 1971). Combinations of disk, sweep, and herbicide treatments were used to control weeds and volunteer wheat during fallow from wheat harvest in July 1968 to sorghum planting in May 1969. For treatments involving herbicides (atrazine and 2,4-D [(2,4-dichlorophenoxy) acetic acid] only or after one sweep tillage operation), water storage during fallow was about double the average amount stored with the tillage-only treatments (disk, sweep, or disk plus sweep). This study showed that residues from irrigated wheat could be managed to enhance the soil water supply for use by a subsequent crop, whether grown with or without irrigation, and thereby make more efficient use of precipitation for crop production. This also decreases the dependence on irrigation water, which is limited and being depleted in the region.

In subsequent studies, an irrigated winter wheat–fallow–dryland grain sorghum (or dryland sunflower) cropping system was evaluated. Unger and Wiese (1979) compared no-, sweep-, and disk-tillage methods for managing wheat residues and controlling weeds during the 10- to 11-month fallow period from wheat harvest to sorghum planting. The results are shown in Table 16. In an irrigated winter wheat–dryland grain sorghum–dryland sunflower rotation study (Unger, 1984a) involving different tillage methods (Table 17), water storage during fallow and sorghum grain yields were highest with no-tillage. The different tillage treatments applied during fallow after wheat had no residual effects on seed yields of the sunflower, which was no-tillage planted into residues of the sorghum crop. In an irrigated winter wheat–fallow–dryland sunflower system, average increases in soil water content during fallow after wheat

Table 16. Tillage effects on water storage, sorghum grain yields, and water use efficiency in an irrigated winter wheat-fallow-dryland grain sorghum cropping system in Bushland, Texas, 1973–1977[a]

Tillage method	Water storage Amount (mm)	Water storage Efficiency (% of precipitation[b])	Grain yield (Mg ha^{-1})	Total water use (mm)	WUE[c] (kg m^{-3})
No-tillage	217 a[d]	35.2 a	3.14 a	350	0.89 a
Sweep	170 b	22.7 b	2.50 b	324	0.77 b
Disk	152 c	15.2 c	1.93 c	320	0.66 c

[a] From Unger and Wiese (1979).
[b] Precipitation averaged 347 mm during fallow.
[c] Water use efficiency based on grain yields, growing season precipitation, and soil water changes.
[d] Column values followed by different letters are significantly different at the 5% level, based on Duncan's multiple range test.

were 38, 53, 61, and 71 mm with disk-, sweep-, limited- (sweep tillage plus herbicides), and no-tillage treatments, respectively. Average seed yields of the dryland sunflower ranged from 1.23 Mg ha^{-1} for sweep- and limited-tillage treatments to 1.38 Mg ha^{-1} for the no-tillage treatment, but the differences were not significant (Unger, 1981). The reason for the limited response of sunflower, compared with that of grain sorghum, to the irrigated-dryland cropping system is not apparent.

Table 17. Effect of tillage method on average soil water storage during fallow after irrigated winter wheat and on subsequent rainfed grain-sorghum yields in Bushland, Texas, 1978–1983[a]

Tillage treatment	Precipitation (mm) Fallow[b]	Precipitation (mm) Growing season	Water storage[c] (mm)	Water storage[c] (%)	Grain yield (Mg ha^{-1})	Total water use (mm)	WUE[d] (kg m^{-3})
Moldboard	316	301	89 b[e]	29 b	2.56 bc	360 bc	0.71
Disk	316	301	109 b	34 ab	2.37 cd	363 bc	0.65
Rotary	316	301	85 b	27 b	2.19 d	357 c	0.61
Sweep	316	301	114 ab	36 ab	2.77 b	386 ab	0.72
No-tillage	316	301	141 a	45 a	3.34 a	401 a	0.83

[a] From Unger (1984a).
[b] Fallow duration of 10 to 11 months.
[c] Based on fallow period precipitation stored as soil water.
[d] Water use efficiency based on grain yield, growing season precipitation, and soil water changes.
[e] Column values followed by the same letter or letters are not significantly different at the 5% level based on Duncan's multiple range test.

V. Crop Growth, Yields, and Water Use

A. Growth and Yields

Limited precipitation and limited amounts of water stored in soil are often the primary factors that limit crop production under dryland conditions. Consequently, when water conservation is increased due to improved weed control, greater water infiltration, lower runoff, or lower evaporation, the potential for more favorable crop production is also increased.

The importance of effective weed control, increased infiltration, and reduced evaporation for conserving water was discussed in Sections III and IV. Frequently, conservation tillage resulted in soil water contents equal to or higher than those with clean tillage, as the data in Tables 2 to 5 and 7 to 17 show or imply. In turn, equal or higher crop yields frequently resulted from the higher soil water contents (Tables 10 to 17 and data of Aujla and Cheema, 1983; Baliyan et al., 1984; Brar et al., 1982; Brun et al., 1985; Doran et al., 1984; Fischer, 1982; Khan and Chatterjee, 1982; Lindwall and Anderson, 1981). As a rule, water conservation and crop growth and yields increased with increasing amounts of residue maintained on the soil surface. Growth factors generally were not discussed, but favorable growth was implied by the favorable yields obtained with conservation tillage in most studies.

In the study by Unger (1978a), wheat residues were placed on the soil at increasing rates at the time of wheat harvest (around 1 July). Water storage during fallow (until sorghum planting around 1 June of the next year) and subsequent dryland sorghum grain yields were about double with the high residue rates (8 and 12 Mg ha^{-1}) compared with the 0-Mg ha^{-1} residue treatment (Table 10). The high amounts of residue resulted in the greatest benefits, but substantial increases in water storage and grain yields also resulted from residue rates of 1, 2, and 4 Mg ha^{-1} compared with the no-residue treatment. In addition, it is impractical to apply large amounts (8 to 12 Mg ha^{-1}) of residues to cropland, and most dryland crops do not produce such amounts. Consequently, most cropping system studies with conservation tillage on dryland involved residue amounts of less than 8 Mg ha^{-1}.

Based on the studies by Greb (1974, 1978, 1979; see Tables 11 and 15), Smika and Wicks (1968; see Tables 12 and 13), and Wicks and Smika (1973; see Table 14), treatments involving herbicides alone or combinations of sweep tillage and herbicides generally resulted in similar grain yields of wheat and sorghum. The reason the combination treatments resulted in yields similar to those with herbicide treatments was because sweep tillage reduces surface residues only about 10% during each operation. As a result, sufficient residues remained with the combination treatments for effective water conservation and the resultant favorable yields. The yields were generally lower with more intensive tillage (plowing, disking, or repeated sweep tillage) because of greater residue reduction than with the herbicide or tillage-herbicide combination treatments. Greater residue reduction was also a factor in the studies by Unger and Wiese (1979) and Unger

(1984a), which showed that sorghum grain yields were highest with no-tillage (see Tables 16 and 17).

Although suitable conservation-tillage systems have been developed for many crops at many locations, results have been unsatisfactory under some conditions. In general, conservation-tillage (reduced- and no-tillage) has been less satisfactory than conventional tillage on poorly drained soils (Griffith et al., 1977); with continuous cropping when volunteer crop plants cause excessive plant populations (Allen et al., 1975); where extremely large amounts of residue are present (e.g., the Pacific Northwest of the United States) that cause problems with weed control, planting, soil fertility, diseases, insects, and rodents (Papendick and Miller, 1977); where residue amounts are too low to cover the surface (unpublished data, O.R. Jones, Bushland, Texas); and where the soil has become eroded or seriously degraded (Charreau, 1977).

Where residue amounts are low, the surface is not protected against raindrop impact and water flow across the surface. Consequently, runoff may be high and water storage low, which in turn results in low crop yields. Under such conditions, tillage that disrupts the dense surface layer is important for enhancing water conservation and resultant crop yields (O.R. Jones, unpublished data, Bushland, Texas; Sherif et al., 1982; Stroosnijder and Hoogmoed, 1984; Willcocks, 1981, 1984). For severely eroded or degraded soils, Lal (1980[?]) suggested growing a suitable cover crop for several years to improve soil structure and water infiltration rates before initiating a conservation tillage system such as no tillage.

B. Water Use and Use Efficiency

In studies referred to in Section VA, effects of tillage treatments on water use by crops were given in only a few cases (see Tables 10, 11, 16, and 17). In general, treatments that resulted in greater water conservation (higher soil water contents at planting) also resulted in greater total water use by the crop (growing-season precipitation plus net soil water extraction). This was expected because the increased amounts of available water generally resulted in greater plant growth and higher yields. The increases in water use, however, did not result in similar soil water contents at crop harvest. Data in Tables 10, 16, and 17 show that differences among treatments in total water use were smaller than differences at crop planting. This suggests that soil water contents remained higher throughout the growing season with the conservation-tillage treatments. Higher water contents provided more water for plants at a higher (less negative) matric potential, which undoubtedly contributed significantly to higher yields with conservation tillage. Another factor contributing to higher yields was more efficient use of growing-season precipitation when surface residues were present (Unger et al., 1986).

The final consequences of higher yields with relatively small increases in total water use were higher water use efficiencies (WUEs) with conservation-tillage treatments than with more intensive tillage or lower-residue treatments (see Tables 10, 11, 16, and 17). The higher WUEs indicate that under the prevail-

ing conditions (climate, cropping, management, etc.), conservation-tillage systems effectively maximize the use of available water resources for grain production on dryland.

VI. Soil Erosion and Environmental Quality

As stated in the introduction to this chapter, conservation tillage is considered to be one of the best defenses against soil erosion, both by wind and by water. The benefits from conservation tillage result from residues maintained on the surface. These residues shield soil from the erosive forces of wind and, thereby, minimize wind erosion. They also dissipate the energy of falling raindrops, thus minimizing soil aggregate dispersion and surface sealing. This, combined with retarded water flow across the surface caused by the residues, helps to maintain more favorable water infiltration rates and reduces runoff, thereby reducing soil erosion by water. Associated with decreased erosion by wind and water is a cleaner environment, namely, less dust in the air and less sediment in water.

A. Wind Erosion

Wind erosion may occur wherever certain soil, climate, and vegetation conditions are favorable. These conditions are (1) a loose, dry, reasonably finely divided soil; (2) a smooth soil surface with limited or no vegetative cover; (3) a large enough field; and (4) a wind strong enough to move soil (Skidmore and Siddoway, 1978).

Each of these conditions often prevails under dryland conditions in some areas. Sandy soils are particularly susceptible to wind erosion because of limited coherence between particles, rapid drying, and small particle sizes. Other soils, however, are not immune to erosion by wind when they are dry and loose or when they have been finely divided by tillage, raindrop impact, and/or freezing and thawing. Soil particles less than 0.84 mm in diameter are generally considered erodible by wind.

Soil smoothness and surface residues are strongly influenced by tillage methods. Rough or residue-covered soil surfaces are most effective for minimizing wind erosion. These result from roughening tillage such as moldboard, lister, or chisel plowing or from residue-conserving tillage methods such as stubble-mulch tillage or no-tillage, provided adequate residues are available. Land smoothing operations such as disking, harrowing, or land planing may leave a soil highly susceptible to wind erosion and generally should not be used on dryland. Raindrop impact, freezing and thawing, and erosion itself also reduce surface roughness.

Field size in the direction of prevailing winds has a major influence on wind erosion; the potential for erosion increases with increased field size if the field is not protected. However, wind erosion may occur on highly erodible fields that are only a few meters wide (Skidmore and Siddoway, 1978). The effect of field width is minimized when adequate residues are present or the surface is adequately rough.

Soil movement (erosion) begins at relatively low wind speeds and increases progressively as wind speed and turbulence increase (Chepil and Woodruff, 1963; FAO, 1978). To minimize wind erosion, wind speed at the soil–air interface must be reduced to below the threshold value at which erosion occurs (Skidmore and Siddoway, 1978). Surface residues, when sufficient amounts are present, are highly effective for keeping wind speeds below the threshold value. The wind erosion process is highly complex and involves particle movement (saltation, surface creep, and suspension), transport, sorting, abrasion, avalanching, and deposition (Woodruff and Siddoway, 1973).

The generalized equation

$$E = f(I\ C\ K\ L\ V)$$

expresses the relative quantity of wind erosion from a field. In the equation, E is the potential annual quantity of erosion per unit area and is a function (f) of soil erodibility (I), local wind erosion climatic factor (C), soil surface roughness (K), equivalent width of field (L), which is the maximum unsheltered distance across the field in direction of prevailing winds, and equivalent quantity of surface vegetative cover (V) (Chepil and Woodruff, 1963). The mathematical relationships among the components are complex but have been computed and developed into tables and graphs that are useful for estimating soil losses and determining the effects of alternative control practices. A guide containing this information for the U.S. Great Plains was published by Craig and Turelle (1964). Tillage methods directly affect the I, K, and V factors through their effects on soil cloddiness, roughness, and surface vegetative cover, respectively.

Surface residues affect wind erosion primarily through influences related to the V factor of the equation, with the principal function being to decrease the force of wind on the soil itself. When residues rather than soil particles absorb the force of wind, erosion is reduced. The effectiveness of residues for controlling wind erosion depends on their amount, kind, texture, height, and orientation. In addition, residues should be anchored in soil because loose residues may be blown away, thus becoming ineffective for controlling wind erosion (McCalla and Army, 1961; Woodruff and Siddoway, 1973; Zingg, 1954).

When crop residues are available, some form of conservation tillage generally is more suitable than clean tillage for controlling wind erosion. No-tillage usually is most effective because it retains anchored residues on the surface. Favorable protection against erosion is usually afforded as well by stubble-mulch tillage, which undercuts the surface but leaves residues partially anchored in soil and roughens the surface. Soil roughening with stubble-mulch tillage is greater on fine-textured (clays, loams, etc.) than on coarse-textured (sands) soils.

In some cases, few or no residues may be available because of low production or use for other purposes. In other cases, available residues may have limited usefulness in controlling erosion. Low residue production is frequently a problem under dryland conditions. It may be especially critical for a crop such as cotton, which produces residues that have little value for controlling wind erosion. When residues are limited, for whatever reason, alternative measures must be relied on to control erosion.

To control wind erosion under limited-residue conditions, the soil should be kept in a rough, cloddy condition. Some surface roughness results from normal crop production operations. To control wind erosion, roughness is also obtained by using tillage or planting operations that cover or replace erodible soil particles at the surface with less erodible materials (Fryrear, 1981), thus reducing wind forces on the erodible particles. Increasing surface roughness, however, also increases wind turbulence and velocity fluctuations at the surface, which may negate some benefits gained by roughening the surface (Lyles et al., 1971).

The most effective soil roughness height for controlling wind erosion is 50 to 130 mm (Armbrust et al., 1964; Woodruff and Lyles, 1967). Tillage that minimizes soil pulverization and smoothing is effective for maintaining surface roughness. For planting small grains, deep furrow and hoe drills produce roughness in the 50- to 130-mm height range and are therefore highly effective in producing erosion-resistant surfaces (Woodruff and Siddoway, 1973). Even greater protection against wind erosion is afforded by using these drills when some residues are present.

The degree of cloddiness resulting from tillage depends on soil texture, the tillage tool used, speed of operation, and soil water content at the time of tillage (Woodruff and Siddoway, 1973). Because of their low cohesiveness, sandy soils contain few clods that resist erosion, regardless of tillage method used. However, if more than about 8% clay is present, the cloddiness of sandy soils can be increased by cultivation (Harper and Brensing, 1950). The resistance of sandy soils to wind erosion can also be increased by plowing, cultivating, and planting them while they are moist. For higher clay content soils, sufficient cloddiness to control erosion generally can be obtained with a variety of tillage implements when the operations are performed within a wide range of water contents. On such soils, even chiseling when the soil is quite dry is generally effective as an emergency measure to control wind erosion (Lyles and Tatarko, 1982).

B. Water Erosion

Although rainfall deficiencies limit crop production in dryland regions, many soils in dryland regions are highly susceptible to water erosion. Reasons for the high susceptibility include (1) low crop yields, which provide limited amounts of residues for protecting the soils; (2) low soil organic matter content, which results in low water stability of soil aggregates and, consequently, in major aggregate dispersion and surface sealing during rainstorms; (3) high-intensity rainstorms that often occur in dryland regions; and (4) poor management (Elwell, 1983, 1985).

Soil erosion involves particle detachment and transport. The energy for detachment is provided by rainfall and flowing water (runoff). Energy for transport is provided mainly by runoff, but raindrop splash also results in some particle transport.

At upslope positions, rainfall and slope gradient provide most of the energy for erosion. On bare soil, most kinetic energy of raindrops is dissipated when the impacting drops detach surface soil particles. Thereafter, splash action and shallow sheet flow transport detached particles to runoff concentrations. Drop impact

also disperses soil aggregates, reduces surface roughness, and promotes surface sealing and crusting, which further increases runoff (Wischmeier, 1973). As runoff increases, rill and, finally, gully erosion may occur. Gully erosion is most obvious, but sheet and rill erosion account for most water erosion on cropland (Hayes and Kimberlin, 1978).

To control water erosion, crop production operations such as tillage and seeding should decrease the impact of raindrops on the soil, maintain favorable water infiltration, decrease runoff velocity, and decrease soil detachability (Engle et al., 1980; McDole and Vira, 1980; Rawitz et al., 1983; Ray, 1986; Wischmeier, 1973). These effects are influenced by rainfall (intensity and duration), land slope (steepness and length), soil condition (texture, organic matter content, roughness, ridging and furrow diking), surface residue (amount, type, and distribution), and engineering-type (contouring, strip cropping, terracing, etc.) factors and practices that have been extensively studied The results have been reviewed and guidelines for controlling erosion have been prepared (Hayes and Kimberlin, 1978; Kimberlin, 1976; Stewart et al., 1975; Wischmeier, 1973; Wischmeier and Smith, 1978). These guidelines generally involve the universal soil loss equation (USLE), which helps to establish relationships among erosion and the factors that influence it.

The USLE is

$$A = R\,K\,L\,S\,C\,P$$

where A is the computed soil loss per hectare, R is the rainfall factor based on the number of erosion index units in a normal year's rainfall at a specific location, K is the soil erodibility factor, L is the length of slope factor, S is the slope gradient factor, C is the crop management factor, and P is the erosion control practice factor. Values for factors of the equation are available for many conditions at numerous locations (Stewart et al., 1975).

The R factor of the equation is based on rainfall records for a location and is therefore fixed. Likewise, the K, L, and S factors for a location are fixed unless major soil alteration operations are performed. Included under the C factor are tillage, rotation, and residue management practices, which can be altered and which have a major effect on erosion. When erosion cannot be effectively controlled by crop management, engineering-type practices that affect the P factor must be used. In this section, the emphasis is on the C factor, mainly as it is affected by crop residues.

The amount, type, distribution, and management of surface residues determine how effective they are in controlling erosion. Residues dissipate raindrop energy, thus decreasing particle detachment, surface sealing, and crusting, and, in turn, runoff. Residues also reduce the water flow rate across the surface, thereby further reducing runoff (Wischmeier, 1973). Because runoff is the major transport mechanism for soil particles, practices that reduce runoff generally reduce soil losses to an even greater extent. This was shown in Tables 2, 3, and 4, and by the data of Ngatunga et al. (1984).

A complete cover of surface residues provides the maximum protection against runoff and soil loss. Greater than 95% cover is achieved with about 5.6 Mg ha^{-1} of small grain straw or about 8.3 Mg ha^{-1} of chopped maize stalks (Wischmeier, 1973). Although a complete cover provides maximum protection, runoff velocities with 1.1 and 2.2 Mg ha^{-1} of wheat straw on the surface were about 50 and 40%, respectively, compared with those from bare soil. Soil losses were reduced to a greater extent and were 31 and 18% for the respective treatments compared with those from bare soil (Meyer et al., 1970).

The effect of residue type on runoff and soil loss is operative, primarily through the degree of surface coverage provided by a given amount (weight) of residues. Wischmeier (1973) reported that wheat and soybean (*Glycine max* L.) residues, when left on the surface at harvest and compared on a dry-weight basis, were equally effective for controlling erosion on a silt loam soil with a 5% slope. In contrast, maize stover at 4.5 Mg ha^{-1} was only half as effective as an equal amount by weight of wheat straw.

Although a complete surface cover of residues provides maximum protection against runoff and soil losses, Wischmeier (1973) showed that a nonuniform distribution of a mulch on the silt loam soil on the 5% slope mentioned earlier was as effective as the same amount of mulch uniformly covering the entire surface. The mulch was placed in rows across the slope, with two-thirds of the area remaining bare. The mulch strips trapped soil particles that were detached by rainfall from the bare strips.

C. Environmental Quality

Besides damaging the land and thereby reducing its productive capacity, erosion by wind and water has a major deleterious effect on the environment. The amount of soil eroded from a given site during a particular wind or water erosion event is highly variable and depends on prevailing conditions. Besides damaging or ruining the land and growing plants, wind erosion fills the air with dust from the soil removed and may bury crops and fences, cover roads, fill waterways, and cause illness in humans and animals (FAO, 1978). Soil removed by water erosion pollutes streams and reservoirs and may damage or destroy crops, roads, fences, and other structures. The sediment also may fill streams and reservoirs, thus increasing the danger of flooding during subsequent storms and negating the water storage capacity of reservoirs. In addition, sediment is the principal carrier of some chemical pollutants (fertilizers, pesticides, nutrients from crop residues, etc.; Stewart et al., 1975). Therefore, erosion may pollute the environment (air and/or water) with chemicals.

The same principles that apply to controlling erosion also apply to controlling pollution. Hence, conservation tillage is a good pollution control practice. However, the effectiveness of any practice for controlling erosion (soil transport) may differ from its effectiveness in controlling pollutant (other than soil itself) transport. This is because the pollutants are generally associated with the finer soil particles that are more readily transported by wind or water. Also, some

chemical pollutants are dissolved by water, and runoff is reduced less than soil loss by erosion control measures (see Tables 2, 3, and 4). Consequently, sediment that reaches downstream bodies of water generally contains more clays, organic matter, nutrients, and pesticides than the original field soil (Frere, 1976; Frere et al., 1977).

While conservation tillage reduces runoff and soil losses, and hence may reduce pollution, it also may enhance pollution because the decaying surface residues and surface-applied fertilizers can contribute soluble nutrients to runoff water. Conservation tillage may also increase groundwater pollution if the higher infiltration with conservation tillage results in deep percolation of water containing dissolved chemicals that may eventually enter the groundwater (Wauchope et al., 1985).

VII. Insects, Plant Diseases, and Other Pests

One of the traditional reasons for performing residue-incorporating tillage has been to control pests such as insects and plant diseases. Consequently, when conservation tillage was introduced, there was widespread concern regarding the effect of surface residues on pest problems. Although much research regarding the effects of conservation tillage on pests has been conducted in recent years, no definite answers are available because pest problems have been less severe, unaffected, or more severe with conservation than with clean tillage in different studies (Cochran et al., 1982; Herrman and Wiese, 1985; Lal, 1986; Moore and Cook, 1984; Parmelee and Alston, 1986; Triplett, 1986). The differences are related to pest species, crop, location, residue amount, climate, and other factors. Consequently, it is not possible to make a universal recommendation regarding pests except that insect and disease problems generally are less severe under dryland conditions than under wetter, more humid conditions. Triplett (1986) attributed the less severe damage from pests with conservation tillage to the higher soil water content resulting from surface residues on untilled soil. This provides healthier, more vigorous plants that are able to resist and outgrow the injury resulting from insect and disease organisms that may be present.

Grain sorghum is an important crop in many dryland regions. Two major pests of this crop have been less severe with conservation tillage than with clean tillage. For sorghum planted after wheat, the incidence of stalk rot was 15% with no tillage, 32% with minimum tillage, and 45% with normal (clean) tillage. The reduced stalk rot incidence was attributed, at least in part, to higher soil water contents with conservation tillage, which also increased sorghum yields (Boosalis and Cook, 1973).

The greenbug (*Schizaphis graminum* Rondani) is a major insect pest of grain sorghum and wheat in the United States. When sorghum was no-tillage planted in wheat residues after fallow, greenbug populations were significantly lower than when the residues were incorporated by tillage before planting sorghum. The reduction in greenbug population was attributed, at least in part, to greater

light reflectance by residues in the no-tillage areas (Burton et al., 1987). Similar responses were found when wheat was planted by minimum- or no-tillage methods in residues from the previous wheat crop (Burton and Krenzer, 1985).

Take-all (*Gaeumannomyces graminis* var. *Tritici*) disease of wheat occurred more frequently or more severely when consecutive wheat crops were no-tillage seeded into the undisturbed stubble of the previous crop than when the seeding was done after the stubble had been incorporated by moldboard or disk plowing (Moore and Cook, 1984). The differences in disease incidence were not accounted for by differences in soil temperature, soil water content, or host plant nutrition. Fertilization with nitrogen, phosphorus, potassium, sulfur, and trace elements suppressed the disease more than nitrogen or sulfur alone, but suppression was similar on the no-tillage and plowed areas.

Although insect and disease problems are variable with conservation tillage, problems with other pests such as birds, rodents, and slugs usually are more severe with conservation tillage, especially no-tillage, than with tillage methods that greatly reduce or eliminate surface residues (Phillips, 1984). Problems with birds and rodents are due to the favorable habitat provided by surface residues. The slug problem is related to the generally wetter conditions within the residue cover than where residues are absent. Control measures are available for the bird, rodent, and slug pests (Phillips, 1984).

Because of the indefinite nature of many pest problems under conservation tillage conditions, it is important that producers recognize that pest problems may occur, that they regularly observe their crops to determine if pests are present, and that they develop or adjust their management programs to deal with the pests (Phillips, 1984; Triplett, 1986).

VIII. Soil Properties

A. Temperature

Surface residues significantly affect soil temperatures, with the primary mechanism of this effect being the change in radiant energy balance of the system (Van Doren and Allmaras, 1978). However, an insulating effect of residues may also be involved because mulched soil is usually warmer than bare soil in cold weather, even during daylight hours (Unger, 1978b). The radiation balance is influenced by reflection of incoming radiation by surface residues, heating of soil and air, and evaporation of soil water (Van Doren and Allmaras, 1978). Soil temperatures generally decrease as reflectance increases. The insulating effect increases with increases in thickness of the surface residue layer (Gupta and Gupta, 1983; Unger, 1978b).

Characteristics that affect radiation reflection include residue age, color, geometry (standing, flattened, or matted), distribution, and amount. Reflection is normally greatest from bright residues (e.g., wheat straw) and decreases with residue aging (discoloration) and decomposition. As a result, temperature differences between residue covered and bare soils are greatest when residues are bright and decrease as they age and decompose.

Gausman et al. (1975) compared reflectance from bare soil and from standing or surface-matted sugar cane (*Saccharum officinarum* L.) after it was frozen and had bleached and turned yellow. Reflectance at all wavelengths was greatest from the matted cane, followed by bare soil and standing cane. Low reflectance from standing cane was attributed to shadows in the cane. Gausman et al. (1975) also evaluated reflectance from dried and bleached avocado (*Persea americana* L.) leaves, and found that maximum reflectance is reached asymptotically as the target thickness increases. For avocado, near maximum reflectance occurred at a leaf area index of 2. Complete surface coverage by randomly placed residues such as wheat straw or maize stover after harvest or after initial subsurface tillage would be needed to obtain maximum reflection. However, the residue cover under field conditions often is incomplete because of natural variation in distribution or partial incorporation by tillage. Hence, less than maximum reflectance usually occurs for a given residue condition in the field (Van Doren and Allmaras, 1978).

Greater reflectance from residues than from bare soil reduces soil heating and potentially also soil water evaporation. However, Hanks et al. (1961) found no direct relationship between net radiation and evaporation under their research conditions. After the surface dried, factors within the soil apparently overshadowed incoming radiation effects on evaporation during the fallow season.

Because reflectance approaches a maximum as surface residue coverage approaches 100% (Van Doren and Allmaras, 1978), residue amounts exceeding those needed for 100% coverage should have no effect on soil temperatures if radiation reflectance alone is involved. Greater residue amounts, however, do affect soil temperatures (McCalla and Duley, 1946; Unger, 1978b), apparently as a result of an insulating effect. In the study by Unger (1978b), wheat straw at 8 or 12 Mg ha^{-1} resulted in lower soil temperatures during a hot period and higher soil temperatures during a cold period than did wheat straw at 4 Mg ha^{-1}, which provided almost 100% surface coverage. Other studies reported generally lower maximum temperatures with residues present than with bare soil (Aston and Fischer, 1986; Black and Siddoway, 1979; Carter and Rennie, 1985; Gerling et al., 1983; Wall and Stobbe, 1984).

The effect of crop residues (conservation tillage) on soil temperatures is most critical at cool locations where the growing season is relatively short and delayed crop establishment may seriously reduce crop yields. In the northern United States (latitude 45°N), soil temperatures under a heavy sod became favorable for planting 6 or 7 days later than in a conventionally tilled (clean) seedbed. At more southerly locations (latitude 35°N or less), little or no delay in soil warming occurred in the spring (Unger and Stewart, 1976). Consequently, conservation tillage should have no major adverse effects on soil temperatures and associated crop planting and establishment in dryland regions, except possibly those in northern North America, northern Africa, Europe, and Asia (north of India), and at similar latitudes in the southern hemisphere.

B. Soil Aggregation

Soil aggregation refers to the binding together of soil particles into secondary units. When sufficiently water stable, aggregates do not readily disperse and, hence, are especially important for maintaining favorable water infiltration rates. They also result in good soil structure, which is important for good plant growth. When sufficiently large, stable surface aggregates aid in controlling wind and water erosion.

The binding substances for aggregates have mineral or organic origins. Mineral substances are particularly important in tropic and subtropic regions, where stable aggregates cemented by iron result in high water infiltration, even after prolonged rainfall (Donahue et al., 1977). Organic substances affecting aggregation are derived from fungi, bacteria, actinomycetes, earthworms, and other forms through their feeding and other actions on plant materials. Plants themselves may directly affect aggregation through exudates from roots, leaves, and stems; leachates from weathering and decaying plant materials; canopies and surface residues that protect aggregates against breakdown with raindrop impact, abrasion by windborne soil, and dispersion by flowing water; and root action, which promotes aggregate formation. If aggregates formed through these processes are maintained on the surface, water infiltration is higher than for an intensively cultivated, poorly aggregated soil (Black and Siddoway, 1979; Donahue et al., 1977). If the aggregates are greater than 0.84 mm in diameter, they are considered nonerodible by wind and, hence, provide protection against wind erosion (see Section VIA).

C. Soil Density and Porosity

Soil bulk density and porosity are inversely related. Hence, any practice that affects the one also affects the other. In general, tillage layer density is lower in plowed than in unplowed soils such as areas in grass or areas not recently plowed (e.g., no-tillage areas). Where residue amounts are low, tillage method per se had little effect on soil density (Johnson, 1950; McCalla, 1959; Unger, 1969), but density decreased when increasing amounts of residue were involved (Black, 1973; Black and Siddoway, 1979; Juo and Lal, 1977; Koshi and Fryrear, 1973).

Soil compaction is undesirable and is associated with increased bulk density and decreased porosity. Compaction generally results from traffic (equipment and/or animal) on the land and has become a severe problem under mechanized conditions, especially where large tractors are used for crop production. Serious natural compaction can also occur, especially on sandy soils; drying rate plays a major role in such compaction (Gerard, 1965, 1986; Taylor et al., 1966).

Soils subject to natural compaction generally are low in organic matter and require loosening to overcome the compaction, which should enhance subsequent plant growth. Conservation tillage would not be suitable for the initial soil loosening but may be suitable for subsequent crop production, provided adequate

residues are available to minimize recompaction. Conservation tillage also has potential for minimizing compaction on other soils because of fewer trips across the field and use of lighter equipment. Compaction may also be reduced by using a tillage rotation involving plowing (moldboard or disk) or conservation tillage techniques (Dickey et al., 1983; Mulvaney and Paul, 1984). Even further reduction in compaction is possible by using a controlled traffic system in conjunction with conservation tillage (Unger and Stewart, 1988).

An important aspect of tillage with respect to soil porosity is its effect on soil fauna activity, especially earthworms. Because earthworm activity and intensive tillage are highly incompatible, there are few earthworms in most cultivated soils. In contrast, Lal (1976) found four to five times greater earthworm activity in no-tillage areas than in plowed soil in the tropics. Earthworm channels, which increase soil porosity, are highly stable and provide for rapid water entry into a soil (Hopp and Slater, 1961).

D. Other Physical Properties

In addition to the physical properties discussed in the preceding section, tillage affects soil texture, crusting, hydraulic conductivity, and water storage capacity. Tillage-induced textural changes result primarily from the mixing and inversion caused by different tillage implements and the effect of a given tillage method on subsequent soil erosion. Tillage per se may alter the sand, silt, and clay content of soil within the tillage layer, depending on tillage depth and mode of operation. Conservation tillage methods should have little effect on texture because they result in limited soil mixing and no soil inversion. However, the indirect effects on soil texture may be large because, though erosion in conservation tillage soils may be slight, erosion may selectively remove fine materials from tilled soils, thus increasing their sand content and decreasing their silt and clay content (Chepil et al., 1962; Juo and Lal, 1977).

Soil crusting, which may affect seed germination, seedling emergence, soil aeration, and water infiltration, results from aggregate dispersion and soil particle sorting and rearrangement during rainstorms, followed by soil drying. Consequently, any tillage method that protects aggregates from dispersion by raindrop impact and flowing or ponded water decreases the potential for soil crusting. Conservation tillage systems that maintain surface residues are especially beneficial for minimizing soil crusting (Johnson, 1950; Juo and Lal, 1977; Lal, 1976; Unger, 1984b).

The saturated hydraulic conductivity of a soil increases with increased porosity. Hence, conservation tillage generally produces greater conductivity than other tillage methods. A cotton bur mulch placed on Acuff loam (Aridic Paleustoll) at 11.2 or 22.4 Mg ha^{-1} resulted in eight times greater hydraulic conductivity in crop rows than did a bare soil (Koshi and Fryrear, 1973). Substantial increases in hydraulic conductivity due to surface residues (conservation tillage) were also reported by Gerard et al. (1987), Hamblin (1984), and Mielke et al. (1984).

The increased hydraulic conductivity in conjunction with the increased infiltration resulting from conservation tillage allows soil profiles to be more readily filled with water. This, coupled with decreased evaporation, often results in higher soil water contents with reduced- and no-tillage systems compared with clean tillage. The increased water supply generally improves crop growth and yields under dryland conditions where limited water frequently is a problem.

Besides resulting in more complete refilling of the soil profile with water, conservation tillage systems may also increase a soil's plant-available water storage capacity. For example, Juo and Lal (1977) reported that soil on residue [bush fallow, Guinea grass (*Panicum maximum*), pigeon pea (*Cajanus cajan* Millsp.), and maize] plots retained 2.1 to 5.8 percentage units more plant-available water (difference between −0.1- and −15-bar matric potentials) than corn plots without residues. Lal (1976) also found higher water-holding capacities in no-tillage than in plowed plots, which he attributed to differences in organic matter content and texture of the surface horizon. Although not specified, the organic matter and fine-material (silt and clay) content apparently decreased in the plowed plots, thus resulting in less water retention.

IX. Economics

To be economically advantageous, conservation tillage systems must either be less costly or result in greater returns than other tillage systems, or both. It is less costly if it reduces labor, equipment, fuel, and other inputs, and it results in greater returns if it increases the quantity or quality of the products to be sold or used relative to the production inputs. Because of rapidly changing prices and the wide diversity of practices used in different dryland regions, assigning monetary values to various cropping systems has little meaning. Consequently, our emphasis is on factors that influence production costs and returns, but some data are presented to illustrate the economics of the different tillage systems.

Labor, power source (animals or tractors), equipment (plows, planters, etc.), and energy (feed or fuel) expenses vary greatly, depending on whether labor-intensive, animal-drawn, or tractor-powered crop production systems are used. Likewise, the economic advantage of using a given crop production system depends on the availability of the different input factors.

Where labor is abundant, it may be economically advantageous to use a labor-intensive system. Where labor is costly, it generally is advantageous to use a tractor-powered system. In either case, crop production expenses can be reduced by eliminating field operations, reducing the number of time-intensive (labor, animal, tractor, or equipment) operations, or using input resources more effectively.

Lower labor, animal, or equipment requirement is a major advantage of conservation tillage because it allows elimination of several operations, depending on the conservation tillage system used. Maximum reduction in operations occurs

Table 1.3. Cost of tillage and herbicides for various cropping sequences with surface irrigation on the U.S. Southern Great Plains[a]

Cropping sequence	Operations and total expenses	
	Clean tillage	Limited or no-tillage
Wheat to sorghum double-cropped	Disk, disk, bed, apply atrazine (1.8 kg ha^{-1}) \$52 ha^{-1}	Apply atrazine (1.8 kg ha^{-1}) \$17 ha^{-1}
Wheat to wheat	Disk, disk, bed, cultivate \$44 ha^{-1}	Disk, bed, cultivate \$26 ha^{-1}
Sorghum to sorghum	Disk, disk, chisel, bed, cultivate \$49 ha^{-1}	Shred, split beds, cultivate \$30 ha^{-1}
Wheat-fallow-sorghum[b]	Disk, disk, disk, bed cultivate, cultivate \$44 ha^{-1}	Apply atrazine (3.4 kg ha^{-1}) and 2,4-D (1.1 kg ha^{-1}) \$30 ha^{-1}

[a] From Wiese et al (1979).
[b] Operations and expenses are for the wheat to sorghum phase of the rotation. For sorghum to wheat, the area was uniformly tilled.

with the no-tillage system, but this system generally involves the use of herbicides to control weeds. As a consequence, savings in labor, equipment, and other costs are offset to some degree by increased expenses for herbicides. Greater cost for herbicides than for tillage was a major deterrent to the adoption of early no-tillage systems. Now, it often is more economical to use herbicides than tillage in some cropping systems (Engle et al., 1980; Harman and Wiese, 1985; Wiese et al., 1986; Zentner and Lindwall, 1982). Further reductions in herbicide costs can be achieved by applying the herbicides with a CDA (controlled droplet applicator; Green et al., 1982). This equipment not only reduces the herbicide requirement for weed control, but also greatly reduces the amount of carrier (usually water) required to dilute the herbicide. The latter may be quite important in countries where water is limited because as little as 5 liters water/ha were adequate when a CDA was used (Taylor et al., 1976; Wiese, 1986).

Under mechanized crop production conditions, labor and equipment requirements per unit area are influenced greatly by the tillage operation performed if the tractor size is constant. As tillage intensity decreases, the labor requirement decreases also. Further labor savings are possible by combining operations (plowing, fertilizing, spraying for weed control, and/or planting) and by using larger pieces of equipment. However, large equipment is more costly and may require a more skilled operator. Consequently, all advantages (less labor, timeliness of operations, etc.) and possible disadvantages (higher tractor, equipment, and other costs; skilled labor requirement; alternate use of unused labor; etc.) must be weighed against each other when considering the use of larger equipment for crop production (Unger and McCalla, 1980).

When production costs remain constant, crop values (quantity or quality) must be higher for a new system to be more economical than the system it replaces.

Table 19. British national average expenses for establishing a cereal crop in stubble

Operation or expense	Operations or expense items (no.) Conventional tillage	Minimum tillage	No-tillage	Expenses (U.K. pounds ha^{-1}) Conventional tillage	Minimum tillage	No-tillage[b]	No-tillage[c]
Plowing	1	–	–	16.70	–	–	–
Disking	2	–	–	12.80	–	–	–
Herbicide (liters)	1.2	1.2	2.4	4.60	4.60	9.20	9.20
Herbicide application	1	1	1	3.70	3.70	3.70	3.70
Harrowing	1	1	1	4.00	4.00	4.00	4.00
Tine cultivation	–	3	–	–	21.00	–	–
Seeding	1	1	1	8.20	8.20	14.20	9.40
Totals				50.00	41.50	31.10	26.30

[a] From ICI – Plant Protection (1976).
[b] Seeding was contracted (hired).
[c] Seeding with farmer's own drill.

Because of higher yields resulting from greater water conservation, stubble-mulch tillage was more economical than oneway-disk tillage for wheat production in Bushland, Texas, even though fuel use was identical (Allen and Fryrear, 1979). When production costs are decreased and yields increase, remain constant, or even decrease slightly, conservation tillage systems are more economical than intensive tillage systems. Additional economic benefits result from conservation tillage if water conservation is increased, which results in higher crop yields (Unger and Wiese, 1979).

Based on herbicides and equipment requirements, production costs for some crops are about twice as high with conventional as with conservation (reduced or no) tillage systems (Tables 18 and 19). Consequently, returns with conservation tillage are much greater if yields are similar. In other cases, production costs are similar with different tillage systems (Unger and Wiese, 1979). However, if yields are increased or if better use of all farm resources occurs with conservation tillage, then economic returns to the crop production enterprise are increased by using the conservation tillage system (Brown and White, 1973; Unger and Wiese, 1979; Windsor, 1984).

X. Summary and Conclusions

A. Accomplishments

Maintaining crop residues on the soil surface through use of conservation tillage systems, initially with subsurface (stubble-mulch) tillage and more recently by reduced or no-tillage methods involving herbicides for weed control, has

contributed greatly to the conservation of soil and water resources. The surface residues, when present at adequate levels, control wind erosion by reducing wind speed at the soil–air interface to below the threshold speed for soil movement. Surface residues reduce water erosion by dissipating the energy of falling raindrops, which minimizes soil aggregate dispersion and surface sealing and maintains favorable water infiltration rates, and by retarding the flow of water across the surface, which reduces soil particle transport.

The water conservation benefits of surface residues result from the more favorable water infiltration and from reduced evaporation. Increases in soil water storage due to surface residues have ranged up to 50 to 75 mm in many cases with conservation tillage compared with clean tillage systems. The additional water has increased grain yields on dryland by as much as 1.0 Mg ha^{-1} in some instances.

Benefits from use of conservation tillage systems besides soil and water conservation and increased crop yields include less air and water pollution, and decreased labor, energy, and equipment requirements. In many cases, the combined effects of using a conservation tillage system have resulted in more economical crop production than is possible with clean tillage systems. This economic advantage should be an incentive for adopting conservation tillage to conserve soil and water resources in general and, particularly, to comply with soil erosion control standards mandated by legislation in some countries in recent years.

B. Needs

Although major advances have been made in developing suitable conservation tillage systems for crop production under many conditions, much remains to be done to make these systems more widely adaptable. To achieve this, an in-depth understanding of the direct and interacting effects of tillage and residue management practices on the physical, chemical, and biological components of the plant–soil environment is essential. Such understanding requires an integrated approach involving scientists from various disciplines to study the physics, chemistry, biochemistry, and biology (micro- and macro-) of the soil–plant environment as well as the physiology, nutrition, and insect and disease vulnerability of the plant itself. Particular efforts are required to develop suitable practices where residue amounts are limited by low production (often common under dryland conditions) and where residues are removed for other purposes (feed or fuel).

It is impractical to research the entire spectrum of problems under all possible conditions. Consequently, it is necessary that pertinent research be conducted where possible to establish basic relationships among the physical, chemical, and biological effects of conservation tillage on the soil–plant environment. When completed, the resultant information, along with that already available in the literature, should be used to develop models that can be used for predicting the effects of various conservation tillage systems on resource conservation and crop production under a wide range of conditions.

References

Allen, R.R., and D.W. Fryrear. 1979. Energy considerations in conservation tillage systems. *In* Conservation Tillage in Texas, B.L. Harris and A.E. Coburn (eds.). pp. 31–45. Texas Agric. Ext. Service Bull. B-1290.

Allen, R.R., J.T. Musick, and A.F. Wiese. 1975. No-till management of furrow irrigated continuous grain sorghum. Texas Agric. Exp. Sta. PR-3332 C.

Armbrust, D.V., W.S. Chepil, and F.H. Siddoway. 1964. Effects of ridges on erosion of soil by wind. Soil Sci. Soc. Am. Proc. 28:557–560.

ASAE (American Society of Agricultural Engineers). 1982. Design, layout, construction and maintenance of terrace systems. *In* Agricultural Engineers Yearbook, p. 538. Am. Soc. Agric. Eng., St. Joseph, Michigan.

Aston, A.R., and R.A. Fischer. 1986. The effect of conventional cultivation, direct drilling and crop residues on soil temperatures during the early growth of wheat at Murrumbateman, New South Wales. Australian J. Soil Res. 24:49–60.

Aujla, T.S., and S.S. Cheema. 1983. Modifying profile water storage through tillage, herbicide, chemical evaporation retardant, and straw mulch and its effect on rainfed chickpea (*Cicer arietinum*). Soil & Tillage Res. 3:159–170.

Baliyan, R.S., V.M. Bhan, and R.K. Mallik. 1984. Studies on possibilities of zero tillage in cotton-wheat rotation. Indian J. Agron. 29:170–172.

Berry, W.A.J., J.B. Mallett, and M.A. Johnston. 1985. Soil-water conservation as affected by primary tillage practices. South African J. Plant and Soil 2:21–26.

Bertrand, A.R. 1966. Water conservation through improved practices. *In* Plant Environment and Efficient Water Use, W.H. Pierre, D. Kirkham, J. Pesek, and R. Shaw (eds.). pp. 207–235. Am. Soc. Agron., Madison, Wisc.

Black, A.L. 1973. Soil property changes associated with crop residue management in a wheat-fallow rotation. Soil Sci. Soc. Am. Proc. 37:943–946.

Black, A.L., and F.H. Siddoway. 1979. Influence of tillage and wheat straw residue management on soil properties in the Great Plains. J. Soil Water Conserv. 34:220–223.

Bond, J.J., and W.O. Willis. 1969. Soil water evaporation: Surface residue rate and placement effects. Soil Sci. Soc. Am. Proc. 33:445–448.

Boosalis, M.G., and G.E. Cook. 1973. Plant diseases. *In* Conservation Tillage, the Proc. of a Natl. Conf., Des Moines, Iowa, March 1973, pp. 114–120. Soil Conserv. Soc. Am., Ankeny, Iowa.

Brar, S.S., J.S. Dhaliwal, G.S. Gill, H.S. Sandhu, and G.K. Singh. 1982. Continuous maize and wheat production under no-tillage and conventional tillage system: A ten-year study. *In* Energy Conservation and Use of Renewable Energies in the Bio-Industries, F. Vogt (ed.). pp. 100–107. Oxford: Pergamon Press Ltd.

Brown, R.E., Jr., and T.K. White. 1973. Analysis of the impact of alternative corn tillage-planting systems on optimal farm organization and income. Indiana Agric. Exp. Sta. Bull. SB-19.

Brun, L.J., J.W. Enz, and J.K. Larsen. 1985. Water use by soybeans in stubble and on bare earth. North Dakota Farm Res. 43(4):32–35.

Burton, R.L., O.R. Jones, J.D. Burd, G.A. Wicks, and E.G. Krenzer, Jr. 1987. Damage by greenbug (*Homoptera: Aphididae*) to grain sorghum as affected by tillage, surface residues, and canopy. J. Econ. Entomol. 80:792–798.

Burton, R.L., and E.G., Krenzer, Jr. 1985. Reduction of greenbug (*Homoptera: Aphidi-*

dae) populations by surface residues in wheat tillage studies. J. Econ. Entomol. 78:390-394.

Burwell, R.E., R.R. Allmaras, and L.L. Sloneker. 1966. Structural alteration of soil surfaces by tillage and rainfall. J. Soil Water Conserv. 21:61-63.

Carter, M.R., and D.A. Rennie. 1985. Soil temperature under zero tillage systems for wheat in Saskatchewan. Canadian J. Soil Sci. 65:329-338.

Charreau, C. 1977. Some controversial technical aspects of farming systems in semi-arid west Africa. *In* Proc. Int. Symp. on Rainfed Agriculture in Semi-Arid Regions, Glen H. Cannell (ed.). pp. 313-360. Riverside, California, April 1977.

Chepil, W.A., W.C. Moldenhauer, J.A. Hobbs, N.L. Nossaman, and H.M. Taylor. 1962. Deep plowing of sandy soils. U.S. Dept. Agric., Agric. Res. Serv. Prod. Res. Rep. No. 64. Washington, DC: U.S. Government Printing Office.

Chepil, W.S., and N.P. Woodruff. 1963. The physics of wind erosion and its control. Adv. Agron. 15:211-302.

Clark, R.N., and O.R. Jones. 1981. Furrow dams for conserving rainwater in a semiarid climate. *In* Proc. Conf. on Crop Production with Conservation in the 80's, Chicago Ill., December 1980, pp. 198-206. Am. Soc. Agric. Eng., St. Joseph, Mich.

Cochran, V.L., L.F. Elliott, and R.I. Papendick. 1982. Effect of crop residue management and tillage on water use efficiency and yield of winter wheat (*Triticum aestivum*). Agron. J. 74:929-932.

Craig, D.G., and J.W. Turelle. 1964. Guide for wind erosion control on cropland in the Great Plains States. U.S. Dept. Agric., Soil Conservation Service.

Dickey, E.C., T.R. Peterson, J.R. Gilley, and L.N. Mielke. 1983. Yield comparisons between continuous no-till and tillage rotations. Trans. Am. Soc. Agric. Eng. 26:1682-1686.

Donahue, R.L., R.W. Miller, and J.C. Shickluna. 1977. *In* Soils – An Introduction to Soils and Plant Growth, 4th ed., pp. 155-171, 302-320, 463-490. Englewood Cliffs, N.J.: Prentice-Hall, Inc.

Doran, J.W., W.W. Wilhelm, and J.F. Power. 1984. Crop residue removal and soil productivity with no-till corn, sorghum, and soybean. Soil Sci. Soc. Am. J. 48:640-645.

Duley, F.L., and L.L. Kelly. 1939. Effect of soil type, slope, and surface conditions on intake of water. Agric. Exp. Sta. Res. Bull. 112, Univ. of Nebraska, Lincoln.

Duley, F.L., and J.C. Russel. 1939. The use of crop residues for soil and moisture conservation. J. Am. Soc. Agron. 31:703-709.

Elwell, H.A. 1983. The degrading soil and water resources of the communal areas. Zimbabwe Sci. News 17:145-147.

Elwell, H.A. 1985. An assessment of soil erosion in Zimbabwe. Zimbabwe Sci. News 19:27-31.

Engle, C.F., R.C. McClellan, and R.E. McDole. 1980. Conservation in crop production. Washington State Univ. Coop. Ext. Service EM4560, 1-5.

FAO. 1978. Soil erosion by wind and measures for its control on agricultural lands. FAO Agric. Devel. Paper No. 71, FAO, Rome.

Fischer, H.H. 1982. Soil tillage and moisture conservation practices on the black clay soils of the Springbok Flats. Crop Prod. 11:81-84.

Frere, M.H. 1976. Nutrient aspects of pollution from cropland. *In* Control of Water Pollution from Cropland, Vol. II – An Overview, B.A. Stewart, D.A. Woolhiser, W.H. Wischmeier, J.H. Caro, and M.H. Frere (eds.). pp. 59-90. U.S. Dept. Agric. Rep. No. ARS-H-5- 2. Washington, DC: U.S. Government Printing Office.

Frere, M.H., D.A. Woolhiser, J.H. Caro, B.A. Stewart, and W.H. Wischmeier. 1977. Control of nonpoint water pollution from agriculture: Some concepts. J. Soil Water Conserv. 32:260–264.

Fryrear, D.W. 1981. Tillage influences monthly wind erodibility of dryland sandy soils. *In* Proc. Conf. on Crop Production with Conservation in the 80's, Chicago, Ill., December 1980, pp. 153–163. Am. Soc. Agric. Eng., St. Joseph, Mich.

Gausman, H.W., A.H. Gerbermann, C.L. Wiegand, R.W. Leamer, R.R. Rodriguez, and J.R. Noriega. 1975. Reflectance differences between crop residues and bare soils. Soil Sci. Soc. Am. Proc. 39:752–755.

Gerard, C.J. 1965. The influence of soil moisture, soil texture, drying conditions and exchangeable cations on soil strength. Soil Sci. Soc. Am. Proc. 29:641–645.

Gerard, C.J. 1986. Laboratory experiments on the effects of antecedent moisture content and residue applications on structural properties of a fragile soil. Soil & Tillage Res. 7:63–74.

Gerard, C.J., P.D. Sexton, and D.M. Conover. 1984. Effect of furrow diking, subsoiling, and slope position on crop yields. Agron. J. 76:945–950.

Gerard, C.J., P.D. Sexton, and D.M. Matus. 1983. Furrow diking for cotton production in the Rolling Plains. *In* Furrow Diking of Cotton, pp. 1–16. Texas Agric. Exp. Sta. Prog. Rep. PR-4174, September 1983.

Gerard, C.J., P. Unger, D. Bordovsky, T. Gerik, F. Hons, and J. Matocha. 1987. Conservation tillage effects on soil physical properties. *In* Conservation Tillage in Texas, pp. 16–28. Texas Agric. Exp. Sta. Res. Mono., College Station, Texas.

Gerling, J.E., H.W. Downs, J. Solie, and J. Stiegler. 1983. Minimum tillage systems for continuous wheat cropping in Oklahoma. Am. Soc. Agric. Eng. Paper No. 83-1525, St. Joseph, Mich.

Greb, B.W. 1974. Yield response to fall weed control in new wheat stubble in a fallow-wheat rotation. *In* Proc. Fourth Annual Colorado Crop Protection Inst., Fort Collins, Colorado, November 1974, B.L. Bohmont (ed.), pp. 33–45. Colorado State Univ., Fort Collins.

Greb, B.W. 1978. Millet production with limited water. Colorado State Univ. Exp. Sta. Pub. No. PR-78, 1–3.

Greb, B.W. 1979. Reducing drought effects on croplands in the west central Great Plains. Info. Bull. No. 420, U.S. Dept. Agric., Washington, DC. U.S. Government Printing Office, pp. 1–31.

Greb, B.W., D.E. Smika, and A.L. Black. 1967. Effect of straw-mulch rates on soil water storage during summer fallow in the Great Plains. Soil Sci. Soc. Am. Proc. 31:556–559.

Green, J.J., E.W. Chenault, D.E. LavaFe, and A.F. Wiese. 1982. Weed control with a controlled droplet applicator. Texas Agric. Exp. Sta. Prog. Rep. PR-4025.

Griffith, D.R., J.V. Mannering, and W.C. Moldenhauer. 1977. Conservation tillage in the eastern Corn Belt. J. Soil Water Conserv. 32:20–28.

Gupta, J.P., and G.N. Gupta. 1983. Effect of grass mulching on growth and yield of legumes. Agric. Water Man. 6:375–384.

Hamblin, A.P. 1984. The effect of tillage on soil surface properties and the water balance of a Xeralfic Alfisol. Soil & Tillage Res. 4:543–559.

Hanks, R.J., S.A. Bowers, and L.D. Bark. 1961. Influence of soil surface conditions on net radiation, soil temperature, and evaporation. Soil Sci. 92:233–238.

Hanks, R.J., and N.P. Woodruff. 1958. Influence of wind on water vapor transfer through soil, gravel, and straw mulches. Soil Sci. 86:160–164.

Harman, W.L., and A.F. Wiese. 1985. Economic appraisal of reduced-tillage practices. *In* Weed Control in Limited-Tillage Systems, A.F. Wiese (ed.). pp. 282–297. Weed Sci. Soc. Am., Champaign, Ill.

Harper, J. and O.H. Brensing. 1950. Deep plowing to improve sandy land. Oklahoma Agric. Exp. Sta. Bull. B-362.

Harrold, L.L., and W.M. Edwards. 1972. A severe rainstorm test of no-till corn. J. Soil Water Conserv. 27:30.

Hauser, V.L. 1968. Conservation bench terraces in Texas. Trans. Am. Soc. Agric. Eng. 11:385–386, 392.

Hayes, W.A., and L.W. Kimberlin. 1978. A guide for determining crop residue for water erosion control. *In* Crop Residue Management Systems, W.R. Oschwald (ed.). pp. 35–48. Spec. Pub. No. 31. Am. Soc. Agron., Madison, Wisc.

Herrman, T., and M.V. Wiese. 1985. Influence of cultural practices on incidence of foot rot in winter wheat. Plant Disease 69:948–950.

Hopp, H., and C.S. Slater. 1961. The effect of earthworms on the productivity of agricultural soil. *In* The Challenge of Earthworm Research, R. Rodale (ed.). pp. 67–83. The Soil and Health Foundation, Emmaus, Pa.

ICI – Plant Protection. Handbook of Direct Drilling, pp. 24–25 (1977 Addendum), 67–86. Birmingham: Kynoch Press.

Johnson, W.C. 1950. Stubble-mulch farming on wheatlands of the Southern High Plains. U.S. Dept. Agric. Circ. No. 860, Washington, DC: U.S. Government Printing Office.

Johnson, W.C. 1964. Some observations on the contribution of an inch of seeding time soil moisture to wheat yields in the Great Plains. Agron. J. 56:29–35.

Johnson, W.C., and R.G. Davis. 1972. Research on stubble-mulch farming of winter wheat. U.S. Dept. Agric. Agric. Res. Serv., Conserv. Res. Rep. No. 16. Washington, DC: U.S. Government Printing Office.

Jones, O.R. 1981. Land forming effects on dryland sorghum production in the southern Great Plains. Soil Sci. Soc. Am. J. 45:606–611.

Jones, O.R., and V.L. Hauser. 1975. Runoff utilization for grain production. *In* Water Harv. Symp. Proc., Phoenix, Ariz., pp. 277–283. U.S. Dept. Agric. ARS W-22.

Juo, A.S.R., and R. Lal. 1977. The effect of fallow and continuous cultivation on the chemical and physical properties of an Alfisol in Western Nigeria. Plant and Soil 47:567–584.

Khan, S.A., and B.N. Chatterjee. 1982. Growing greengram with minimum tillage. Indian J. Agric. Sci. 52:117–119.

Kimberlin, L.W. 1976. Conservation treatment of erodible cropland: Status and needs. *In* Soil Erosion: Prediction and Control, pp. 339–346. U.S. Dept. Agric. Agric. Res. Serv. Spec. Publ. 21. Washington, DC: U.S. Government Printing Office.

Koshi, P.T., and D.W. Fryrear. 1973. Effect of tractor traffic, surface mulch, and seedbed configuration on soil properties. Soil Sci. Soc. Am. Proc. 37:758–762.

Lal, R. 1976. No-tillage effects on soil properties under different crops in Western Nigeria. Soil Sci. Soc. Am. J. 40:762–768.

Lal, R. 1980 [?]. No-tillage farming in the tropics. *In* No-tillage Research: Research Reports and Reviews, R.E. Phillips, G.W. Thomas, and R.L. Blevins (eds.). pp. 103–151. Lexington: Univ. of Kentucky.

Lal, R. 1986. No-tillage and surface-tillage systems to alleviate soil-related constraints in the tropics. *In* No-Tillage and Surface-Tillage Agriculture: The Tillage Revolution, M.A. Sprague and G.B. Triplett (eds.). pp. 261–317. New York: John Wiley & Sons.

Lang, P.M., and J.B. Mallett. 1984. Effect of the amount of surface maize residue on infiltration and soil loss from a clay loam soil. South African J. Plant and Soil 1:97–98.

Lemon, E.R. 1956. The potentialities for decreasing soil moisture evaporation loss. Soil Sci. Soc. Am. Proc. 20:120–125.

Lindwall, C.W., and D.T. Anderson. 1981. Agronomic evaluation of minimum tillage systems for summer fallow in southern Alberta. Canadian J. Plant Sci. 61:247–253.

Lyles, L., L.A. Disrud, and R.K. Krauss. 1971. Turbulence intensity as influenced by surface roughness and mean velocity in a wind-tunnel boundary layer. Trans. Am. Soc. Agric. Eng. 14:285–289.

Lyles, L., and J. Tatarko. 1982. Emergency tillage to control wind erosion: Influences on winter wheat yields. J. Soil Water Conserv. 37:344–347.

Mannering, J.V., and C.R. Fenster. 1983. What is conservation tillage? J. Soil Water Conserv. 38:141–143.

McCalla, T.M. 1959. Microorganisms and their activity with crop residues. Nebraska Agric. Exp. Sta. Bull. No. 453:1–31.

McCalla, T.M., and J.T. Army. 1961. Stubble mulch farming. Adv. Argon. 13:125–196.

McCalla, T.M., and F.L. Duley. 1946. Effects of crop residues on soil temperature. Agron. J. 38:75–89.

McDole, R.E., and S. Vira. 1980. Minimum tillage for soil erosion control under dryland crop production. Univ. Idaho Coop. Ext. Serv. Agric. Exp. Sta. Current Info. Series No. 523:1–4.

Meyer, L.D., W.H. Wischmeier, and G.R. Foster. 1970. Mulch rates required for erosion control on steep slopes. Soil Sci. Soc. Am. Proc. 34:928–931.

Meyers, P.C. 1983. Why conservation tillage? J. Soil Water Conserv. 38:136.

Mieike, L.N., W.W. Wilhelm, K.A. Richards, and C.R. Fenster. 1984. Soil physical characteristics of reduced tillage in a wheat-fallow system. Trans. Am. Soc. Agric. Eng. 27:1724–1728.

Moore, K.J., and R.J. Cook. 1984. Increased take-all of wheat with direct drilling in the Pacific Northwest. Phytopathology 74:1044–1049.

Muchiri, G., and F.N. Gichuki. 1983. Conservation tillage in semi-arid areas of Kenya. *In* Soil and Water Conservation in Kenya, D.B. Thomas and W.M. Senga (eds.), pp. 395–419. Inst. for Development Studies and Faculty of Agric., Univ. of Nairobi, Kenya.

Mulvaney, D.L., and L. Paul. 1984. Rotating crops and tillage—Both sometimes better than just one. Crops & Soils 36(7):18–19.

Ngatunga, E.L.N., R. Lal, and A.P. Uriyo. 1984. Effects of surface management and soil erosion from some plots at Mlingano, Tanzania. Geoderma 33:1–12.

Onstad, C.A. 1972. Soil and water losses as affected by tillage practices. Trans. Am. Soc. Agric. Eng. 15:287–289.

Papendick, R.I., and D.E. Miller. 1977. Conservation tillage in the Pacific Northwest. J. Soil Water Conserv. 32:49–56.

Parmelee, R.W., and D.G. Alston. 1986. Nematode tropic structure in conventional and no-tillage agroecosystems. J. Nematology 18:403–407.

Pathak, P., S.M. Miranda, and S.A. El-Swaify. 1985. Improved rainfed farming for semi-arid tropics—implications for soil and water conservation. *In* Soil Erosion and Conservation, S.A. El-Swaify, W.C. Moldenhauer, and A. Lo (eds.), pp. 338–354. Ankeny, Iowa: Soil Conserv. Soc. Am.

Phillips, S.H. 1984. Other pests in no-tillage and their control. *In* No-tillage Agricul-

ture – Principles and Practices. R.E. Phillips and S.H. Phillips (eds.). pp. 171–189. New York: Van Nostrand Reinhold Co.

Phillips, W.M. 1969. Dryland sorghum production and weed control with minimum tillage. Weed Sci. 17:451–454.

Rawitz, E., J. Morin, W.B. Hoogmoed, M. Margolin, and H. Etkin. 1983. Tillage practices for soil and water conservation in the semi-arid zone. I. Management of fallow during the rainy season preceding cotton. Soil & Tillage Res. 3:211–232.

Ray, B. 1986. Conservation tillage to control soil erosion. Pesticides (Bombay) 20(2): 11–16.

Richardson, C.W. 1973. Runoff, erosion, and tillage efficiency on graded-furrow and terraced watersheds. J. Soil Water Conserv. 28:162–164.

Richey, C.B., D.R. Griffith, and S.D. Parsons. 1977. Yields and cultural energy requirements for corn and soybeans with various tillage-planting systems. Adv. Agron. 29:141–182.

Ritchie, J.T., and E. Burnett. 1971. Dryland evaporative flux in a subhumid climate. II. Plant influences. Agron. J. 63:56–62.

Rockwood, W.G., and R. Lal. 1974. Mulch tillage: A technique for soil and water conservation in the tropics. Span 17:77–79.

Russel, J.C. 1939. The effect of surface cover on soil moisture losses by evaporation. Soil Sci. Soc. Am. Proc. 4:65–70.

SCSA (Soil Conservation Society of America). 1982. Resource Conservation Glossary. Ankeny, Iowa: Soil Conserv. Soc. Am.

Sherif, S., M.S. Chaudhry, and S. Khan. 1982. Dryland wheat production in the western part of Libya. II. Subsoiling and its residual effects. Libyan J. Agric. 11:23–30.

Skidmore, E.L., and F.H. Siddoway. 1978. Crop residue requirements to control wind erosion. *In* Crop Residue Management Systems, W.R. Oschwald (ed.). pp. 17–33. Spec. Pub. No. 31. Am. Soc. Agron., Madison, Wisc.

Smika, D.E. 1976a. Mechanical tillage for conservation fallow in the semiarid Central Great Plains. *In* Conservation Tillage, B.W. Greb (ed.). pp. 78–91. Proc. Great Plains Workshop, Fort Collins, Colo. Great Plains Agric. Council, Publ. No. 77.

Smika, D.E. 1976b. Seed zone soil water conditions with reduced tillage in the semiarid Central Great Plains. *In* Proc. 7th Conf. Int. Soil Tillage Res. Org., Uppsala, Sweden, 1976. 37.1–37.6.

Smika, D.E. 1983. Soil water change as related to position of wheat straw mulch on the soil surface. Soil Sci. Soc. Am. J. 47:988–991.

Smika, D.E., and G.A. Wicks. 1968. Soil water storage during fallow in the Central Great Plains as influenced by tillage and herbicide treatments. Soil Sci. Soc. Am. Proc. 32:591–595.

Stewart, B.A., D.A. Woolhiser, W.H. Wischmeier, J.H. Caro, and M.H. Frere. 1975. Control of water pollution from cropland. Vol. 1. A manual for guideline development. U.S. Dept. Agric. Rep. No. ARS-H-5-1. Washington, DC: U.S. Government Printing Office.

Stroosnijder, L., and W.B. Hoogmoed. 1984. Crust formation on sandy soils in the Sahel. II. Tillage and its effect on the water balance. Soil & Tillage Res. 4:321–337.

Taylor, H.M., G.M. Roberson, and J.J. Parker, Jr. 1966. Soil strength-root penetration relations for medium- to coarse-textured soil materials. Soil Sci. 102:18–22.

Taylor, W.A., C.R. Merrett and J.A. Drinkwater. 1976. An experimental tractor mounted, very low volume uniform-drop size sprayer. Weed Res. 16:203–208.

Triplett, G.B. 1986. Crop management practices for surface-tillage systems. *In* No-Tillage and Surface-Tillage Agriculture: The Tillage Revolution, M.A. Sprague and G.B. Triplett (eds.). pp. 149–182. New York: John Wiley & Sons.

Unger, P.W. 1969. Physical properties of Pullman silty clay loam as affected by dryland wheat management practices. Texas Agric. Exp. Sta. Misc. Pub. MP-933.

Unger, P.W. 1976. Surface residue, water application, and soil texture effects on water accumulation. Soil Sci. Soc. Am. J. 40:298–300.

Unger, P.W. 1978a. Straw-mulch rate effect on soil water storage and sorghum yield. Soil Sci. Soc. Am. J. 42:486–491.

Unger, P.W. 1978b. Straw-mulch effects on soil temperature and sorghum germination and growth. Agron. J. 70:858–864.

Unger, P.W. 1981. Tillage effects on wheat and sunflower grown in rotation. Soil Sci. Soc. Am. J. 45:941–945.

Unger, P.W. 1984a. Tillage and residue effects on wheat, sorghum, and sunflower grown in rotation. Soil Sci. Soc. Am. J. 48:885–891.

Unger, P.W. 1984b. Tillage effects on surface soil physical conditions and sorghum emergence. Soil Sci. Soc. Am. J. 48:1423–1432.

Unger, P.W., R.R. Allen, and A.F. Wiese. 1971. Tillage and herbicides for surface residue maintenance, weed control, and water conservation. J. Soil Water Conserv. 26:147–150.

Unger, P.W., and T.M. McCalla. 1980. Conservation tillage systems. Adv. Agron. 33:1–58.

Unger, P.W., and J.J. Parker. 1976. Evaporation reduction from soil with wheat, sorghum, and cotton residues. Soil Sci. Soc. Am. J. 40:938–942.

Unger, P.W., J.L. Steiner, and O.R. Jones. 1986. Response of conservation tillage sorghum to growing-season precipitation. Soil & Tillage Res. 7:291–300.

Unger, P.W., and B.A. Stewart. 1976. Land preparation and seedling establishment practices in multiple cropping systems. *In* Multiple Cropping, R.I. Papendick, P.A. Sanchez, and G.B. Triplett (eds.) pp. 255–273. Spec. Pub. No. 27. Am. Soc. Agron., Madison, Wisc.

Unger, P.W., and B.A. Stewart. 1988. Conservation techniques for vertisols. *In* Vertisols. Their Distribution, Properties, Classification and Management, L.P. Wilding and R. Puentes (eds.) pp. 165–181. Texas A&M University Printing Center, College Station, TX.

Unger, P.W., and A.L. White. 1979. Managing irrigated winter wheat residues for water storage and subsequent dryland grain sorghum production. Soil Sci. Soc. Am. J. 43:582–588.

Van Doren, D.M., Jr., and R.R. Allmaras. 1978. Effect of residue management practices on the soil physical environment, microclimate, and plant growth. *In* Crop Residue Management Systems, W.R. Oschwald (ed.), pp. 49–83. Spec. Pub. No. 31. Am. Soc. Agron., Madison, Wisc.

Wall, D.A., and E.H. Stobbe. 1984. The effect of tillage on soil temperature and corn (*Zea mays* L.) growth in Manitoba. Canadian J. Plant Sci. 64:59–67.

Wauchope, R.D., L.L. McDowell, and L.J. Hagen. 1985. Environmental effects of limited tillage. *In* Weed Control in Limited-Tillage Systems, A.F. Wiese (ed.), pp. 266–281. Champaign, Ill.: Weed Sci. Soc. Am.

Wicks, G.A., and D.E. Smika. 1973. Chemical fallow in a winter wheat-fallow rotation. J. Weed Sci. Soc. Am. 21:97–102.

Wiese, A.F. 1986. Herbicide application. *In* Research Methods in Weed Science, 3rd ed. N.D. Camper (ed.), pp. 1–27. Champaign, Ill.: Southern Weed Sci. Soc.

Wiese, A.F., and D.W. Staniforth. 1973. Weed control in conservation tillage. *In* Conservation Tillage, the Proc. of a Natl. Cont., Des Moines, Iowa, March 1973, pp. 108–114. Ankeny, Iowa: Soil Conserv. Soc. Am.

Wiese, A.F., P.W. Unger, R.R. Allen, O.R. Jones, and W.L. Harman. 1986. Minimum tillage systems for the Texas Panhandle. Texas Agric. Exp. Sta. MP-1597.

Wiese, A.F., P.W. Unger, R.R. Allen, and J.T. Musick. 1979. Herbicides make limited tillage work. *In* What's New in Water Conservation?, pp. E-1-6. Proc. Crop Prod. and Utiliz. Symp., February 1979, Amarillo, Tex.

Willcocks, T.J. 1981. Tillage of clod-forming sandy loam soils in the semi-arid climate of Botswana. Soil & Tillage Res. 1:323-350.

Willcocks, T.J. 1984. Tillage requirements in relation to soil type in semi-arid rainfed agriculture. J. Agric. Eng. Res. 30:327-336.

Windsor, T. 1984. Dryland farming for increased food production. *In* The Role Farm Management in Food Production, pp. 217-222. Fifth Int. Farm Management Congress, Farnham Royal, Slough, UK. Commonwealth Agric. Bureaux.

Wischmeier, W.H. 1973. Conservation tillage to control water erosion. *In* Conservation Tillage, the Proc. of a Natl. Conf., Des Moines, Iowa, March 1973, pp. 133-141. Ankeny, Iowa: Soil Conserv. Soc. Am.

Wischmeier, W.H., and D.D. Smith. 1978. Predicting rainfall erosion losses—A guide to conservation planning. U.S. Dept. Agric., Sci. and Educ. Admin., Agric. Handbook No. 537. Washington, DC: U.S. Government Printing Office.

Woodruff, N.P., and L. Lyles. 1967. Tillage and land modification to control wind erosion. *In* Tillage for Greater Crop Production, pp. 63-67, 70. Pub. No. 168, Am. Soc. Agric. Eng., St. Joseph, Mich.

Woodruff, N.P., and F.H. Siddoway. 1973. Wind erosion control. *In* Conservation Tillage, the Proc. of a Nat'l Conf., Des Moines, Iowa, March 1973, pp. 156-162. Ankeny, Iowa: Soil Conserv. Soc. Am.

Zentner, R.P., and C.W. Lindwall. 1982. Economic evaluation of minimum tillage systems for summer fallow in southern Alberta. Canadian J. Plant Sci. 62:631-638.

Zingg, A.W. 1954. The wind erosion problem in the Great Plains. Trans. Am. Geophys. Union 35:252-258.

Tillage and Residue Management Effects on Soil Organic Matter Dynamics in Semiarid Regions

J.L. Smith and L.F. Elliott

I. Introduction 69
II. Characteristics of Semiarid Regions 70
III. Properties and Factors Affecting Soil Organic Matter 72
A. Water and Temperature 72
B. SOM Turnover and C:N Ratio 74
C. Rate and Method of Crop Residue Addition 75
D. Soil Type 76
IV. The Effect of Residues on Soil Structure 76
V. Tillage and Residue Management Effects on Soil Organic Matter and Nutrients 77
VI. Tillage Strategies for Improved Management of Organic Matter and Plant Nutrients 82
VII. Cropping Methods for Maintaining Soil Organic Matter and Nutrients in Semiarid Areas 83
VIII. Summary and Conclusions 84
References 85

I. Introduction

The organic matter content of agricultural soils is highly correlated with their potential productivity, tilth, and fertility. Although the amount of soil organic matter (SOM) in most semiarid dryland soils is relatively low, ranging from 0.5 to 3% and typically less than 1%, its influence on soil properties is of major significance. Even at low concentrations organic matter is the major substance facilitating soil aggregation and structural stability. These properties are mainly responsible for enhanced air and water relationships for root growth and in addition protect soils from wind and water erosion. The humic fraction of SOM

1990 by Springer-Verlag New York Inc.
Advances in Soil Science, Volume 13

causes the gradual darkening of soils, which increases their capacity to absorb heat and to warm rapidly in the spring.

Organic matter in semiarid regions is the major pool for critical plant nutrients. In these areas with low or intermittent rainfall the N, P, S contents of the soil average 0.12%, 0.05%, and 0.03%, respectively, with 95% of the N, 40% of the P, and 90% of the S being associated with the organic matter component. Since the soil organic matter constitutes the predominant pool of plant nutrients, the decomposition and fluctuation within this pool are of major significance to nutrient storage and cycling. In many dryland cropping systems, depending on fertilizer additions and crop rotation, 50% or more of the nitrogen required by the crop comes from the mineralization of SOM. The microbial action that mediates this decomposition and nutrient release process is regulated by perturbations of the system such as wetting of dry soil, tillage, and addition and placement of residue. These types of perturbations affect the dynamics of SOM decomposition, the size of the microbiol biomass pool, and nutrient release.

Intensive cropping and tillage systems have led to substantial decreases in the organic matter levels of much of the world's prime farmland through increased microbial decomposition and wind and water erosion of inadequately protected soils. This decrease in SOM levels has been paralleled by declines in soil productivity. The major factor regulating the decline in SOM concentrations is the management of crop residues. Residue management has included removing residue by burning, baling, and grazing, totally incorporating it into the soil, or leaving it on the soil surface. Each treatment has a varying affect on SOM levels, with total removal accompanied by intensive tillage being the most severe since the soil-stabilizing effect of residues is lost, leaving the soil susceptible to wind and water erosion. The loss of SOM and associated nutrients with residue treatment and tillage will greatly influence the nutrient cycling dynamics in semiarid regions, which produce most of the world's basic food crops. Perhaps the most important current priority in world agriculture is to devise tillage and residue management strategies and systems that will effectively control erosion, increase the quantity and quality of soil organic matter, and restore soil productivity to optimum levels.

The purposes of this chapter are (1) to assess the influence of tillage and residue management on SOM transformations and plant nutrient availability and (2) to formulate strategies for improving the productivity and sustainability of low-input farming systems in semiarid regions.

II. Characteristics of Semiarid Regions

Semiarid regions characteristically support dryland farming systems by virtue of the native climate. Dryland farming depends on yearly rainfall and timing in contrast to irrigated arid lands and humid regions with adequate moisture for crop production. Semiarid dryland agricultural areas represent large amounts of land throughout the world producing significant quantities of basic crops such as wheat (*Triticum vulgare*), grain sorghum (*Sorghum vulgare*), and millet (*Pennisetum americanum*), as well as regionally important crops such as cotton (*Gos-*

sypium hirsutum), peas, groundnut (*Arachis hypogaea*), and beans (Dregne and Willis, 1983; Kanwar, 1976). Agricultural production in these semiarid regions is typically limited by water and soil productivity factors.

The characteristics used to delineate semiarid regions from other climatic zones are not always clear and precise. Definitions of semiarid zones have been based on temperature, rainfall, dry season length, growing season, potential evaporation, or a combination of these parameters (Oram, 1977; Bailey, 1979). However, generally two semiarid zones are recognized based on physical–climatic classification—the semiarid tropical zone close to the equator and the semiarid steppe or midlatitude zone (Bowden, 1979). The steppe region has also been referred to as the semiarid Mediterranean region (Oram, 1977). Together these semiarid zones occupy 14.2×10^6 km^2 and constitute 11% of the world land area.

The semiarid tropics include areas of Australia, India, Africa, Brazil, and Asia. These areas are characterized by a zeric frost-free climate with summer precipitation. Precipitation ranges from 400 to 800 mm annually, with 80% occurring during a several-month-long rainy season. The soils of these areas are varied; however, red soils (Luvisols, FAO/UNESCO, Aridisols, U.S.) and black soils (Vertisols) predominate in the crop-producing areas (Oram, 1977; Kanwar, 1976). The red soils have a history of weathering and erosion, which accounts for the low nutrient status, particularly of nitrogen (N) and phosphorus (P). These soils are generally shallow, have low water-holding capacity and argillic horizons, and are susceptible to erosion when wet. In contrast, the black soils have higher nutrient status; however, they are difficult to manage because of the high montmorillonite clay content. This soil type has high base saturation and good water-holding capacity, and supports a greater SOM content. It is hard in the dry season, slick when wet, and highly erodible, particularly during fallow periods (Kanwar, 1976). From these descriptions, it appears that management factors play a large role in the productivity of these soils.

The semiarid steppe region includes North America and many countries of Eurasia. In North America the region spans from the Canadian prairies to northern Mexico and in Eurasia along an east–west zone. The midlatitude steppe zone is characterized by definite warm and cold seasons and annual precipitation of 250 to 500 mm occurring during the October to April period (Bowden, 1977). Like the semiarid tropical region the steppe zone has inadequate and unrealiable rainfall; however, rainfall storage is more efficient in the steppe zone. The soils of the semiarid steppe region are quite distinct from those of the semiarid tropic region and vary substantially between North America and Eurasia. Generally the steppe region soils have formed from sedimentary rock, in contrast to the crystalline rock of the tropic region. This fertile parent material has developed deep soil profiles under grass vegetation, thus the soils are rich in inorganic nutrients and SOM. The soil classifications for the steppe zone are chernozems (Mollisols) and Luvisols (Aridisols); however, there is considerable regional variation. The soils have a moderate to high base saturation and good water-retention characteristics, and they present few cultivation problems. Erosion of these soils can be a problem, especially in areas where precipitation is in the form of snow or in areas of moderate to steep slopes.

The difference in SOM and nutrient content, water retention, and soil erodability between semiarid steppe and tropical regions produces significant differences in crop yields and dry matter production. Thus, efficient cropping systems and residue management practice may vary considerably between these regions. The specific practices for managing residues to optimize soil productivity will need to be tailored for each soil and subclimate, though the principles apply to all climatic zones.

III. Properties and Factors Affecting Soil Organic Matter

Soil organic matter is a heterogeneous mixture of living, dead, decomposing organic, and inorganic compounds for which the precise composition is unknown. SOM is derived from plant, animal, and microbial tissue and contains various amounts of carbon, hydrogen, oxygen, nitrogen, phosphorus, sulfur, and traces of other elements. Approximately 15% of the SOM can be identified as polysaccharides, polypeptides, phenols, and other simple organic compounds (Alexander, 1977). The rest of the SOM is considered humic material, a dark amorphous colloidal substance derived from the chemical, physical, and biological transformation of plant and animal material.

SOM can absorb up to 90% of its weight as water, which substantially increases the water-holding capacity of mineral soil. Its colloidal nature allows it to impart a substantial buffering capacity to the soil through its large cation and anion exchange capacity. This exchange capacity is from 2 to 30 times the exchange capacity of the mineral colloids. In addition to physical properties SOM can increase the availability of micronutrients through complexation and in addition hold substantial amounts of nitrogen, phosphorus, and sulfur in organic forms. Table 1 summarizes the effects of SOM on soil properties.

The equilibrium level of SOM is determined by a number of interacting factors including precipitation, temperature, soil type, tillage, cropping systems, the type and quantity of crop residue returned to the soil, and the method of residue application (i.e., disked-in, plowed-down, or surfaced-mulched). Reductions in SOM over time in agricultural soils are largely due to tillage, less residue return, and soil erosion. Carbon loss by tillage is caused by greater oxidation of SOM and ranges from 20 to 50% in soils dominating the semiarid regions (Mutatkar and Raychaudhari, 1959; Mann, 1986). The following is a brief discussion of those parameters which specifically affect the decomposition and accumulation of organic residues, the dynamics of residual SOM, and the availability of nutrients derived from organic materials.

A. Water and Temperature

Water and temperature are the principle factors regulating the decomposition of SOM and crop residues. The decomposition of these materials depends on soil microbial activity, which is governed to a large extent by temperature and

Table 1. General properties of SOM and associated effects on soil properties

Property	Remarks	Effect on soil
Color	The typical dark color of many soils is caused by organic matter	May facilitate warming
Water retention	Organic matter can hold up to 20 times its weight in water.	Helps prevent drying and shrinking. May significantly improve the moisture-retaining properties of sandy soils.
Combination with clay minerals	Cements soil particles into structural units called aggregates	Permits exchange of gases stabilizes structure, increases permeability.
Chelation	Forms stable complexes with Cu^{2+}, Mn^{2+}, Zn^{2+}, and other polyvalent cations.	May enhance the availability of micronutrients to higher plants.
Solubility in water	Insolubility of organic matter is because of its association with clay. Also, salts of divalent and trivalent cations with organic matter are insoluble. Isolated organic matter is partly soluble in water.	Litttle organic matter is lost by leaching.
Buffer action	Organic matter exhibits buffering in slightly acid, neutral, and alkaline ranges.	Helps to maintain a uniform reaction in the soil.
Cation exchange	Total acidities of isolated fractions of humus range from 300 to 1400 meg/100g.	May increase the cation exchange capacity (CEC) of soil. From 20 to 70 percent of the CEC of many soils (e.g., Mollisols) is caused by organic matter.
Mineralization	Decomposition of organic matter yields CO_2, NH^+, NO_3, PO_4, and SO_4.	A source of nutrient elements for plant growth.
Combines with organic molecules	Affects bioactivity, persistence and biodegradability of pesticides	Modifies application rate of pesticides for effective control.

From F.J. Stevenson, Humus Chemistry, 1982. Copyright © 1982 John Wiley & Sons, Inc.

moisture. Across climatic zones it is quite common to find a direct relationship between rainfall and SOM content. As temperature increases across zones of constant moisture and similar plant material, SOM and nitrogen content will decrease. In general low temperatures and high rainfall favor SOM increases and high temperatures and low rainfall favor SOM decreases. We would then expect

higher rates of SOM decomposition in the semiarid tropics versus the steppe zone causing SOM contents to be lower.

These relationships of SOM decomposition and accumulation are also governed by the type and amount of plant biomass. Crop residue and its nutrient status and decomposability govern the amount and characteristics of the SOM produced.

Soil microorganisms can function over wide temperature ranges (0°C to above 60°C), but exhibit maximum growth and activity in the temperature range of about 20 to 30°C. Significant microbial decomposition of wheat straw can occur at temperatures as low as 0°C, but peaks about 30°C. Even though temperatures are optimum, residue decomposition will be slow if water is limiting. When temperatures increase, more evaporation occurs, and in many cases causing maximum microbial activity to occur below the optimum temperature because water is limiting. This is especially true in semiarid regions where some version of conservation tillage has left most of the crop residues at the surface where it is subject to rapid drying. Usually organic wastes and residues decompose rapidly at a water potential of about −0.3 bars. As the medium becomes wetter, a point is reached at which water limits oxygen diffusion and the system becomes anaerobic, thus slowing the rate of residue decomposition. As the system dries below −0.3 to −1.0 bars, water potential bacterial activity begins to decrease and activity decreases rapidly at water potentials below −5.0 bars. Fungi can grow at much lower water potentials than bacteria (e.g., −40 to −50 bars or lower water potential); however, the rate of decomposition of organic residues in soil, such as wheat straw, at such low water potentials is markedly slow compared with that which occurs at higher water potentials (Stott et al. 1986). The practical upper limit for temperature and lower limit for water potential, and their mutual interaction, would greatly advance our knowledge of residue decomposition, particularly where residues are concentrated mainly at or near the soil surface. Unfortunately, this relationship is not well understood at this time.

B. SOM Turnover and C:N Ratio

The mean residence time of SOM or the average time to transform the total SOM pool is variable and times of 250–1,900 years have been reported. While microbes produce SOM through the decomposition of organic residues, they also utilize the SOM or humus as a carbon source. It is difficult to ascribe a turnover rate for SOM over broad areas. However in the Sahelian Zone of West Africa, SOM mineralization during the cropping season is on the order of 4–5 percent per year. Annual precipitation for this area ranges from 250 to 800 mm. By contrast, the steppe semiarid regions have a SOM mineralization rate of about 2 percent. The rate of mineralization also depends on whether residues are harvested. Since factors such as climate and soil type are constants, the only major factors influencing SOM transformations are tillage, cropping practices, residue management, and the extent of erosion. The chemical composition of organic residues will influence the rate and extent of decomposition by the soil microflora and thus the potential for increasing SOM. High C:N ratio materials are more resis-

Table 2. Effect of wheat straw return on soil organic matter and soil nitrogen in semiarid soil near Lind, Washington, 1922–1940[a]

Straw return rate (kg/ha)	Gain or loss soil organic matter (kg/ha)	Gain or loss soil nitrogen (kg/ha)
0	−2685	−381
896	− 562	−240
1792	+ 886	−186
3584	+1326	− 11

V.T. Smith, L.C. Wheeting, and S.C. Vandecaveye, Effects of organic residues and nitrogen fertilizers on semiarid soil. Soil Science 63:393–410. © by Williams & Wilkins, 1946.
[a] Residue return rate is the amount of residue applied annually after wheat harvest and during the fallow year.

tant to decomposition due to lignaceous compounds and nitrogen limitations for decomposer organisms. Crop residues that contain readily oxidizable carbon and low levels of nitrogen, such as wheat and rice straw, can induce a high microbiological demand for nitrogen. If this demand is not met by nitrogen in the residue, inorganic soil nitrogen or fertilizer nitrogen will be immobilized in microbial cells effectively reducing the availability of nitrogen to plants. Most cereal straws have C:N ratios ranging from 80 to 120:1 and their decomposition will result in immobilization of nitrogen, whereas residues with C:N ratios of 25:1 or a nitrogen content of about 1.5% will not be nitrogen deficient during the decomposition process. The nitrogen content or C:N ratio of crop residue can be useful for predicting decomposition rates, however, the C:N ratio ignores the substrate quality or microbial availability of the C and N to microorganisms. It has been hypothesized that the gross nitrogen mineralization rate is not dependent upon substrate C:N ratio but on the substrate degradability. This substrate quality is important especially where organic materials have a high lignin content or contain highly resistant nitrogenous components.

C. Rate and Method of Crop Residue Addition

In the semiarid winter wheat region of eastern Washington, USA, a study was conducted from 1922 to 1940 to determine the effects of return rate of crop residues on changes in the content of SOM and soil nitrogen (Smith et al., 1946). The low mean annual precipitation of 230 mm necessitated a summer fallow system whereby a crop was grown and residue returned every other year. When no residue was returned to the soil, the net loss of SOM was 2,685 kg/ha and the soil nitrogen level was essentially in balance with crop removal (Table 2). There was a net gain of 336 kg/ha of organic matter at a residue return rate of 1,792 kg/ha, but a net loss of soil nitrogen at 186 kg/ha. Thus, based on these data it appears that an equilibrium level for organic matter in this particular coarse-textured soil, climatic conditions, cropping system and tillage practices, was reached at a residue return rate of 1,300 to 1,500 kg/ha. However, this rate of residue return

would be associated with a substantial soil nitrogen deficit (200 kg/ha) that would have to be supplemented with fertilizer nitrogen to sustain crop yields.

The method of application (or placement) of residues will also regulate the rate of decomposition. Residues placed on the soil surface will not decompose as rapidly as those which are buried or incorporated because of fluctuations in temperature and moisture. Under laboratory conditions, surface applied residues will decompose about as rapidly as those that are incorporated in soil since the surface residues are not exposed to the extremes of temperature and moisture. Intimate soil contact for inoculation of residue by microorganisms appears unnecessary; the indigenous microflora which colonizes cereal straw provides adequate inoculum to facilitate decomposition, even for surface applied residues (Reinertsen, 1985). Most of the chemical components identified in SOM are decomposition products that remain from the initially applied organic materials or the cellular products of dead microorganisms. SOM is dynamic and will not increase beyond a certain level unless heavy applications of organic wastes are made and/or the rate of decomposition is decreased.

D. Soil Type

An important property of SOM is that it combines with clay particles to form stable aggregates. The extent of clay aggregation is a direct controlling factor in SOM dynamics (Tisdall and Oades, 1982). Clay minerals protect microbial metabolites produced during the decomposition of crop residues. This protection is greater with more stable aggregates and finer clays and is affected by the make-up of the microbial populations and types of crop residues. Studies utilizing labeled extracts from straw and radiocarbon dating have shown reductions in the degradation of readily decomposable compounds due to amorphous and fine fraction soil material (Zunino et al., 1982; Paul, 1984). The stabilizing effect of soil texture can have a dramatic effect on the levels of SOM that can be maintained in specific cropping areas.

IV. The Effect of Residues on Soil Structure

The major factor in soil structure formation is the quality and quantity of organic matter being supplied to the soil by microbial decomposition of plant material. This organic colloidal amorphous material can bind soil particles, plant residues, and living organisms together to create discrete structure forming aggregates. The stability of these aggregates depends on soil texture, type and amount of SOM, and the nature of the microflora.

Crop residue provides a fresh carbon source for microbial biomass production which will increase soil aggregation through several different mechanisms. Soil microorganisms can aggregate soil particles by attraction of dissimilar surface charges. Extracellular mucigels and gums, from metabolic by-products of decomposition and plant roots, are major aggregating materials. These binding mater-

ials are probably complex chainlike organic compounds that bridge across soil particles and are slowly degraded and must be continually replaced to maintain favorable soil structure. In this continual dynamic system soil aggregation and nutrient transfers are driven by crop residues. If the residues are low in nitrogen, and external nitrogen is not available, massive quantities of extracellular polysaccharides and gums are produced which can physically "glue" soil particles together.

The amount and type of residue substantially influences soil structure and thus other measurable soil physical properties. In an Australian study of six soil series in southern Queensland (Dalal and Mayer, 1986a), it was quite evident that bulk density increased less due to tillage in soils where residue was left on the land. A study using wheat straw mulch at rates of 0 to 6730 kg/ha showed significant increases in SOM with concurrent increases in the nonerodible soil aggregate fraction in addition to a significant decrease in bulk density (Black, 1973). In addition, each increase of 1000 kg/ha of residue decreased the erodible fraction by 8%. In the semiarid wheat region of Kansas, significant differences were found in stable aggregates and hydraulic properties of soils cropped to winter wheat or gain sorghum (Skidmore et al., 1986). This may be related to different crop rooting patterns and subsequent in situ root death and decomposition.

V. Tillage and Residue Management Effects on Soil Organic Matter and Nutrients

The use of reduced tillage practices and proper residue management can substantially increase long-term crop production in semiarid rain-fed regions. Increased crop production is due to conservation of yield limiting water, more efficient nutrient availability and cycling, and the decrease in losses of soil by erosion processes. By the nature of these two management tools, tillage practices and residue management become somewhat synonymous. Reduced tillage operations result in a higher percentage of the crop residues remaining on the soil surface. Surface-managed crop residues promote soil aggregation and water infiltration and retention, and reduce surface evaporation. In addition residue decomposition rates are reduced providing a more equilibrated substrate base for microbial activity. Since the microbial biomass of the soil is large enough to act as a source-sink for nutrients the stable supply of an energy source (residues) affects nutrient cycling transformations. The overall effect of crop residues and tillage practices can be altered by soil properties and by specific crop and temperature-moisture relationships. Thus management practices, for maximum benefit, vary from the semiarid steppe to the semiarid tropics, and programs and alternatives must be developed on a regional basis.

When virgin soils in the Great Plains were farmed according to conventional tillage practices, including moldboard plowing to a 15-cm depth, followed by disking and cultivating operations, more than 50% of the SOM and about the same amount of organic nitrogen was lost during the first 50 years of cultivation

(Bauer and Black, 1981). This loss is most rapid during the first few years of cultivation, and eventually an apparent equilibrium is established, provided constant management practices are employed. The time required to reach this equilibrium will vary depending on climatic conditions, extent of erosion, type and rate of residue return, and soil type.

In addition to numerous studies of carbon and nitrogen decline in the U.S. Great Plains region, many studies have been conducted in other semiarid regions of the world. In studying the brown prairie soils of western Canada, Doughty et al. (1954) found that after 14 years of cultivation, up to 26% of the organic matter and 33% of the nitrogen of these soils were lost. Annual losses of carbon and nitrogen in these semiarid steppe soils decreased by half in the second 20-year period of cultivation (Doughty et al., 1954; Campbell et al., 1975). In long-term studies, covering 60 to 80 years, carbon and nitrogen losses from Canadian prairie soils due to cultivation ranged between 50 to 60% and 40 to 60%, respectively (Campbell et al., 1976; Veroney et al., 1981). In semiarid tropical regions there is substantially less information concerning the effects of cultivation on chemical and physical soil properties. In a study of the six soils dominating the landscape of southern Queensland Australia, Dalal and Mayer (1986b) found carbon losses averaged 36% and nitrogen losses averaged 36% in soils cultivated for 20 to 70 years (Figure 1). In addition, 17% of the phosphorus and 30% of the sulfur was lost. In this study several chemical and physical properties were measured with the conclusion that the properties that were most affected by cultivation were associated with SOM. A study of 212 soil samples from the Delhi district in India showed theoretical carbon and nitrogen losses of 11 and 17% for cultivated and virgin soils (Mutatkar and Raychaudhuri, 1959). The relatively low losses of carbon and nitrogen are possibly due to the alluvial nature of these soils as well as low erosion rates. Kanwar (1984) has pointed out the increasing importance of sulfur in tropical plant nutrition which emphasizes the seriousness of the decline in SOM.

In an effort to reduce SOM loss in cultivated soils several reduced tillage management systems have been proposed. These practices include no-tillage, reduced-tillage, stubble-mulching, and shallow conventional plowing. Each practice has beneficial aspects; however, there have been problems with reduced-tillage systems such as high equipment costs and varied reductions in yield.

Bauer and Black (1981) reported the effects of stubble mulching for 25 years on soil carbon, nitrogen concentrations, and soil bulk density. In the Great Plains stubble mulching maintained soil organic carbon higher in coarse and fine textured soils by 44 and 13%, respectively, compared to conventionally plowed soils. In medium-textured soils there was no significant difference in SOM levels. In addition they could find no differences in soil bulk density for the two tillage systems. Dick (1983) investigated the effect of no-tillage, minimum tillage, and conventional tillage on soil carbon, nitrogen, and phosphorus concentrations. These management practices had been applied to the sites for the previous 18 years. The results showed significantly greater amounts of carbon, nitrogen, and phosphorus under no-till surface (0 to 30 cm) soil compared to minimum and conventional

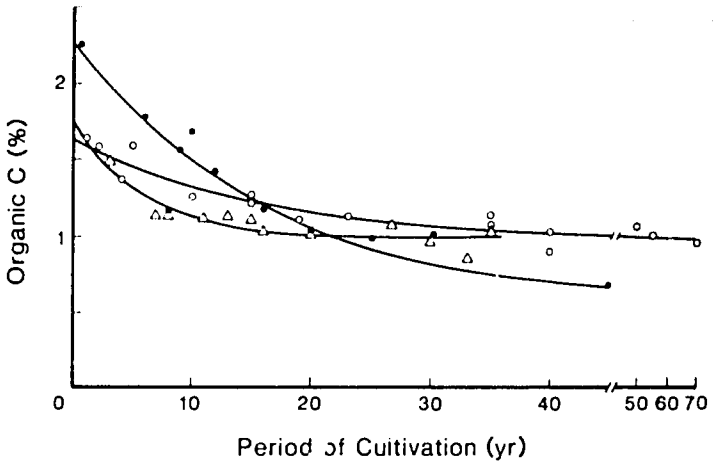


Figure 1. The effect of 0 to 70 years of cultivation on the organic carbon content of selected Australian soils (from Dalal and Mayer, 1986b).

tillage systems. The loss of SOM under no-till averaged 6% during this time period versus 20% for minimum and conventional tillage sites, respectively.

In addition to maintaining favorable soil chemistry for plant production, tillage systems affect the biological soil component as well. Doran (1980b) investigated the effects of reduced tillage on soil biochemical transformations and microbial biomass activity. His results showed differences in total number and types of organisms under no-tillage management. In addition he determined that the average metabolic status of the greater population under no-tillage is less oxidative and lower than under conventional tillage. The differences in microbial biomass levels were related to soil water content, organic C and N concentrations and soil pH. The larger biomass population increases the potential for nitrogen immobilization which should be considered in developing a fertilizer management practice. In a field study using ^{15}N labeled urea fertilizer, Carter and Rennie (1984a,b) investigated soil microbial nitrogen transformations in no-tillage and shallow tillage systems. They found only slight periodic differences in nitrogen cycling between the tillage systems, with the immobilization and stabilization of fertilizer nitrogen being similar. The lack of differences due to tillage may be due to the shallow depth (10 cm) of the tillage operation. They did, however, conclude that the variation in biomass nitrogen corresponded with crop residue distribution. Carter (1986) reported that biological properties of sorts were influenced by the degree of soil mixing, incorporation of crop residues, soil moisture, and root growth all of which are related to tillage practices. For spring cereals under semiarid conditions, he was able to show an increase in microbial biomass of 10 to 23% after 4 years of no-tillage compared to shallow tillage. These microbial and biochemical differences are affected by cropping systems and residue management which will be addressed shortly.

Crop residue management is defined as the use of crop residues for soil protection or improvement (Oschwald, 1978). Thus as previously mentioned, by virtue of minimizing tillage operations residue is conserved and soil protection is enhanced. Crop residues influence many physical, chemical, and biological parameters of soils and proper management can increase soil productivity and reduce losses from erosion. Management practices for crop residues include complete removal by burning stubble or other methods, retaining residues at or above the soil surface, shallow mixing (5 to 10 cm), and completely incorporating residue into soil by conventional tillage operations. Each of these practices has distinct consequences associated with them even though some effects may overlap. Proper residue management practices to maintain and even build soil productivity will vary regionally and will be affected by climate, topography, and cropping systems.

Residue production in semiarid regions is a significant source of carbon, nitrogen, and other important nutrients. In 1973 residue production in the United States totaled 363 million metric tons for nine leading crops (Larson et al., 1978). These residues contained 4×10^6 MT of N, 0.5×10^6 MT of P and 4×10^6 MT of K accounting for 40%, 10%, 80%, respectively, of the fertilizer applied to crops that year. In the semiarid dryland, grain producing areas of the United States, residue production ranges from 3500 kg ha^{-1} to 6000 kg ha^{-1} for winter cereals (Douglas et al., 1980). In the Canadian prairie region residue production from a crop-fallow rotation averages 3800 kg ha^{-1} while the average is and 3000 ha^{-1} for continuous cropping (Voroney et al., 1981). In addition the root residue component supplies an additional 2100 kg ha^{-1} to the soil system. Small grain stubble residue in dryland systems of Australia typically range from 4000 to 5000 kg ha^{-1} (Dalal and Mayer, 1986a). These soils range between 1 and 2% organic carbon thus an average residue input (5000 kg ha^{-1}) represents an input of 2000 kg ha^{-1} yr^{-1} of carbon or 5 to 10% of the total soil carbon. If root material is considered these values would increase by 10 to 40%. In addition these amounts of residues contain 33.5 kg-N ha^{-1}, 3.5 kg-P ha^{-1}, and 48.5 kg-K ha^{-1} assuming typical concentrations of N, P, K, for wheat. It is readily apparent that managing residues will effect not only soil carbon but other nutrients as well.

The most direct beneficial aspect of managing residues is the increase in water conservation in dryland cropping systems when reduced tillage (high surface residues) is employed. The management of surface residues as stubble mulches can greatly increase the productivity of semiarid systems by conserving water and reducing erosion. Freebairn and Boughton (1985) studied the hydrologic effects of managing residues by burning, incorporating, and mulching stubble. They found stubble mulching approximately doubled the infiltration rate of the soil and reduced the total runoff by 40% over stubble incorporation and 65% over stubble burning. In addition, stubble mulching gave 25 to 30 mm more soil water storage than either the stubble burning or incorporation treatments. In India, Giri and Singh (1984) found that straw mulching decreased evaporation and water use from dryland wheat, saving 35 mm of water over the control and increased the farmers net return by 17%. A problem of surface residue placement has been seen in lower

initial yields as the residues immobilize various amounts of nitrogen. However, in many instances this temporary reduction of yield is offset by greater yield with increased available water and the initial net benefit of the residue is decreased erosion. When the new residue-conserving practice comes to a soil–residue equilibrium with respect to nitrogen there will be a net increase in yield due to the moisture conservation along with the benefit of decreased erosion.

Reduced tillage and surface management of residues has a significant ecological effect on the microbiological component of soils. From the soil microbiological standpoint soils are generally carbon limited, that is, readily available carbon substrates are limited. Reduced tillage usually concentrates the residue carbon source near the soil surface (0 to 10 cm) concentrating the microbial biomass in this zone compared to a more uniform distribution to 30 to 40 cm in a conventional residue incorporation system. Crop residue management will influence microbial activity, soil nutrient pools and microbial response to applications of lime and herbicides (Power and Legg, 1978; Doran, 1980a,b). Nutrient cycling components depend on abiotic changes and the type and quantity of residue added. For example, residues with nitrogen concentrations above 1.5 enhance nitrogen availability while those below 1.5% cause availability to decrease. Douglas et al. (1980) showed that mineralization or immobilization of wheat straw nitrogen and sulfur depended on residue placement and initial nutrient content. Agrawal et al. (1974) showed no significant differences in corn yield when wheat residues were incorporated with nitrogen at two different depths (0 to 15 and 0 to 30 cm). However, when no nitrogen was added the residue incorporated to 30 cm yielded twice as much grain, suggesting less overall residue immobilization of nitrogen. More detailed field studies are needed to explore the long-term effects of residues on nutrient cycling.

Proper crop residue management can increase water retention, prevent erosion, alter nutrient availability, and possibly reverse the decline in SOM due to cultivation. In a semiarid wheat-fallow system, Rasmussen et al. (1980) investigated the effect of seven crop residue treatments on SOM during a 45-year period. The treatments included incorporation with and without nitrogen fertilizer and incorporation with pea-vines or manure. Only the addition of manure with incorporated straw prevented the decline of SOM carbon and nitrogen. Changes in soil carbon depended on the amount of residue added and were independent of the type of residue. Regression analysis indicated that 5000 kg ha^{-1} yr^{-1} of residue was necessary to maintain SOM at the present level when cropped in wheat–fallow rotation with similar residue management practices. Khiani and More (1984) also showed that manuring positively affected soil physical properties and increased SOM content. Even with continuous cropping of a black soil in India, farm yard manure, and crop residues increased the organic carbon and nitrogen content by 20 to 40% in three years (Mathan et al., 1978). Bairathi et al. (1974) found that different legume crop residues had different effects on soil properties, however, all residues increased the organic C and N and the available P and decreased the bulk density of the soil. Using straw mulch rates from 0 to 6730 kg/ha, Black (1973) noted that SOM, carbon and nitrogen

increased significantly to the 15-cm depth but not below, after four crop-fallow cycles. Extractable phosphorus and nitrification also increased, as did the nonerodible soil fraction. Power et al. (1986) determined that corn and soybean residue had differential effects on the availability of nitrogen to subsequent crops from several soil nitrogen sources. These studies point out that management of residue type, placement, and amount in semiarid systems has significant effects on nutrient cycling and SOM buildup.

VI. Tillage Strategies for Improved Management of Organic Matter and Plant Nutrients

There are several ways in which the SOM content and the fertility level of eroded and degraded soils can be increased. These include the regular addition of organic wastes and residues, use of green manures, legumes in the rotation, reduced tillage, use of fertilizers, and supplemental irrigation.

One method for increasing the level of organic matter in depleted soils is to drill or plant seeds directly into the residues which remain from the previous crop and to place or band the required fertilizer. Weeds can then be controlled chemically on larger commercial-type farms, or where farms are small and labor is available they can be hand-pulled and harvested for forage. SOM begins to increase, especially near the surface, and the soil microbial biomass also increases. Surface residues protect the soil against wind and water erosion, the reduced tillage slows microbiological activity, and a new equilibrium level for SOM is attained. However, in semiarid regions, a fallow period is almost essential for moisture conservation, which may require shallow tillage to disrupt capillary flow. Also, limited shallow tillage may be required as soon as possible after a rainfall to help minimize surface evaporative losses and to maintain adequate moisture in the seed zone. While this tillage stimulates some loss of SOM, if tillage is timed primarily to maximize water conservation, the effect should be minimal. This again assumes that weed control is timely either with chemicals or hand labor.

In semiarid regions of Australia it was found that a wheat–bare fallow rotation with intensive tillage increased wheat yields. Apparently, this was due to the mining of the soil nitrogen. However, the yield increase was only temporary and was followed by a rapid decline in soil fertility, deterioration of soil structure, and increased soil erosion. Eventually, the wheat–fallow system was replaced by a wheat–legume and reduced tillage system which soon led to improved soil tilth, decreased erosion, increased fertility, and significantly higher yields (Donald, 1963, 1981). This particular system has now been introduced in North Africa and appears to be promising for improving soil productivity.

The benefits of a wheat–*Medicago* sp. rotation were apparent in Algeria and Tunisia where after one year the level of soil nitrogen was increased from 20 to 60 kg/ha. In Tunisia it was found that wheat yields with a wheat–*Medicago* sp.

rotation were essentially the same as with wheat–fallow. However, there were fewer cultivations where *Medicago* sp. was in the rotation (Bakhtri, 1977). It was also noted that the soil was easier to till and that the same yields with *Medicago* sp. in the rotation could probably have been obtained with less fertilizer nitrogen.

Reduced tillage, return of residues, and a legume in the rotation provides the greatest opportunity for maintaining or restoring soil productivity in terms of SOM and nitrogen in semiarid regions. The use of green manures in these farming systems should be considered, in view of their potential for restoring soil productivity.

In many semiarid regions there are important competitive uses for crop residues (i.e., they are collected from the fields for fuel, fodder, and fiber). Crop residues or any organic residues are absolutely essential for maintaining and restoring the tilth, fertility, and productivity of agricultural soils. Thus, research is needed to determine what minimal amounts of surface residues can provide at least partial protection of soils from wind and water erosion, promote water infiltration, and decrease runoff. Moreover, if the benefits of crop residue management can be demonstrated to farmers in terms of increased crop yields, it is entirely possible that they would return at least some residue to the soil.

VII. Cropping Methods for Maintaining Soil Organic Matter and Nutrients in Semiarid Areas

Recent developments in machinery and no-till cropping methods have opened new avenues for protecting SOM and soil nutrients. These include tools for deep loosening of soil with minimum soil disturbance and direct-drilling methods for seeding through residues and simultaneously placing fertilizer. The benefits of fertilizer placement are well documented. The methods employed, however, will vary according to situation and need.

For semiarid soils such as some of those in Iraq that have been eroded to the C horizon special efforts will be required. These include soil loosening with deep phosphorus placement, direct-drilling, return of crop residues, and inclusion of a legume in the rotation. The reasons for soil loosening and deep phosphorus and sulfur placement is that soil structure is so poor that roots will not penetrate to the lower soil horizon. The loosening allows root penetration, and deep phosphorus and sulfur placement will also encourage deeper rooting.

The farming system of choice for the badly eroded soils would return crop residues evenly spread on the soil surface at or after harvest, which returns nutrients, benefits soil structure, and prevents erosion. The soil should be loosened deep, with minimum disturbance, in the fall after harvest and seeded to a drought-tolerant legume. The legume should be allowed to grow for a year and a half and then mowed or killed in late spring or early summer and left on the surface or lightly worked in as a green manure using shallow tillage. Weeds must be controlled by hand-pulling, chemicals, or mowing. Seed should be direct-

drilled into the soil using a planter that precisely places fertilizer in a band, just below or to the side of the seed. In severely eroded soils phosphorus, potassium, nitrogen, and sulfur are all likely to be deficient and should be banded at rates adequate for crop needs. If phosphorus has been deep-banded during the soil loosening operation, only enough phosphorus will be needed during drilling to get the roots down to the deep band. For badly eroded soils the legume in the rotation may be required for several cycles.

For soil containing higher levels of organic matter and mineralizable nitrogen, the legume could be excluded from the rotation if tillage is reduced. In some areas occasional plowing may be advisable on fine-textured soils to increase water intake. Soil crusting and slow infiltration rates can be alleviated by placement of crop residues at or near the surface and will likely substitute for plowing in most cases. It may take several cropping cycles before SOM is significantly increased and soil structure improves. Stubble-mulched fields can be seeded and fertilizer banded in a one-pass operation in much the same fashion as for no-tillage systems. Where soil nitrogen is adequate, or if there is a legume in the rotation, it may only be necessary to use phosphorus and sulfur fertilizers.

Cropping rotations have been practiced over the long history of agriculture. Studies dating from the 1840s on have shown that nitrogen supplied to grain crops was the major reason for using crop rotations containing legumes (Triplett and Mannering, 1978). With the advent of inexpensive nitrogen fertilizers, crop rotations containing legumes declined. Only recently has the value of crop rotations specifically including legumes been recognized as critical in maintaining SOM and soil productivity. McGill et al. (1986) studied the nutrient dynamics in a Canadian Luvisol after 50 years of cropping to a 2-year rotation (wheat-fallow) or 5-year rotation (wheat-oats-barley-forage-forage). Their results showed that the soil cropped to the 5-year rotation contained greater amounts of organic C and N. In addition they found that microbial turnover (i.e., carbon mineralization) was twice as fast in the 2-year rotation. The 5-year rotation doubled the input of carbon into the soil over the 2-year system and had a greater percentage of the organic C and N in biological form. These results suggest that longer cropping system rotations which include forages or legumes will conserve SOM, maintain a greater biological nutrient pool, and put more nutrients into the soil than intensive rotations.

Effective control of wind and water erosion, increased retention and storage of precipitation, and conservation of SOM and plant nutrients in semiarid regions require some form of reduced tillage farming. Increased tillage and intensity with both primary and secondary implements can soon result in excessive erosion, and the loss of nutrients and SOM in runoff which, in turn, leads to a significant decrease in soil productivity.

VIII. Summary and Conclusions

Soil organic matter levels in semiarid regions are declining mainly because of intensive tillage practices which stimulate the microbiological decomposition of crop residues and residual SOM (i.e., humus). Adoption of new high-speed inten-

sive tillage practices and machinery will only accelerate the problem. Moreover, the rate and amount of organic wastes and residues being added back to the land are insufficient to offset the rate of decline. Loss of soil organic matter results in poorer soil structure, reduced infiltration rates, increased crusting, decreased water-holding capacity, increased resistance to root penetration, decreased nutrient availability, and accelerated soil erosion by both wind and water. While intensive tillage produces a flush of nutrients such as nitrogen with an associated yield increase, the short-term result and the flush of nutrients and crop yield will diminish with each tillage season.

Reduced tillage systems that will maintain and improve soil productivity can be adapted to the semiarid regions. With reduced tillage, SOM levels will increase as well as nutrient storage and availability. Soil physical properties will also improve. For severely eroded soils, reduced tillage may not be completely adequate for restoring soil productivity. In these cases some type of soil fracturing and deep placement of phosphoric fertilizer may be needed, as well as the introduction of a drought-tolerant legume in the crop rotation system. Legumes can provide significant quantities of nitrogen to other crops in the system, thereby increasing their yield potential with a minimum input of nitrogen fertilizer. Legumes will also help maintain SOM levels and improve or restore soil productivity.

Research Needs for Semiarid Regions

1. Determine the effect of different kinds and amounts of surface applied organic materials on soil sealing and crusting, and on soil aggregation and stability.
2. Conduct studies on direct seeding into soils under semiarid conditions, with and without surface residues, and determine the effect on water conservation and crop yields.
3. Determine the effect of deep soil fracturing and deep placement of phosphoric fertilizer on restoring the productivity of eroded/degraded soils.
4. Determine the conditions necessary for the successful introduction and establishment of legumes in cropping systems under semiarid conditions.
5. Determine the effect of legumes in crop rotations for improving soil physical properties such as soil aggregation, structure, bulk density, and water-holding capacity.
6. Determine the minimum amount of crop residue that is needed for significant increases in soil water conservation and crop yields, in semiarid tropics and steppe systems.
7. Investigate the effect of reduced tillage and residue management on rhizosphere nutrient cycling for semiarid cropping systems.

References

Agrawal, R.P., M.L. Batra, J. Nath, and P.K. Khanna. 1974. Effect of nitrogen levels and depths of mixing of wheat residues on crop yields and soil nitrogen. J. Indian Soc. Soil Sci. 22:77–79.

Alexander, M. 1977. Introduction to soil microbiology. New York: John Wiley & Sons.

Bailey, H.P. 1979. Semi-arid climates: Their definition and distribution. P. 73-97. *In* A.E. Hall et al. (eds.). Agriculture in semi-arid environments. New York: Springer-Verlag.

Bairathi, R.C., M.M. Gupta, and S.P. Seth. 1974. Effect of different legume crop residues on soil properties, yield and nutrient uptake by succeeding wheat crop. J. Indian Soc. Soil Sci. 22:304-307.

Bakhtri, M.N. 1977. Wheat-forage legume rotation and integration of crop and sheep husbandry in the Near East and North Africa. *In* G.H. Cornell (ed.). Proceeding of an international symposium on rainfed agriculture in semi-arid regions. pp. 520-538. University of California, Riverside.

Bauer, A., and A.L. Black. 1981. Soil carbon, nitrogen, and bulk density comparisons in two cropland tillage systems after 25 years and in virgin grassland. Soil Sci. Soc. Am. J. 45:1166-1170.

Black, A.L. 1973. Soil property changes associated with crop residue management in a wheat-fallow rotation. Soil Sci. Soc. Amer. Proc. 37:943-946.

Bowden, L.W. 1977. Geographic aspects of the world's semi-arid tropics. *In* G.H. Cannell (ed.). Proceeding of an international symposium on rainfed agriculture in semi-arid regions. pp. 60-72. University of California, Riverside.

Bowden, L. 1979. Development of present dryland farming systems. *In* A.E. Hall et al. (eds.). Agriculture in semi-arid environments. pp. 45-72. New York: Springer-Verlag.

Campbell, C.A., W. Nicholaichuk, and E.G. Warder. 1975. Effects of a wheat-summer-fallow rotation on subsoil nitrate. Can. J. Soil Sci. 55:279-286.

Campbell, C.A., E.A. Paul, and W.B. McGill. 1976. Effect of cultivation and cropping on the amounts and forms of soil N. *In* Western Canadian Nitrogen Symposium Proceedings. pp. 7-101. Calgary, Alberta.

Carter, M.R., and D.A. Rennie. 1984a. Dynamics of soil microbial biomass N under zero and shallow tillage for spring wheat, using ^{15}N urea. Plant and Soil 76:157-164.

Carter, M.R., and D.A. Rennie. 1984b. Nitrogen transformations under zero and shallow tillage. Soil Sci. Soc. Am. J. 48:1077-1081.

Carter, M.R. 1986. Microbiol biomass as an index for tillage-induced changes in soil biological properties. Soil & Tillage Res. 7:29-40.

Dalal, R.C., and R.J. Mayer. 1986a. Long-term trends in fertility of soils under continuous cultivation and cereal cropping in Southern Queensland I. Overall changes in soil properties and trends in winter cereal yields. Aust. J. Soil Res. 24:265-279.

Dalal, R.C., and R.J. Mayer. 1986b. Long-term trends in fertility of soils under continuous cultivation and cereal cropping in Southern Queensland. II. Total organic carbon and its rate of loss from the soil profile. Aust. J. Soil Res. 24:281-292.

Dick, W.A. 1983. Organic carbon, nitrogen, and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. Soil Sci. Soc. Am. J. 47:102-107.

Donald, C.M. 1963. Grass or crop in the land use of tomorrow. Aust. J. Sci. 25:386-395.

Donald, C.M. 1981. Agriculture in the Australian Economy. D.B. Williams (ed.). Sydney University Press.

Doran, J.W. 1980a. Microbiol changes associated with residue management and reduced tillage. Soil Sci. Soc. Am. J. 44:518-524.

Doran, J.W. 1980b. Soil microbiol and biochemical changes associated with reduced tillage. Soil Sci. Soc. Am. J. 44:765-771.

Doughty, J.L., F.D. Cook, and E.G. Warder. 1954. Effect of cultivation on the organic matter and nitrogen of Brown soils. Can. J. Agric. Sci. 34:406-410.

Douglas, C.L., Jr., R.R. Allmaras, P.E. Rasmussen, R.E. Ramig, and N.C. Roager, Jr. 1980. Wheat straw composition and placement effects on decomposition in dryland agriculture of the Pacific Northwest. Soil Sci. Soc. Am. J. 44:833-837.

Drenge, H.E., and W.O. Willis. 1983. Preface. *In* H.E. Drenge and W.O. Willis (eds.). Dryland Agriculture. p. xiv. Agronomy 23.

Freebairn, D.M., and W.C. Boughton. 1985. Hydrologic effects of crop residue management practices. Aust. J. Soil Res. 23:23-35.

Giri, G., and R.R. Singh. 1984. Water consumption and economics of wheat production as influenced by mulch and transpiration suppressants under drylands. Indian J. Agron. 29:173-178.

Kanwar, J.S. 1976. Soil and water management—The key to production in rainfed agriculture of semi-arid tropics. J. Indian Soc. Soil Sci. 24:230-239.

Kanwar, J.S. 1984. Sulphur and food production in the tropical countries—Problems, projections and policy implications. J. Indian Soc. Soil Sci. 32:583-594.

Khiani, K.N., and D.A. More. 1984. Long term effect of tillage operations and farmyard manure application on soil properties and crop yield in a Vertisol. J. Indian Soc. Sci. 32:392-393.

Larson, W.E., R.F. Holt, and C.W. Carlson. 1978. Residues for soil conservation. *In* W.R. Oshwald (ed.). Crop residue management systems. pp. 1-15. Spec. Pub. 31. Madison, Wisc.: American Society of Agronomy.

Mann, L.K. 1986. Changes in soil carbon storage after cultivation. Soil Sci. 142: 279-288.

Mathan, K.K., K. Sankaran, N. Kanakabushani, and K.K. Krishnamoorthy. 1978. Effect of continuous rotational cropping on the organic carbon and total nitrogen content in a black soil. J. Indian Soc. Soil Sci. 26:283-285.

McGill, W.B., K.R. Cannon, J.A. Robertson, and F.D. Cook. 1986. Dynamics of soil microbiol biomass and water-soluble organic C in Breton L after 50 years of cropping to two rotations. Can. J. Soil Sci. 66:1-19.

Mutatkar, V.K., and S.P. Raychaudhuri. 1959. Carbon and nitrogen status of soils of arid and semi-arid regions of India. J. Indian Soc. Soil Sci. 7:255-262.

Oram, P.A. 1977. Agriculture in the semi-arid regions: Problems and opportunities. *In* G.H. Cornell (ed.). Proceeding of an international symposium on rainfed agriculture in semi-arid regions. pp. 2-59. University of California, Riverside.

Oschwald, W.R. 1978. Preface. *In* W.R. Oschwald (ed.). Crop residue management systems. pp. vii-viii. Spec. Pub. 31. Madison, Wisc.: American Society of Agronomy.

Paul, E.A. 1984. Dynamics of organic matter in soils. Plant and Soil 76:275-285.

Power, J.F., and J.O. Legg. 1978. Effect of crop residues on the soil chemical environment and nutrient availability. *In* W.R. Oshwald (ed.). Crop residue management systems. pp. 85-100. Spec. Pub. 31. Madison, Wisc.: American Society of Agronomy.

Power, J.F., J.W. Doran, and W.W. Wilhelm. 1986. Uptake of nitrogen from soil fertilizer and crop residues by no-till corn and soybeans. Soil Sci. Soc. Am. J. 50:137-142.

Rasmussen, P.E., R.R. Allmaras, C.R. Rohde, and N.C. Roager, Jr. 1980. Crop residue influences on soil carbon and nitrogen in a wheat-fallow system. Soil Sci. Soc. Am. J. 44:596-600.

Reinertsen, S.A., L.F. Elliott, V.L. Cochran, and G.S. Campbell. 1984. Role of available carbon and nitrogen in determining the rate of wheat straw decomposition. Soil Biol. Biochem. 16:459-464.

Skidmore, E.L., J.B. Layton, D.V. Armbrust, and M.L. Hooker. 1986. Soil physical

properties as influenced by cropping and residue management. Soil Sci. Soc. Am. J. 50:415–419.

Smith, V.T., L.C. Wheeting, and S.C. Vandecaveye. 1946. Effects of organic residues and nitrogen fertilizers on a semiarid soil. Soil Sci. 61:393–410.

Stevenson, F.J. 1982. Humus chemistry. New York: John Wiley & Sons.

Stott, D.E., L.F. Elliott, R.I. Papendick, and G.S. Campbell. 1986. Low temperature or low water potential effects on the microbial decomposition of wheat residues. Soil Biol. Biochem. 18:577–582.

Tisdall, J.M., and J.M. Oades. 1982. Organic matter and water-stable aggregates in soils. J. Soil Sci. 33:141–163.

Triplett, G.B., Jr., and J.V. Mannering. 1978. Crop residue management in crop rotation and multiple cropping systems. *In* W.R. Oschwald (ed.). Crop residue management systems. pp. 198–206. Spec. Pub. 31. Madison, Wisc.: American Society of Agronomy.

Voroney, R.P., J.A. Van Veen, and E.A. Paul. 1981. Organic C dynamics in grassland soils. 2. Model validation and simulation of the long-term effects of cultivation and rainfall erosion. Can. J. Soil Sci. 61:211–224.

Zunino, H.F. Borie, S. Aguilera, J.P. Martin, and K. Harder. 1982. Decomposition of ^{14}C-labelled glucose, plant and microbial products and phenols in volcanic ash-derived soils of Chile. Soil Biol. Biochem. 14:37–43.

Tillage Systems and Equipment for Dryland Farming*

O.R. Jones, R.R. Allen, and P.W. Unger

I. Introduction 89
A. State of the Art 90
B. Objectives 90
II. Factors Affecting Selection of Tillage System 90
A. Climatic Factors 90
B. Crop to Be Grown 92
C. Soil Characteristics 93
D. Economic Level and Preference of Producer 96
E. Social Influences 97
F. Government Policies 98
III. Tillage Systems 98
A. Clean Tillage 98
B. Conservation Tillage 105
IV. Summary and Needs 124
References 125

I. Introduction

Tillage is performed for the purposes of controlling weeds, insects, and diseases; improving the soil's physical condition by destroying compacted plowpans or other dense layers; incorporating fertilizer, herbicide, and plant residues; conserving soil and water; and preparing a seedbed. Although tillage has many advantages, it also has disadvantages such as tending to destroy soil structure, burying surface residues, and increasing evaporation from the tilled zone. The latter problem is

*Contribution from the USDA-Agricultural Research Service, Conservation and Production Research Laboratory, P.O. Drawer 10, Bushland, Texas 79012.

1990 by Springer-Verlag New York Inc.
Advances in Soil Science, Volume 13

particularly important in dryland farming, which is defined as farming that requires cropping practices including adaptations to soil water deficiency during the growing season (Cannell and Dregne, 1983). Dryland tillage practices should be aimed at (1) conserving the maximum amount of water possible in the root zone during noncrop periods and (2) creating a seedbed that allows the crop to be established at the optimum time to use the limited water supply efficiently.

A. State of the Art

No one type or system of tillage can be called "state of the art." Each dryland area has its own unique tillage requirements, based on climate, crop to be grown, soil properties and capabilities, and the economic level and preference of the producer. In the Great Plains of North America, no-tillage production of wheat using herbicides to control weeds and the use of large disk or hoe-press opener drills adapted for no-till seeding may be considered state of the art, while in the semiarid tropics (SAT) of India, seeding, fertilizing, and cultivation of millet or sorghum with an improved animal-drawn tool carrier designed by Jerry Nolle (ICRISAT, 1983) is considered state of the art.

B. Objectives

Some type of tillage system is used in the production of all crops. It may range from the very simple, such as using a stick to punch holes for planting, to the very complex, using primary and secondary tillage along with pesticides and fertilizer. Between these extremes, an infinite variety of tillage systems are being used to produce the world's supply of food and fiber. It is not our intent to discuss every system. Rather, our objectives are to (1) discuss factors affecting selection of tillage systems; (2) describe and discuss adaptation, equipment, and advantages and disadvantages of major tillage systems; and (3) briefly discuss research needs.

II. Factors Affecting Selection of Tillage System

Many factors are considered by the producer in tillage system selection. Chief among these are climate and soil; but many other factors, not as readily apparent, also affect the type of tillage systems selected. We discuss those factors we feel have a significant impact on tillage systems.

A. Climatic Factors

1. Precipitation

Because precipitation (or the lack of it) is often the major factor limiting crop production in dry-farmed regions, tillage practices that enhance soil water stor-

Table 1. Minimum residue needed at seeding time for erosion control (South Dakota)[a]

Soil textures	Wheat (kg/ha)	Sorghum or corn, (kg/ha)
Coarse (sand, loamy sand, loamy fine sand)	1960	3925
Moderately coarse and fine (fine sandy loam, sandy loam, silty clay, clay)	1400	2800
Medium and moderately fine (very fine sandy loam, loam, silty loam, clay loam, sandy clay loam)	840	1680

Source: Williamson et al. (1976).

age and reduce runoff are desirable. Systems that increase infiltration, trap snow, and reduce subsequent evaporation can increase production. Maintaining a crust-free soil surface can increase infiltration. Infiltration is also enhanced by removing or disrupting soil profile layers that may restrict water movement within the soil. Evaporation can be reduced by storing water deeper in the soil or by improving the microclimate at the soil-air interface. For example, mulches can be used to intercept or reflect incoming solar radiation and to increase surface roughness, thus reducing temperature and wind speed.

Even in precipitation-deficit areas, excess water may be present for a short time, which may require beds and furrows for drainage. Tillage also exposes wet soil and hastens drying, thus allowing for timely establishment of crops.

Tillage systems that enhance infiltration and control wind and water erosion are also desirable. Systems that maintain residues on the surface or leave a roughened surface aid in both wind and water erosion control. The residues required to control water erosion at seeding time from various soil types in the U.S. Great Plains are shown in Table 1.

2. Temperature

Temperature strongly affects crop adaptation. In subtropical climates, crops are usually not affected by low temperatures. In temperate zones, however, where the growing season is of limited duration, extending the growing season for a few days may make it possible for a crop to mature before frost, thus making more efficient use of water supplies for crop production. Tillage systems can be used to manipulate soil temperatures so that crops can be planted earlier. Usually, clean-tilled soils warm up quicker in the spring, thus allowing earlier planting than where residues are present. Radke (1982), in the northern United States, used a combination of mulching and ridging to achieve temperatures similar to those in clean-tilled soil yet maintained erosion protection with a mulch, thus using manipulative tillage to achieve a specified purpose.

Soil temperature is largely a function of the radiation balance, which is significantly affected by tillage. Light-colored surfaces reflect radiation, while dark-colored surfaces absorb it (Wilsie, 1962). Thus, a soil covered with fresh, bright-

colored plant residues may be several degrees Celsius cooler than a freshly tilled soil. Under high temperature conditions, a mulch may beneficially influence crop growth (Rockwood and Lal, 1974).

3. Wind

Wind erosion control is often a critical factor in tillage system selection. The four principles of wind erosion control discussed by Lyles et al. (1983) are as follows:

1. Establish and maintain vegetation or vegetative residues.
2. Produce or bring to the soil surface nonerodible aggregates or clods.
3. Reduce field width along prevailing wind erosion direction.
4. Roughen the land surface.

Tillage is involved in three of the four principles and is an important facet of wind erosion control. Tillage can influence both wind speed and surface roughness, the two main factors influencing wind erosion. Wind speed is a climatic effect that can be modified at the soil surface by ridging, by the presence of a crop or crop residues, or by large soil clods. When winds are predominantly from one direction, tillage to form ridges should be perpendicular to the prevailing wind (Massoud, 1975). Likewise, crop or crop residue barriers should be planted perpendicular to the prevailing wind.

Tillage can also be used to control surface roughness. A rough cloddy surface maintained through the wind erosion season with listers or chisels has historically been the most successful means of controlling wind erosion on sandy soils where low-residue-producing crops such as cotton are grown (Fig. 1; Bilbro and Fryrear, 1983). Soil aggregates or particles on the surface should be larger than 0.84 mm to minimize wind erosion (Unger, 1984).

Wind is also a significant environmental factor in the turbulent transfer of water vapor to the atmosphere from the soil surface during Stage 1 drying (Lemon, 1956). Reduction of wind speed and turbulence with plant residues provides a method to reduce evaporation and conserve water (Unger and Stewart, 1983).

B. Crop to Be Grown

Crops differ in their response to soil conditions produced by tillage. For example, on a dense clay loam soil, wheat and sorghum with deep fibrous root systems responded to tillage-induced increases in the total amount of water available but not to changes in soil physical conditions resulting from tillage methods (Unger, 1984). Sugarbeet, on the other hand, responded favorably to both tillage-induced increases in water infiltration and reduced bulk density and improved aeration (Mathers et al., 1971).

Tillage can provide soil conditions required for establishment and contribute to growth requirements of specific crops. Root and tuber crops need a deep, loose seedbed without restricting zones that hamper root growth and harvesting opera-

Figure 1. Dryland cotton, grown extensively in the U.S. southern Great Plains, does not produce sufficient residues to control wind erosion (USDA-ARS photo).

tions. Small seeded crops such as some legumes and grasses need precision planting and must have a firm, finely granulated seedbed, whereas many crops such as millets, sorghum, and wheat can be successfully established and grown over a wide range of soil physical conditions.

C. Soil Characteristics

1. Slope

Soil slope and slope length are major factors controlling soil erosion. On level or gently sloping land, most tillage systems perform well. As slopes increase, the choice of tillage systems that can be used effectively to produce crops and control erosion becomes limited. Through the use of supporting practices such as terracing or contour cropping, however, the range of adapted tillage systems can be increased. When land leveling is performed on steep slopes, the resulting narrow benches may severely restrict the choice of tillage method. On extreme slopes, tillage may be restricted to hand implements only (Unger, 1984). When supporting practices are not used on sloping soils, a conservation tillage system that uses surface residues to control erosion is appropriate.

Table 2. Effect of tillage-induced plow layer porosity and surface roughness on cumulative infiltration of simulated rainfall

Tillage treatment[b]	Surface conditions (cm)		Cumulative infiltration[a] (cm)		
	Pore space[c]	Roughness	To initial runoff	To 2.5-cm runoff	To 5.0-cm runoff
Untilled	8.1	0.8	0.9	2.1	2.4
Plow	13.7	5.0	17.1	21.7	23.0
Plow-disk-harrow	12.4	2.5	5.3	7.3	8.4
Cultivated	9.7	2.9	5.7	8.3	9.1
Rotovated	11.7	1.5	2.4	3.8	4.1

Source: Burwell et al. (1966).
[a] Water applied at 12.7 cm/hour rate.
[b] Plowing and rotovating performed to a 15-cm depth, cultivating to a 7.5-cm depth on otherwise untilled soil.
[c] Measured to the tillage depth.

2. Soil Texture

Texture is a basic soil property that strongly influences many other soil properties such as strength, bulk density and porosity, water-holding capacity, and hydraulic conductivity. Texture classifies the relative proportions of the different-size mineral particles (sand, silt, and clay) contained in the soil. While the tillage system does not normally change soil texture, tillage affects most soil properties related to texture.

Infiltration rates are inherently low on fine-textured soils. However, rates can be limited by soil crusts on all soils that are unprotected from raindrop impact by crop residues or water-stable aggregates. As infiltration rates decrease, runoff increases, thus accelerating soil loss to erosion. Tillage can be effective on all soils for breaking crusts, increasing random roughness and infiltration, thus decreasing erosion and increasing water stored in the soil profile for subsequent crop production (Table 2). The most effective tillage methods for increasing infiltration are those that maintain as much organic material as possible at or near the soil surface or those that leave the surface rough and more resistant to crusting.

On fine-textured soils with low infiltration rates, temporary surface storage of water can reduce runoff. Soil ridging on the contour (Fisher and Burnett, 1953) and basin listing (tied-ridges) (Jones and Clark, 1987) are effective tillage practices for retaining surface water until it can infiltrate. Basin listing prevented runoff from a 24-hour, 114-mm storm on a clay loam soil in Texas (Clark and Jones, 1981; Fig. 2).

Coarse-textured soils (sands and sandy loams) can be susceptible to wind erosion because of low organic matter content and poor aggregation. Maintaining standing residues on the soil surface effectively controls wind erosion and, in temperate climates, aids in snow trapping. When the amount of residue is inadequate to control erosion, ridging with listers or chiseling can produce clods that

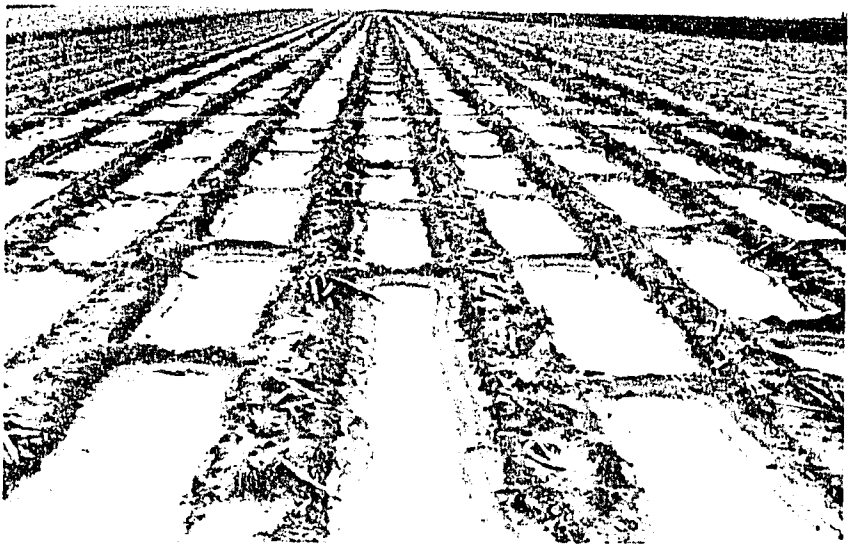


Figure 2. Water conservation with tied-ridges in the U.S. Great Plains (USDA-ARS photo).

resist erosion. If the soil water content is high enough to form clods, tillage is more effective for wind erosion control when performed perpendicular to the prevailing wind direction (Massoud, 1975). At least 8% clay is needed in the surface layer of sandy soils for tillage to produce clods resistant to wind erosion (Harper and Brensing, 1950).

3. Depth

When tillage depth is limited by bedrock or undesirable materials, noninverting tillage is required using rolling-type equipment such as disk harrows or plows and disk-opener planters. Sweep and chisel implements can be used when equipped with tripping shanks. Excessive tillage on shallow soils may accelerate erosion, and consideration should be given to using a conservation tillage system with minimum soil disturbance and herbicides to control weeds. On deep soils, any tillage system that achieves the desired soil condition and conserves soil and water can be used (Unger, 1984).

4. Restricting Layers

Tillage can have a major effect on water infiltration, erosion, and crop production on soils that have a restricting layer such as a hardpan, fragipan, plowpan, a naturally dense horizon, or a compacted layer caused by tractor, implement, or

animal traffic. Many of these soils with restricting layers can be improved by deeper than normal plowing, chiseling, or mixing of profile layers (Bradfield and Blanchar, 1977; Burnett and Hauser, 1967; Campbell et al., 1974; Doty et al., 1975; Eck et al., 1977; Eck and Taylor, 1969; and Musick and Dusek, 1975). The effectiveness of deep tillage was usually greatest when the soil was relatively dry. The benefits usually observed from deep tillage were greater water infiltration and conservation and better root growth, which allowed roots to extract water and nutrients from a larger soil volume. The economics of deep tillage are often unfavorable except for production of high-value crops. A fairly recent concept in which only a portion of the soil restricting zone is affected is in-row subsoil tillage, in which a narrow chisel subsoiler is operated in front of the planter opener. This tillage method has been effective in allowing row crop root penetration through a root-restricting compacted tillage zone on coarse-textured soils (Trouse, 1978; Smith et al., 1983).

5. Salinity and Drainage

Saline soils occur in regions with arid or semiarid climates, usually as a result of restricted drainage resulting from a high groundwater table or low permeability of the soil (USDA, 1954). The rapid appearance of a salinity problem in a previously unaffected soil is usually associated with irrigation. However, problems with saline seeps on dryland farms in the U.S. northern Great Plains became severe in the 1970s as a result of soil water conservation with summer fallow (Halvorson and Black, 1974). This example illustrates that changes in cropping and, possibly, tillage practices that drastically affect soil water storage can result in unforeseen salinity problems.

Improved drainage and growing salt-tolerant crops are suggested methods for combating salinity, but success with tillage has been reported on some alkali- and salt-affected soils when added gypsum was mixed with soil or when the soil was deep plowed (60-cm depth) to mix naturally occurring gypsum with the surface layer. The benefits from plowing and gypsum treatments were improved infiltration, root growth, leaching of salts, and greater crop yields (Cairns and Bowser, 1977; Rasmussen et al, 1964; Sandoval et al., 1972).

D. Economical Level and Preference of Producer

Crop production involves a relatively long-term economic investment, and the economic resources available affect the tillage system employed. The cash, goods, labor, and other resources that are available influence the amount of resources expended for crop production, which in turn influences the type of tillage system and related practices used to produce the crop (Constantinesco, 1976).

For a subsistence farmer, the major crop production input is labor. Seed may be saved from a previous crop, traded for, or purchased; but rarely will such farmers expend cash for other production inputs. Hence, tillage implements and systems are simple. Except possibly for land clearing and some preplanting weed

control by burning or hand labor, subsistence farmers do little or no land preparation before sowing a crop, which is usually done by broadcasting the seeds (Fosbrooke, 1974; Moody, 1974). Subsequently, weeds are controlled by hand, either by pulling, hoeing, or slashing. Use of plows, even if they were affordable, is often impractical because the crops are often not planted in rows, but may be interplanted, and tree stumps and roots may interfere with plowing on cleared forested land (Moody, 1974). Likewise, chemical (herbicidal) weed control may not be practical when crops may be interplanted or otherwise planted close together, making it impossible to chemically control weeds in one crop without adversely affecting an adjacent susceptible crop. In addition, the high cost of some herbicides limits their use (Moody, 1974).

In contrast to the subsistence farmer, the farmer whose economic level is more favorable has a wide range of available tillage systems. Depending on the particular farmer's economic level, tillage and other cultural operations (planting, weeding, etc.) may be done by hand, with animal-drawn implements, or by a variety of tractor-powered implements. Because tractor sizes vary widely, the type and intensity of tillage may also vary widely, and cropping practices ranging from the use of conservation tillage to very intensive systems involving numerous tillage and related operations are possible. Under more favorable economic conditions, most crops usually are planted in rows; thus, cultivation for weed control is usually possible because, where necessary, stumps and roots are removed during the land clearing operation. However, some hand labor may be required to control weeds within the planted row unless herbicides are used. In many situations, use of herbicides rather than labor is more economical. Also, where labor is limited, herbicides may be used to control weeds that cannot be controlled with tillage (Unger, 1984).

While economic levels strongly influence the tillage system employed, another factor contributing to the diversity of systems employed is the producer's preference. This preference may be based on upbringing, education, peer pressures, systems used by neighbors, and personal ambitions. Whether for economic or personal preference reasons, the system employed should (1) be based on the prevailing climatic, crop, and soil factors discussed previously, (2) provide the farmer a favorable return for inputs expended, and (3) result in conservation of the land resources, which is imperative because future generations also will produce their foods on lands we now use.

E. Social Influences

Social influences on crop production and associated tillage systems are vast and varied, with the rapidly increasing world population undoubtedly being the factor with the greatest influence. Increasing population pressures have resulted in more intensive cropping of some lands and, in other cases, cropping of lands marginally suited for agricultural purposes, often by poorly adapted tillage methods. Such practices have resulted in a decline in soil fertility and crop yields and even food shortages in extreme cases (FAO, 1978a; Fosbrooke, 1974) because the systems used are not conducive to soil and water conservation.

For satisfactory introduction and adoption of improved practices, producers must be made aware that such practices are necessary (Fosbrooke, 1974). The required changes may involve adoption of tillage systems and related practices that are conducive to soil and water conservation, but they must also maintain or increase crop production, or both. Where such need has been widely recognized, producers sometimes have formed organizations for collective action to combat conservation problems. Such action has, in some areas, stimulated the adoption of satisfactory practices, for example, conservation tillage, which aids in conserving soil and water resources and maintaining and improving crop yields.

F. Government Policies

As for social influences, governmental policies (including laws, regulations, etc.) have a major effect on crop production practices and associated tillage systems. Local, state, regional, and national governmental policies that encourage crop production on lands not adequately protected by use of suitable tillage systems and other conservation measures may adversely affect resource conservation and crop yields. Such production may be for domestic consumption or export and may be encouraged through decrees, proclamations, laws, or payment of subsidies. Adverse effects on resources and crop yields result from policies that encourage or permit (1) crop residue removal or burning, (2) use of unsuitable tillage and related practices, and (3) introduction of poorly planned programs (FAO, 1977).

When the need for resource conservation and for sustained or increased crop production is recognized and when a sufficient number of people are aware and desire improved practices, then economically sound practices will be selected or developed and policies and implementation plans formulated to achieve this goal. For successful implementation, the producer must be aware that a change is necessary. Policy makers must also be aware that a change is needed (Fosbrooke, 1974). Then, all agencies must cooperate to implement plans successfully and efficiently (Carpenter, 1980; FAO, 1977). To ensure final adoption by the producer, education and technical assistance are usually required. In addition, assistance in the form of food or cash may be necessary so that adoption of the practices does not result in undue financial hardships for the producer (Carpenter, 1980; FAO, 1977, 1978a, 1978b; Fosbrooke, 1974). Adoption of improved conservation and production practices usually benefits the entire country, not just the producer on whose land the practices may be applied.

III. Tillage Systems

A. Clean Tillage

1. Description

With clean tillage, all plant residues are removed or buried and growth of volunteer plants and weeds is prevented. Only the desired crops are allowed to grow. This is the traditional method of tillage on most dry cropland. The initial tillage

Table 3. Effect of tillage equipment on surface residue remaining after each operation

Tillage machine	Approximate residue maintained (%)
Subsurface cultivators	
Wide-blade cultivator, rodweeder	90
Mixing-type cultivators	
Heavy-duty cultivator, chisel, and other type machines	75
Mixing and inverting disk machines	
One-way flexible disk harrow, one-way disk, tandem disk, offset disk	50
Inverting machines	
Moldboard, disk plow	10

Source: Anderson (1968).

operation may be some type of primary tillage with a moldboard or disk plow or, possibly, chisels to incorporate residues, kill weeds, alleviate compaction with deep soil loosening, and begin seedbed preparation for the next crop. Secondary tillage operations to control weeds, pulverize clods, and prepare firm seedbeds are performed with disk harrows, sweeps, field cultivators, and a myriad of other powered and hand equipment. After planting, weeds are controlled by cultivation, hoeing, or herbicides. Alternatively, under drier climatic conditions, the primary tillage operation is eliminated and only secondary tillage operations are performed, with incorporation of additional residues occurring with each subsequent operation until all residues have disappeared, usually by seeding time. The effects of various selected tillage operations on residue incorporation are shown in Table 3. Moldboard plowing buries most residue, whereas only 10% of residue is buried with a sweep or rodweeder (Anderson, 1968).

2. Adaptation

Clean tillage can be used on land that is relatively flat and has few limitations for crop production, namely, on prime agricultural land (Class I). As wind and water erosion potential increases, supporting conservation measures must be used if clean tillage is utilized and the choice of crops is restricted to those that provide adequate protection against soil and water losses.

Most crops can be grown with clean tillage, and some small seeded crops require clean tillage to prepare the firm, uniform seedbed for precision planting. However, clean tillage may not always be the best tillage system for Class I land. Other types that leave some or all residues on the surface may improve crop production through greater water conservation, less crusting, and improved seedling establishment and plant growth (Unger, 1984).

3. Equipment

A wide variety of equipment is adapted to clean tillage. The particular piece of equipment selected depends on the operation to be performed (Table 4). Clean

Table 4. Equipment requirements for performing selected clean-tillage operations

Operation	Equipment
Soil inversion	Moldboard plow, disk plow
Soil loosening	Chisel plow, subsoiler (ripper), paratiller (paraplow)
Soil mixing (seedbed preparation)	Powered rotary tiller, disk harrow, powered oscillating harrow, offset disk, chisel plow, field cultivator
Soil finishing	Tooth harrows (spike and spring tooth), rotary hoe, roller packer, combination roller harrow
Furrowers	Lister (ridger), disk bedder, ripper-bedder
Row cultivators	Tooth cultivators, rolling cultivators
Tool carriers	Animal- or tractor-drawn—carry moldboards, listers, cultivators
Seeders	Grain drills, row planters, combination cultivator-seeders, ripper-planters

tillage usually involves soil inversion (Fig. 3a,b) or repeated operations with mixing tools (Figs. 4 and 5) until most residues are covered. Deep soil loosening involves subsoilers or slant-leg tillers such as the paratiller (paraplow)[2] (Figs. 6 and 7). Soil loosening tools usually do not cover more than 10 to 20% of the residues. Animal- or tractor-drawn tool carriers can be used to carry moldboards and cultivators (Willcocks, 1981). Soil smoothing and firming for seedbed preparation are accomplished with finishing tools.

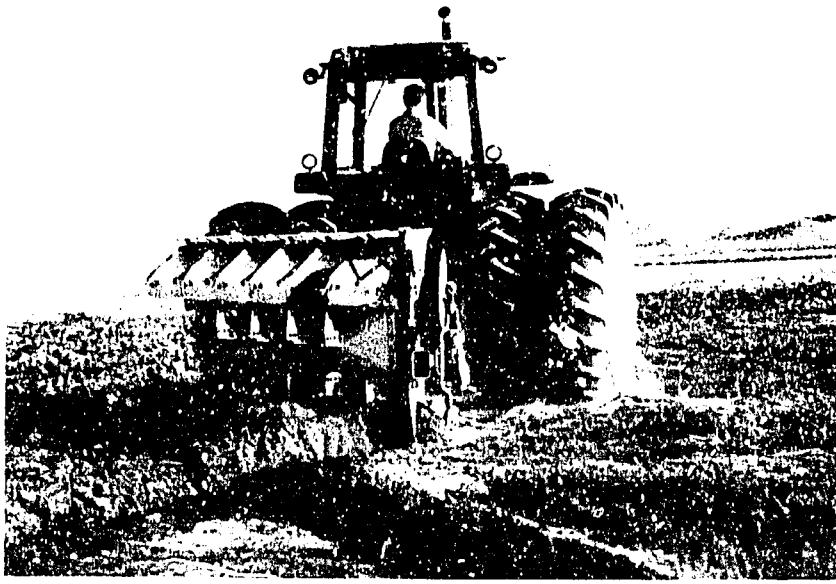
For solid seeding, hand or machine broadcasting can be performed and seed covered with a rake or harrow. Grain drills (Figs. 8 and 9) can be used for larger fields, and row planters can be used for row crops. Where soil compaction is a problem on coarse-textured soils, such as in the southeastern United States, rippers (chisels) may be mounted ahead of planter row units so that plant roots can penetrate through the loosened zone to reach deeper soil water and nutrients. For bed or furrow planting, listers or disk bedders open the furrows and form the beds. Ripper-bedders include shanks that can be mounted to rip ahead of where beds or furrows are formed. Rolling cultivators can be used to smooth and firm the beds before row crops are planted.

4. Advantages

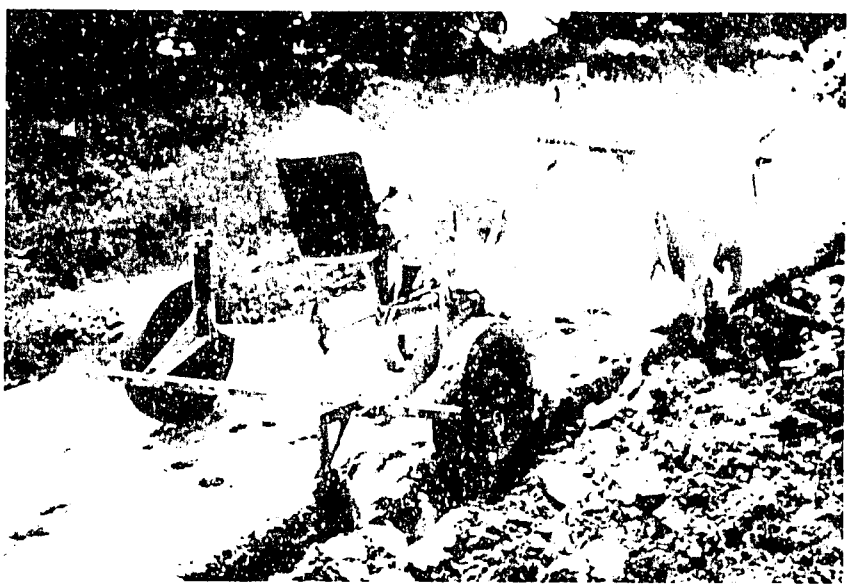
Clean tillage has many advantages over other tillage types that leave residues on the surface. Some advantages are as follows:

1. Easier and improved weed control, both before and after crop establishment.

[2]The mention of a manufacturer, trade name, or proprietary product is for information only and does not imply endorsement by USDA to the exclusion of another product which may be suitable, nor does it imply registration under FIFRA as amended.



a



b

Figure 3.(a) Reversible moldboard plow (photo courtesy Deere & Co., Moline, Ill.). **(b)** Animal drawn moldboard plow mounted on tool carrier (photo courtesy Overseas Div. AFRC Institute of Engineering Research, Silsoe, Beds., U.K.).

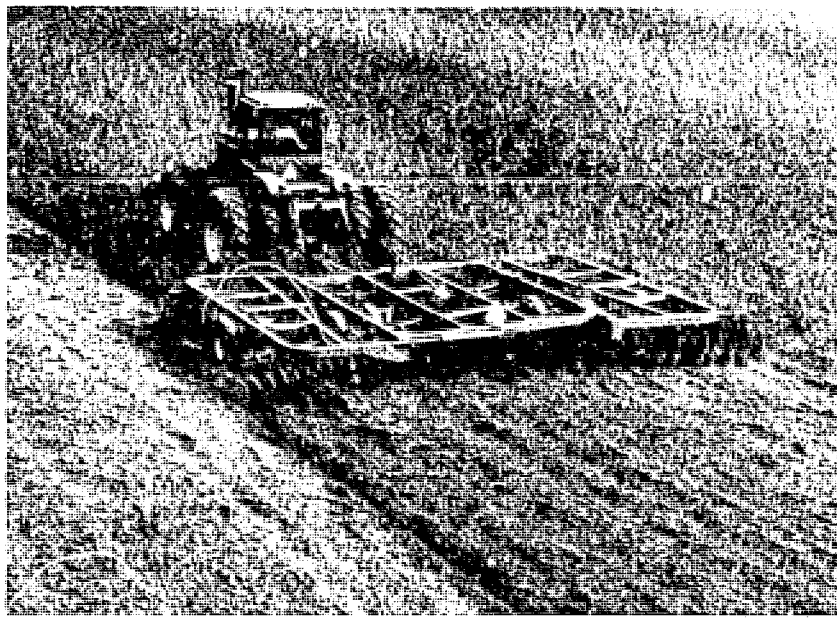


Figure 4. Double-offset disk harrow (photo courtesy Deere & Co., Moline, Ill.).

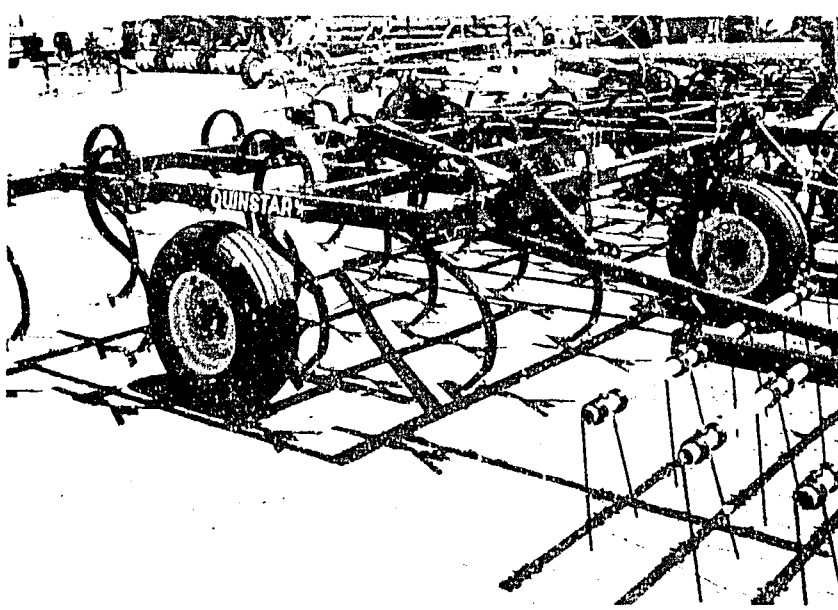


Figure 5. Field cultivator equipped with S-Tynes and a spring Tyne harrow (USDA-ARS photo).

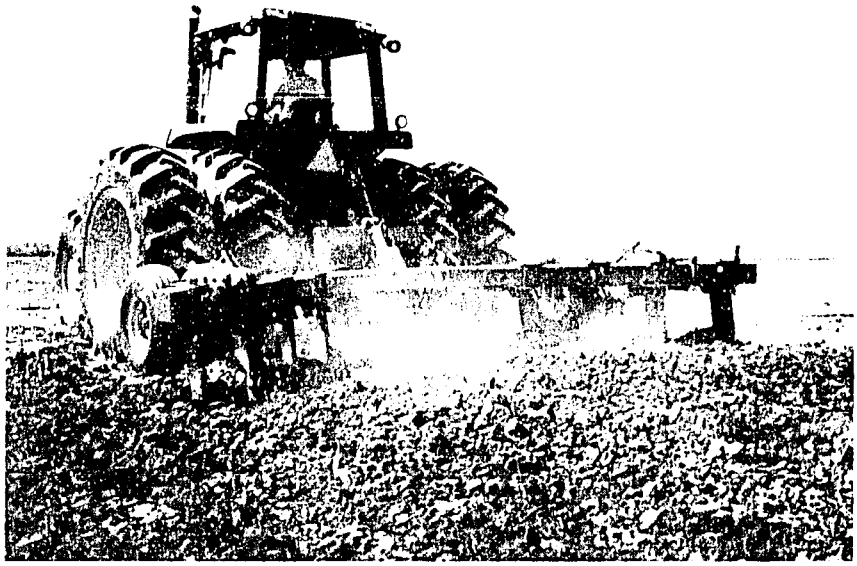


Figure 6. Subsoiler (ripper) (photo courtesy Deere & Co., Moline, Ill.).

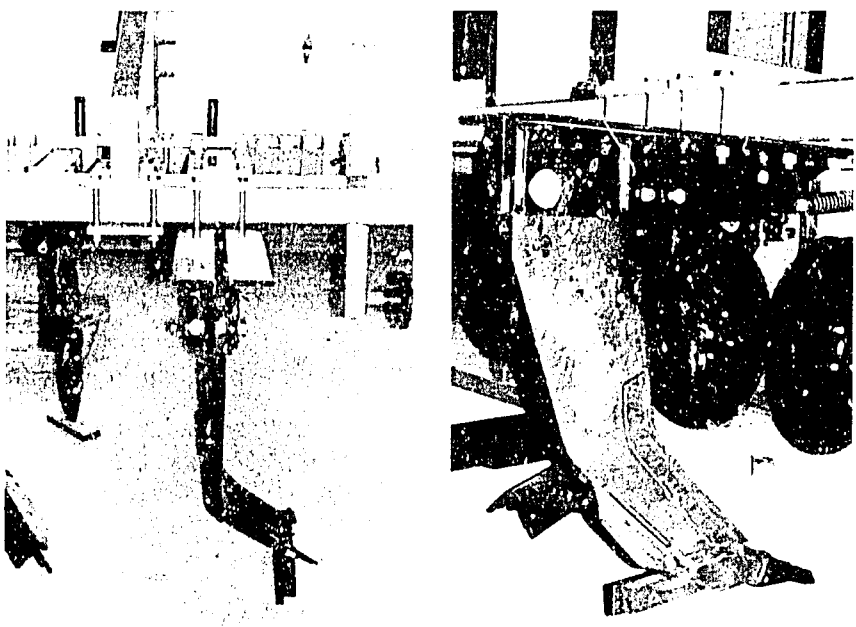


Figure 7. Paratill (successor to paraplow) slant-leg shanks loosen soil to about 35 cm with minimum surface disturbance (photo courtesy Tye Co., Lockney, Texas).

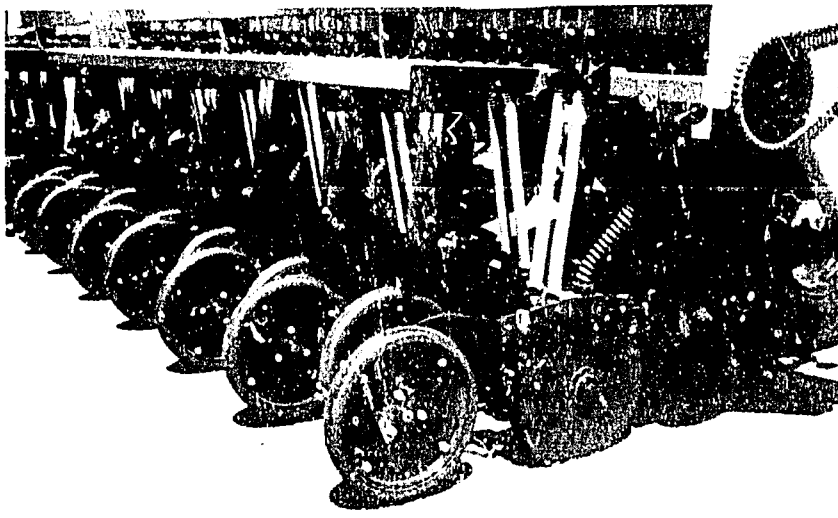


Figure 8. Grain drill with double-disk opener and press wheel (USDA-ARS photo).

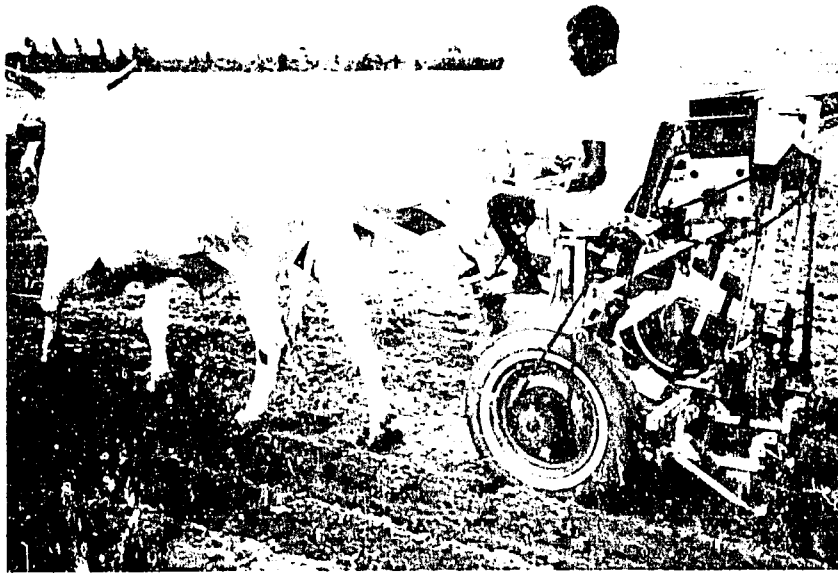


Figure 9. Animal drawn planter with fertilizer applicator (photo courtesy Overseas Div. AFRC Institute of Engineering Research, Silsoe, Beds., U.K.).

2. Easier planting. Nearly any type of drill or planter will operate better when no residues are present. Precision planting is possible.
3. Improved aeration in the tillage zone.
4. Increased infiltration through destruction of soil crusts and restricting layers in the soil and increased pore space and surface roughness.
5. Increase in rate of nitrogen mineralization through incorporation of organic matter and improved aeration and microbial activity (Doran and Power, 1983).
6. Decreased wind and water erosion potential with roughened soil surface and clods produced by primary tillage.
7. Earlier planting in some instances because tilled soils dry more quickly than soils that have crop residue.

5. Disadvantages

Most disadvantages of clean tillage are related to soil and water conservation. Some of these disadvantages are as follows:

1. Increased wind and water erosion potentials because the soil surface is unprotected.
2. Increased evaporation because tillage usually results in soil drying to the depth of tillage; thus, several tillages can result in a large cumulative loss of water to evaporation.
3. Increased evaporation rate because there are no residues to affect wind profiles and to reflect incoming radiation.
4. Decreased infiltration and increased runoff due to soil crusting as a result of soil aggregate dispersion from raindrop impact.
5. Decreased capillary and macropore continuity, which can decrease infiltration through destruction of soil structure.
6. Increased compaction below the tillage zone from tillage implements and tractor traffic, which may restrict plant rooting and water movement.

B. Conservation Tillage

Stubble mulch, reduced, and no tillage are all forms of conservation tillage, which is discussed extensively in chapter 3 by Unger. The primary advantage of conservation tillage systems in dry-farmed areas is improved conservation of soil and water resources, which results from maintaining crop residues on the soil surface.

1. Stubble-Mulch Tillage

a. Description

Stubble-mulch tillage was developed as a wind erosion control practice by a coordinated research effort at 16 locations in the Great Plains of the United States (Zingg and Whitfield, 1957). With stubble-mulch tillage, residues are

Table 5. Equipment used for stubble-mulch tillage

Operation	Equipment
Soil undercutting	Blade plows with blades up to 2.1 m in width, sweep tillers with blades up to 1 m width, blades mounted on tool bars or carriers, rodweeders
Soil mixing	Disk harrow, one-way disk tiller, chisel plow, treader
Seeders	Hoe-press drill, deep-furrow disk drill, air-seeder where seed is released behind point openers or sweeps, lister planter or row planter with shallow furrowing attachments

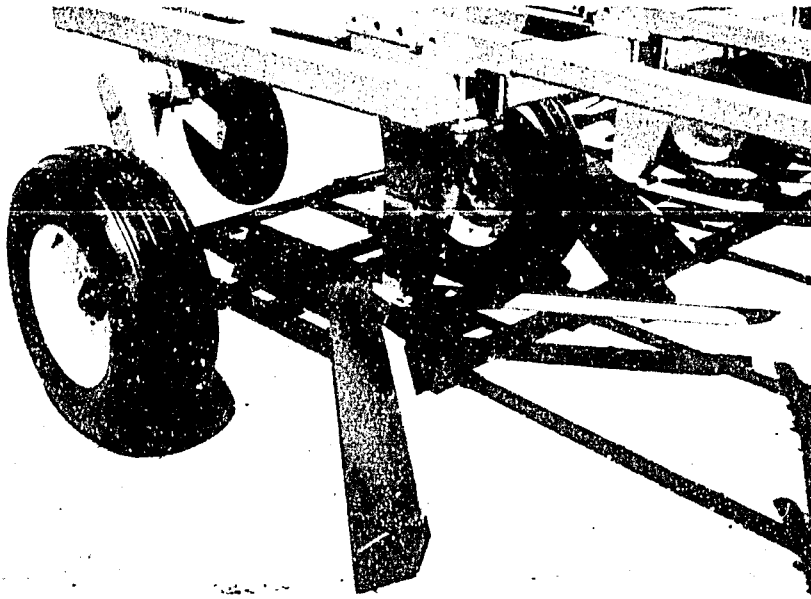
maintained on the soil surface with subtillage using sweeps, blades, mulch treaders, and rodweeders. Chisels are sometimes used to alleviate compaction resulting from several subtillage operations conducted at the same depth. Alternatively, the sweep machine or blade is operated deeper (at approximately a 125-mm depth) during the initial tillage after crop harvest, with subsequent operations with sweeps, blades, or rodweeders at shallower depths. Stubble-mulch tillage was originally developed for wheat production (Johnson and Davis, 1972) but is also successful in a wheat–sorghum–fallow rotation (Fenster and McCalla, 1971).

b. Adaptation

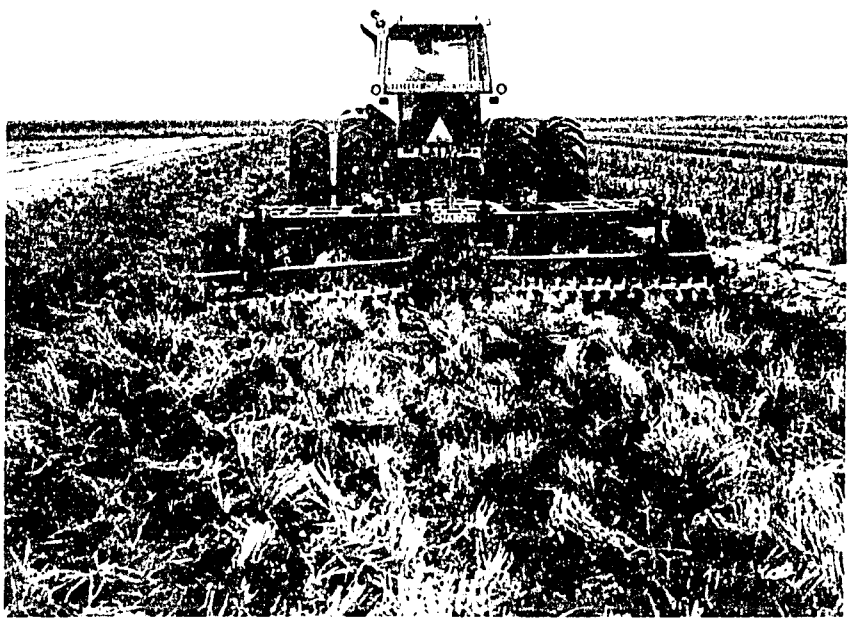
Stubble-mulch tillage can be used in most dryland areas for the production of both row and small grain crops. Hand-, animal-, and tractor-drawn equipment can be used for stubble-mulch tillage; however, animal or tractor power may be required for occasional deeper tillage to alleviate compaction problems that develop when tillage is performed continuously at a shallow depth. Willcocks (1981, 1984) reported infiltration problems and lowered sorghum yields with shallow (100 mm) sweep tillage. Tillage to 200 mm alleviated the problem.

c. Equipment

Equipment used to perform stubble-mulch tillage is listed in Table 5. Development of stubble-mulch equipment was discussed by Allen and Fenster (1986), and its application was reviewed by Fenster (1973, 1977). Undercuttting blades or sweeps greater than 0.75-m-wide cover only about 10% of the residue with each operation (Fig. 10a). Treaders attached to blade plows break up heavy stubble and help to uproot weeds (Fig. 10b). Small sweeps such as those that can be mounted on chisel plows (Fig. 11) cover about 20% of the residue with each operation (Fenster, 1973). Disk implements such as one-way disk tillers (Fig. 12) cover from 30 to 70% of the residue with each operation, depending on the angle of the disk gangs and the depth of operation. Repeated operations with disk tillers cover most of the residue. Rodweeders can be used for shallow tillage before planting. The rod, usually rotating counter to the direction of travel, firms the



a



b

Figure 10.(a) Sweep plow with 1.5-m V-blades (75°) (USDA-ARS photo). **(b)** Sweep plow with attached stubble treader (USDA-ARS photo).

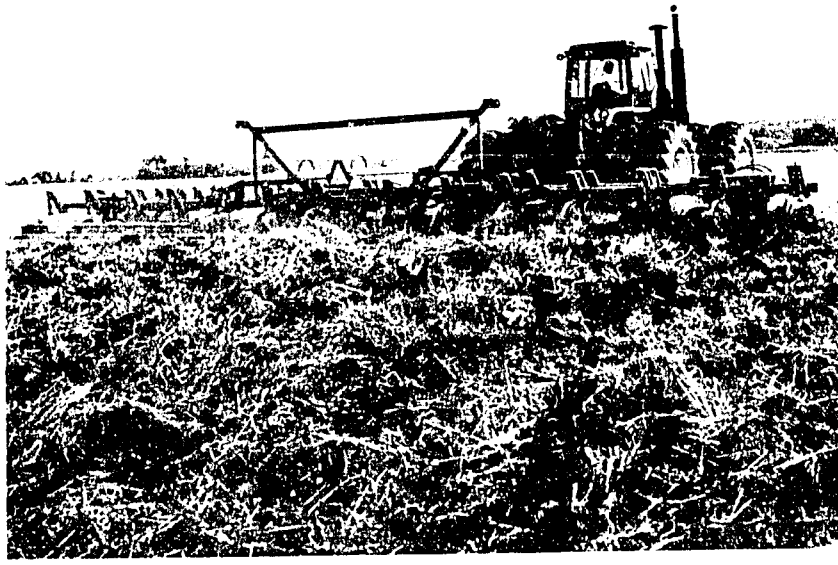


Figure 11. Chisel plow in stubble (photo courtesy Deere & Co., Moline, Ill.).

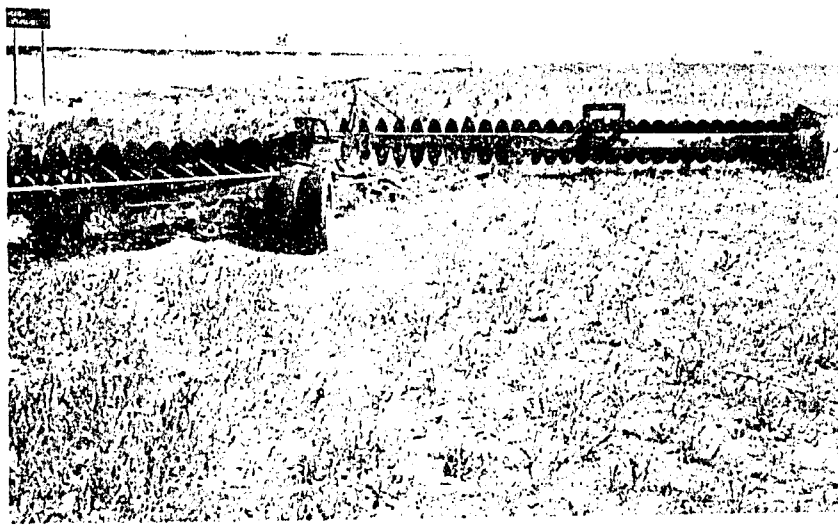


Figure 12. One-way disk plow (USDA-ARS photo).

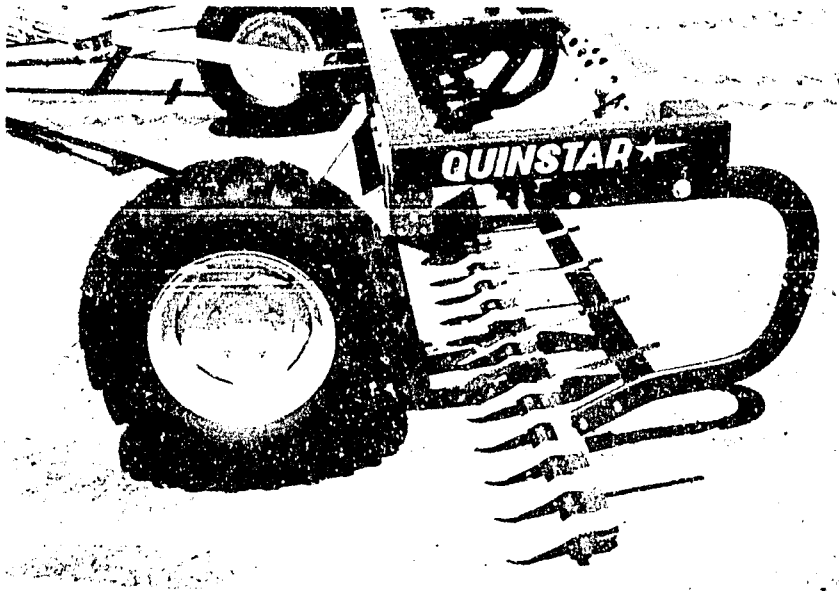
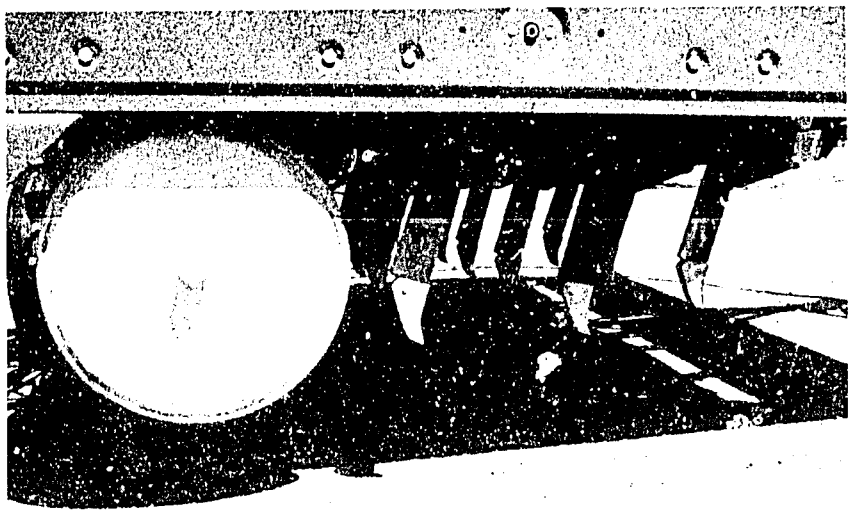


Figure 13. Semichisel rodweeder. Ground-driven rod rotates opposite to direction of travel (USDA-ARS photo).

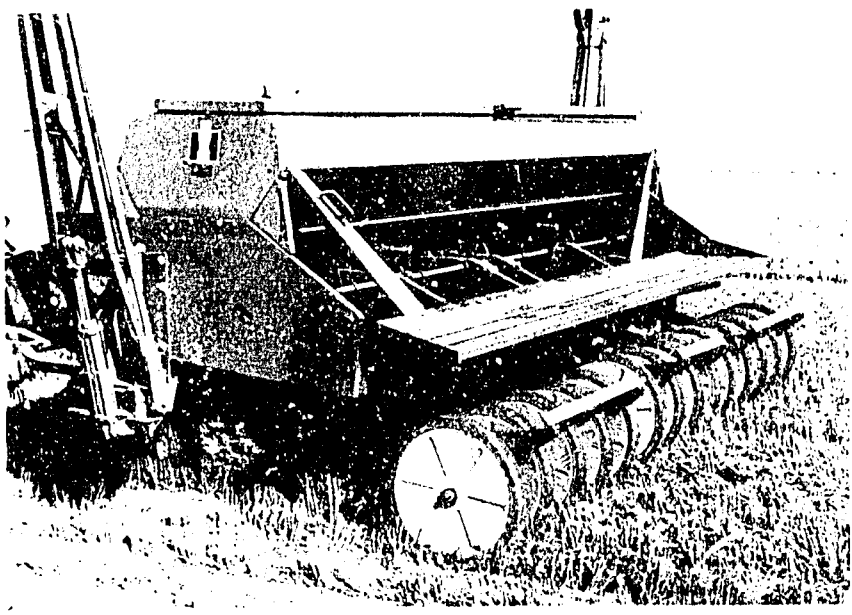
soil beneath the rod. Some rodweeders have semichisel points mounted ahead of the rod to aid in soil penetration (Fig. 13).

Hoe-press drills are well adapted to seeding small grains through stubble-mulch residue (Fig. 14a,b) (Allen and Fenster, 1986). The drills have openers staggered for residue clearance. The hoe opener can operate deep enough to place seed in moist soil without leaving too much soil cover over the seed (Fig. 14c). Wilkins et al. (1983) in Oregon developed hoe-opener tips to simultaneously seed and apply liquid fertilizer 5 cm below the seed. Klocke (1979) in Nebraska developed a hoe-press drill with coulters mounted in front of the seed openers for use in heavy residues. Recently, commercial suppliers have introduced models of hoe-press drills with coulters. Grain drills with double disk openers preceded by coulters also operate well in stubble-mulch seeding.

Another recent development for seeding in stubble-mulch culture has been the air-seeder (Fig. 15). Seed is metered and transported by air from central seed hoppers for placement behind point or sweep openers. The air-seeders can be mounted on field cultivator, chisel, or sweep plow frames. Some seeders feature independent flexing linkage and press wheels for each seed row. Studies by Allen (1988) at Bushland, Texas, revealed that press wheels are necessary for good seed/soil contact with air-seeders. Air-seeders generally have great capacity to operate through residue without plugging; and the relatively wide machines, up to 20 m, can seed large areas rapidly.



a



b

Figure 14.(a) Hoe-press drill in transport position (USDA-ARS photo). **(b)** Hoe-press drill operating in stubble (USDA-ARS photo). **(c)** Side and front views of seeding with hoe press drill. Seed is placed into moist soil without excessive soil cover over seed. (Redrawn from Pumphrey, 1974.)

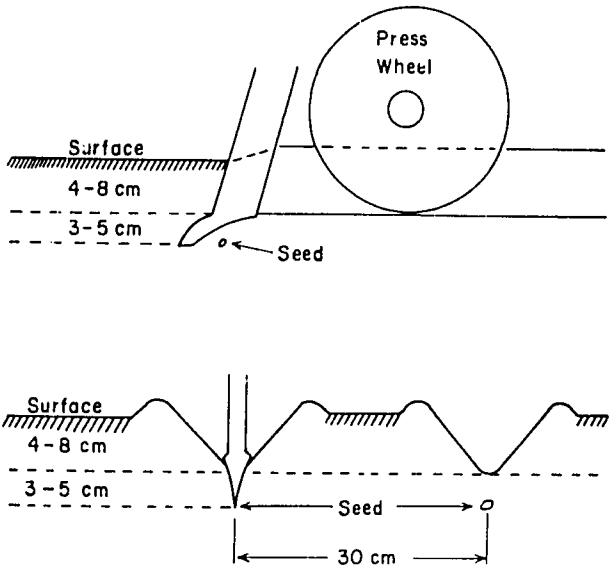


Figure 14(c).

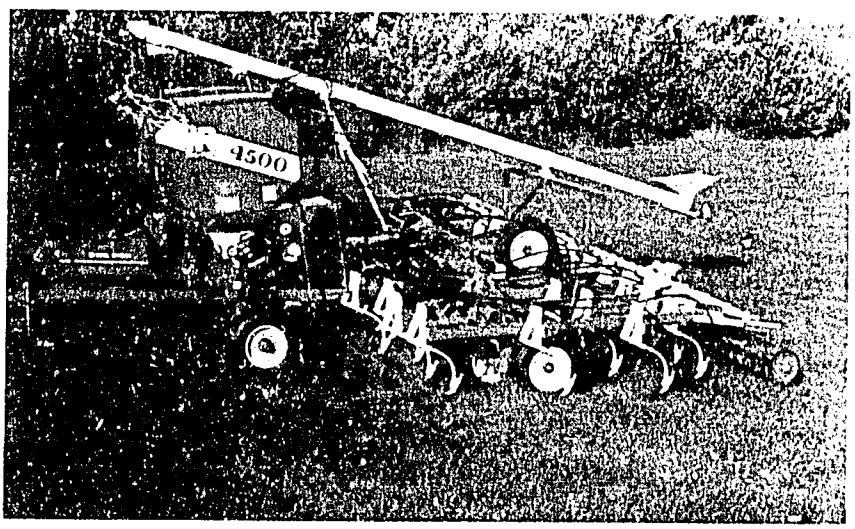


Figure 15. Air-seeder mounted on a field cultivator. The unit can cultivate, fertilize, and seed in one pass (photo courtesy Wil-Rich Div. Hutchinson Wil-Rich Manufacturing Co., Wahpeton, N.D.).

For row-crop planting in stubble-mulch residue, lister planters or unit planters with small residue-clearing shovels or disk furrower attachments mounted ahead of the planters can be used. Residue-clearing attachments can also remove dry soil as the residue is cleared ahead of the planter.

d. Advantages

Most of the advantages of stubble-mulch tillage in the Great Plains are related to improved soil particle aggregation and alteration of wind profiles compared with one-way disk tillage or moldboard plowing. These include the following:

1. Reduced soil and water losses due to water erosion on stubble mulch compared with moldboard plowing. Soil loss was reduced 20% and runoff by 50% (Zingg and Whitfield, 1957).
2. Soil water contents at seeding and wheat yields were increased 13 and 17%, respectively, on stubble mulch in comparison with one-way tillage in a semi-arid climate (Johnson and Davis, 1972).
3. Increased resistance to wind erosion due to the integrative effects of residues, soil structure, and surface roughness (Zingg and Whitfield, 1957).
4. Improved organic matter content with stubble mulch compared with one-way disk (Unger, 1982).

e. Disadvantages

Most disadvantages are related to less effective weed control with subtillage than with clean tillage and to fertility problems associated with surface residue management. These include the following:

1. Less effective weed control because with stubble-mulch tillage a small rain (3–4 mm) received within a few hours of tillage can cause weeds to reset. Also, grassy weeds (primarily *Bromus tectorum*) are more of a problem with subtillage, whereas plowing (soil inversion) tends to keep grassy weeds under control.
2. In subhumid areas where fertility as well as water can be limiting, stubble-mulch tillage reduced wheat yields, reduced harvest index, and resulted in a lower level of accumulated nitrates in the soil profile (Zingg and Whitfield, 1957).
3. Deeper tillage is required occasionally to alleviate compaction problems. This may necessitate purchasing additional equipment.

2. Reduced Tillage

a. Definition

We define reduced tillage as a tillage sequence that reduces the total number of tillage operations required to produce a crop in comparison with conventional tillage and maintains a sufficient amount of residues on the surface to control wind and water erosion. This concept includes combining tillage and planting

operations and/or using a combination of tillage and herbicides to reduce trips across the field.

Reduced tillage is applicable to both row-crop and small grain production. Although mechanized equipment may be required for some applications, the principles of reduced tillage can be applied with hand-, animal-, or tractor-powered equipment. The reduced tillage system chosen depends on equipment available, soil and climatic conditions, crop to be grown, size and type of farming operation, and the managerial ability and personal preferences of the producer (Griffith et al., 1977).

b. Description of Specific Systems

Spring-plow (moldboard), wheel-track plant. Plowing is performed 12 to 24 hours before crop planting; and planting, with or without strip tillage, is performed in tractor or planter wheel tracks to allow good seed–soil contact. Planting within a few hours of plowing ensures that soil clods are still moist, and wheel traffic or strip tillage breaks the clods and helps form a good seedbed. The primary advantage of this system over fall plowing is that crop residues from the previous crop are maintained on the surface until plowing (Unger, 1984).

Fall-chisel, field cultivate. In this system of summer row-crop production, moldboard plowing is replaced with a chisel operation performed to a 0.20- to 0.25-m depth in the fall. Chiseling retains more residues on the soil, providing erosion protection. In the spring, a seedbed is prepared with a field cultivator (Unger, 1984).

Disk-plant. With this method, the initial disking operation is usually performed with a tandem or offset disk in the fall with one or more subsequent diskings in the spring before row crops are planted. With the reduced tillage treatments (fall chisel and disking), the total number of tillage operations is not reduced compared to a full plow system, but tillage is less intense, retaining some residues on the surface for erosion protection (Unger, 1984). The disk-plant method is also applicable to small grain production.

Till-plant. Several types of till-plant systems for row crops have been developed permitting tillage and planting to be performed in one operation. The most successful system, developed in Nebraska, involves planting on ridges formed during cultivation of the previous corn or sorghum crop. A wide sweep with trash guards preceded by a coulter is operated ahead of the planter opener at a 50- to 80-mm depth to move old stalks and root crowns laterally into the area between the rows, leaving a residue-free zone for planting. Preemergence herbicides are often banded over the planted row at the same time tillage and planting are performed. Subsequently, after plants emerge, weeds are controlled in the interrow area with one or two cultivations. During the last cultivation or after crop harvest, soil is moved toward the crop row with a rolling- or disk-type cultivator, reforming the ridge. In some till-plant systems, a bed-splitter is used after harvest so that the position of the planted row and the interrow area are alternated each year (Unger, 1984).

Subsoiler-planter. Equipment that performs subsoiling and planting in a single operation has been developed in the southeastern United States to alleviate soil compaction. The procedure may have application in subhumid areas; but in semiarid areas, excessive seed and root zone drying may occur. With this equipment, a ripper (chisel) loosens a slot in the row area through the compacted zone, treading wheels firm loose soil back into the chisel opening, and the crop is planted with unit planters, all in one operation. Coulters are operated in front of the chisels to cut residues (Smith et al., 1983).

Strip-tillage. With a strip-tillage system, a narrow band of soil approximately 0.2-m wide is rotary tilled ahead of an attached planter unit; thus, tillage and planting are performed in one operation. Preemergence herbicides may be banded over the tilled strip, with cultivators used for weed control in the nontilled interrow areas. Standard rotary tillers can be adapted for strip tillage by removing some of the blades. One disadvantage of strip-tillage is that weed and volunteer crop seeds are incorporated in the row area, whereas with the till-plant system, weed and volunteer crop seeds are moved laterally into the interrow area where they can be controlled with cultivation.

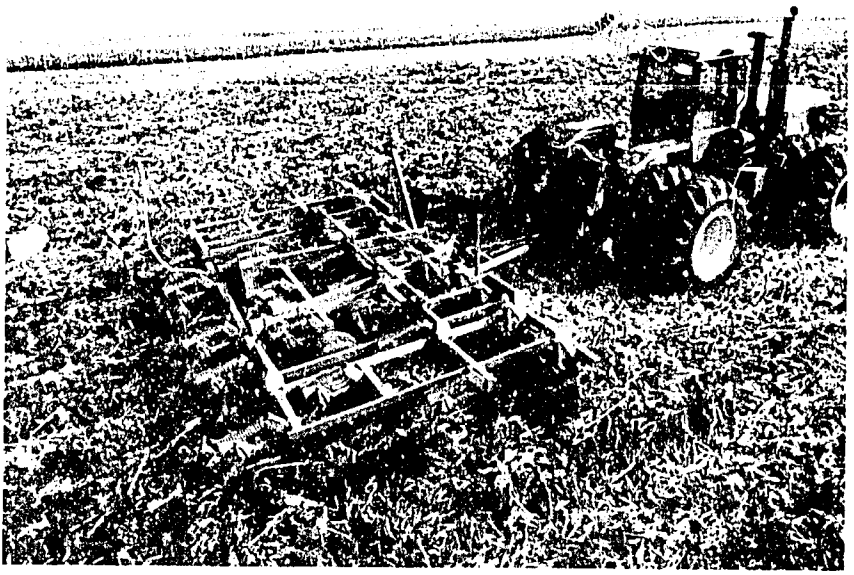
Herbicide-tillage combination. Herbicides can be used to control weeds and maintain high water infiltration rates during the noncrop period, with tillage being performed later to relieve compaction and prepare a seedbed. Alternatively, herbicides can be applied at or near planting time to control weeds after the crop emerges, thus reducing seasonal cultivation requirements and possibly providing weed control after harvest. Another variation is to use tillage initially to control existing weeds, to loosen the soil, and to incorporate some residues when excessive amounts of residues may be present. Herbicides are then applied to provide weed control during the remainder of the noncrop period. Reduced- or no-tillage planters can also be used with this system.

The primary advantage of using a herbicide-tillage system in dryland farming is that most residues can be maintained on the surface during the noncrop period, thus providing protection against erosion, conserving water, and increasing crop yields (Papendick and Miller, 1977; Smika and Wicks, 1968).

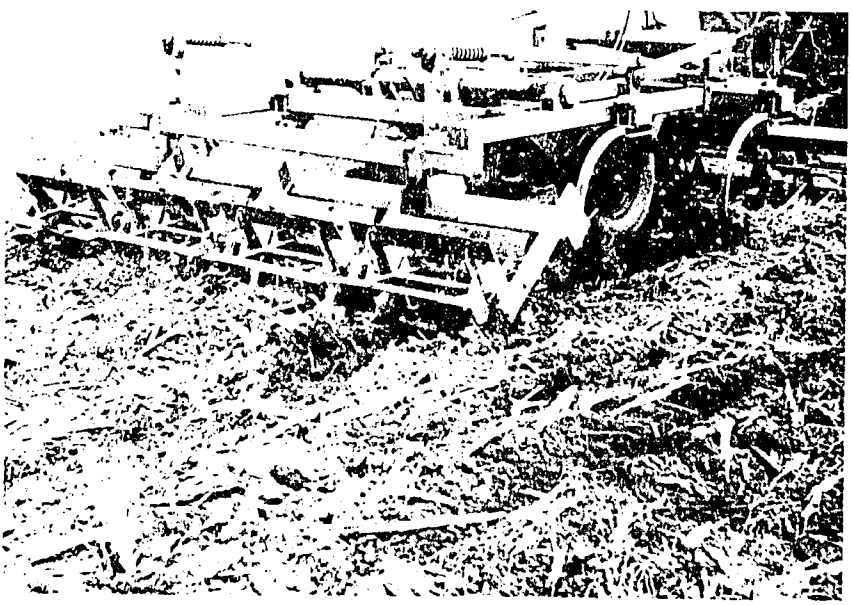
Other systems. Other reduced-tillage systems that maintain residues on the surface during the major part of the noncrop period are lister plow (corrugate)–plant; rotary till-plant; and sweep (subtillage)–plant. These systems are similar to previously discussed systems, differing primarily in the type of implement used.

c. Equipment

Much of the equipment described in the clean-till and stubble-mulch tillage sections can be adapted for use in reduced-tillage systems. Some specialized equipment has been developed that combines tillage operations, such as those shown in Figure 16a and b, and Figure 17. Other equipment has been developed especially for water conservation on drylands. Storm runoff can be reduced and infiltration increased by use of furrow-diking (basin listing or tied-ridges) equipment, shown in Figure 18a and b. Dikes or dams can also be made by hand for



a



b

Figure 16.(a) Chisel plow with disk stalk cutters (photo courtesy Deere & Co., Moline, Ill.). **(b)** Chisel plow with front and rear paddle-blade stalk cutters (USDA-ARS photo).

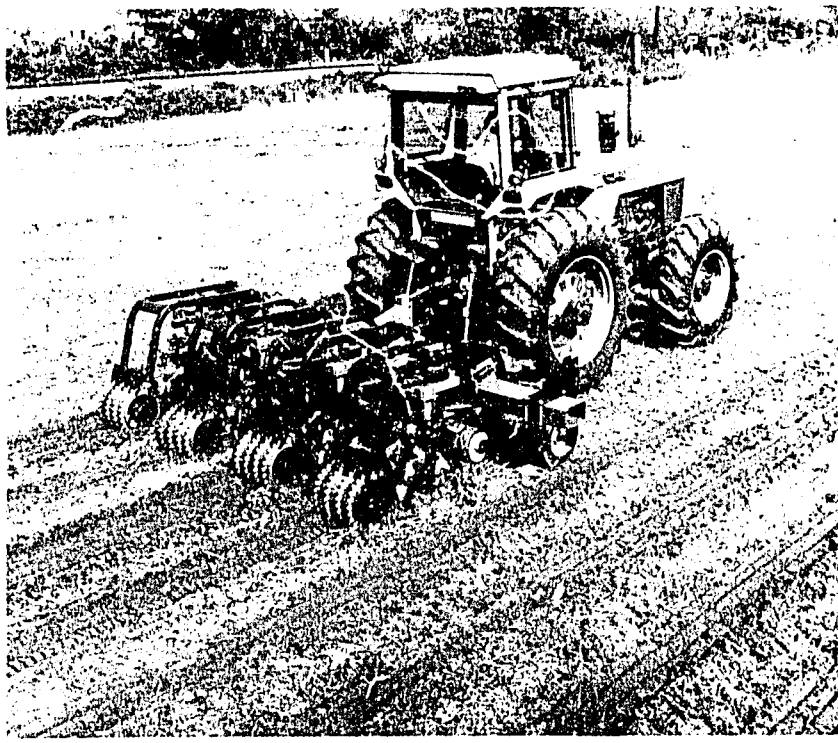
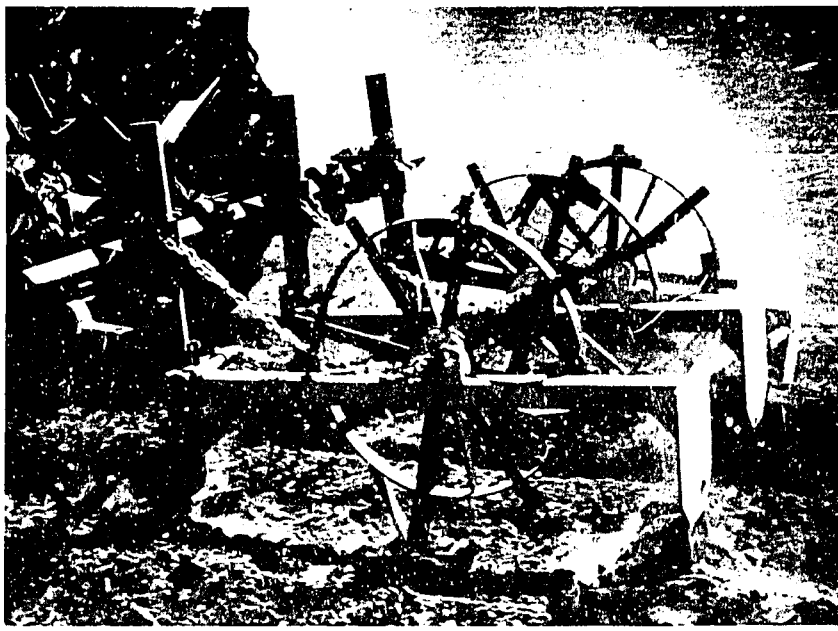


Figure 17. Seedbed preparation with an in-row ripper and strip tillage (photo courtesy Bush Hog, Selma, Ala.).

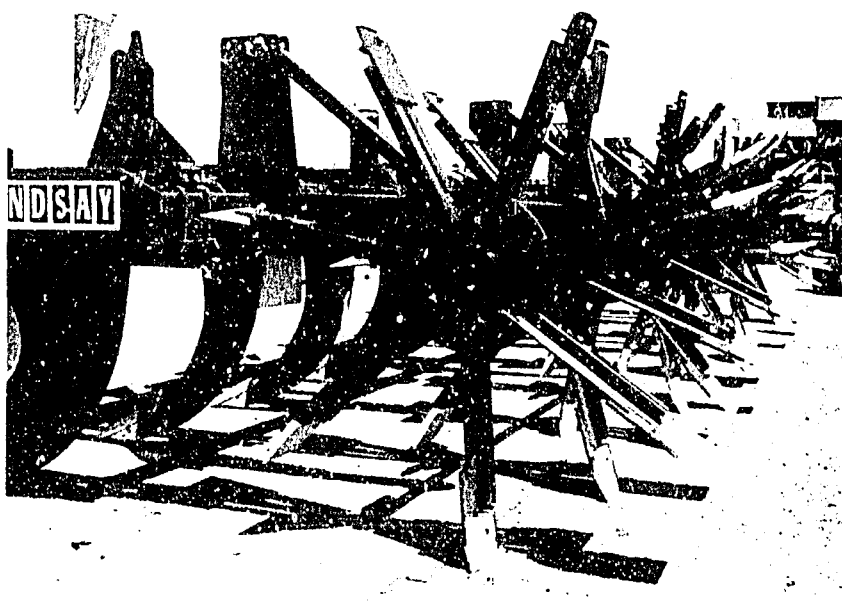
small fields. The furrow diking concept is applicable to both clean and reduced tillage systems.

Herbicides are often used in reduced- and no-tillage systems. For these systems to function effectively, herbicides must be precisely applied. This can be accomplished with sprayers ranging from knapsack sprayers to the largest tractor-mounted units. Recent research has shown that the efficacy of contact herbicides can be greatly increased by using a low volume of water as carrier (<65 L/ha) (Wiese and Chenault, 1987). Thus, the low-volume, hand-pulled, ground-driven sprayer shown in Figure 19 may be an important development for small farmers (Behrens and Kemp, 1983). Other improvements to herbicide application equipment include the Canadian developed wind drift shield (Fig. 20).

Seeding equipment also can be similar to that used in stubble mulch or in no-till systems. No-till drills with coulters mounted ahead of seed openers may be needed to prevent residue plugging on disk opener drills and on some point-opener drills (see Fig. 23a). Row-crop planting equipment usually requires either residue-clearing attachments (disk furrowers or shovels) or residue-cutting attachments (coulters; Figs. 21 and 22). Coulters should be sharp to avoid "hair-



a



b

Figure 18.(a) Wheel-type raising shovel row unit for constructing tied-ridges (USDA-ARS photo). **(b)** Ripper-dammer tool bar mounted equipment for constructing in-row basins and increasing infiltration (USDA-ARS photo).

Figure 19. Hand-pulled, controlled droplet herbicide applicator (photo courtesy Overseas Div. AFRC Institute of Engineering Research, Silsoe, Beds., U.K.).

pinning" residue in loosened soil surfaces. Some operators prefer to use both coulters and residue-clearing devices. Some planters have staggered double-disk openers, where the leading disk cuts residue and penetrates the soil and the trailing disk opens the seed slot.

Where soil compaction is a problem, in-row rippers mounted between coulters and double-disk openers can be used to open the soil profile for subsequent plant root development. Press wheels are essential for seed slot closure, to allow good seed–soil contact. Press wheel types in general use are a single-press wheel that runs over the seed slot directly behind the planter and a double-press wheel with wheels angled and straddling the seed row so the seed slot is squeezed shut (Morrison, 1978).

3. No-Tillage

a. Description

No tillage is defined as a method of mulch farming that uses herbicides or other methods to control weeds and volunteer crop plants and maintain plant residues

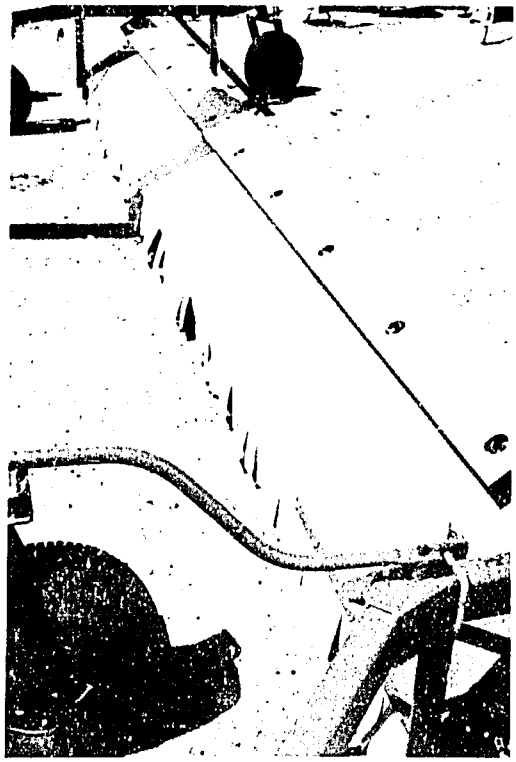


Figure 20. Boom sprayer with wind-drift shield (USDA-ARS photo).

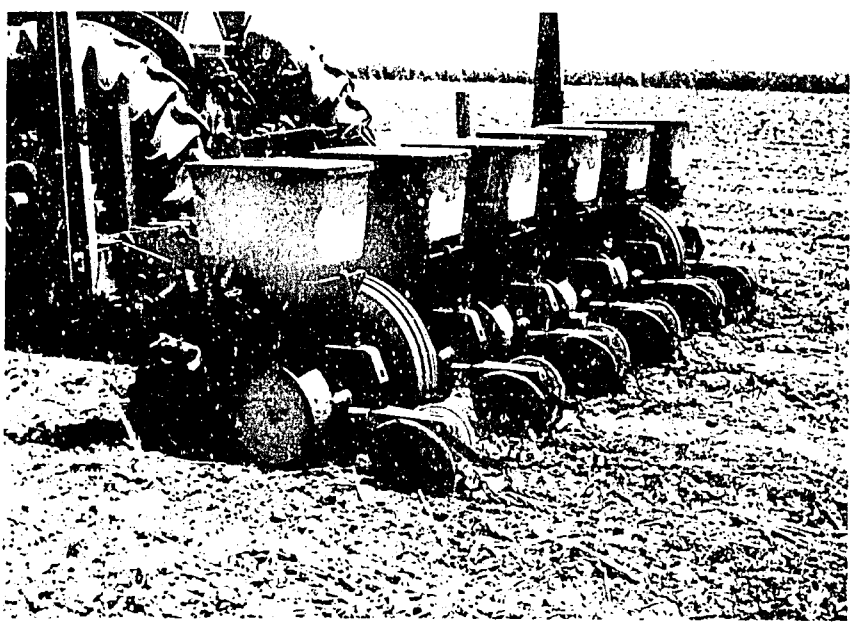


Figure 21. Row planter with residue-cutting coulter, double-disk openers, and double-angled press wheels for reduced-tillage or no-till applications (USDA-ARS photo).

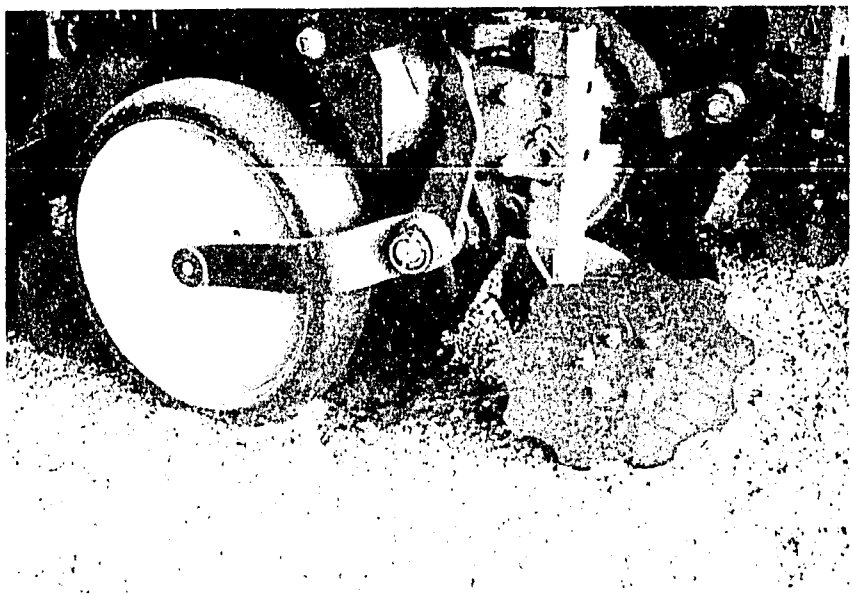


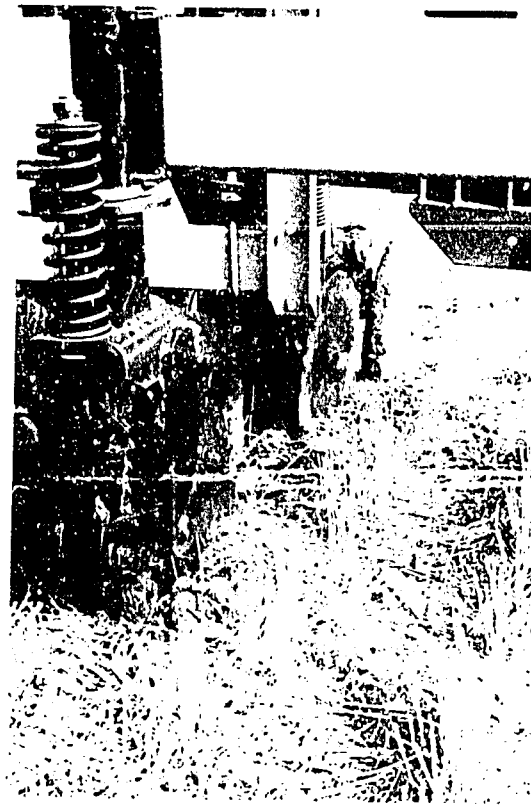
Figure 22. Row planter with disk furrower and staggered double-disk openers. Depth control wheels straddle the double-disk openers (USDA-ARS photo).

on the soil surface. No seedbed preparation is performed; planting is performed with a minimum of soil disturbance using coulters, disks, or other types of openers to cut residues and open a small slit in the soil for seed placement or, alternatively, seeds are placed in holes punched in the soil. No cultivation is performed after planting, and chemicals or manual methods are used to control weeds. In practice, no-tillage planting systems should disturb no more than 25% of the soil surface (Lessiter, 1982).

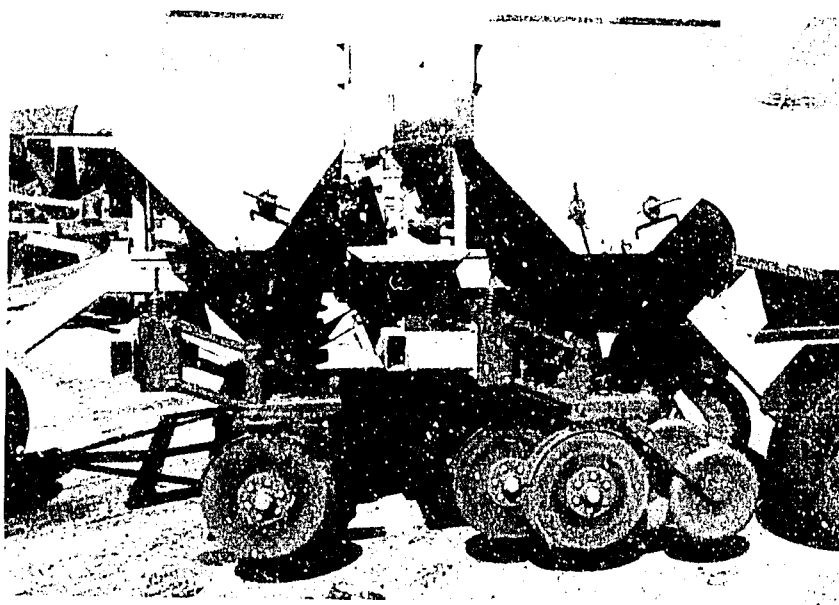
No tillage has many synonyms, including no-till, zero-tillage, slot planting, ecofallow, sod planting, chemical fallow, and direct drilling. No tillage was initially used for pasture renovation and controlling weeds in orchards. However, as more effective herbicides came on the market in the late 1950s and 1960s, no-tillage systems rapidly developed for field crop production (Unger, 1984). By the early 1980s, no-tillage farming methods were used on approximately 3.3 million hectares in the United States (Lessiter, 1982). Most no-tillage farming in the United States involves the production of corn and soybean in humid regions. Systems have been developed, however, for dryland crop production in subhumid and semiarid regions in both temperate and tropical climates (Wicks, 1986; Unger and Wiese, 1972; Unger, 1984; Lal, 1986).

b. Adaptation

The adoption of no-tillage systems is limited by many constraints, including soil, climate, crop, and equipment. Yet we believe that practical no-tillage systems can



a



b

Figure 23.(a) No-till drill with coulters and double-disk opener (USDA-ARS photo). **(b)** No-till drill where front disk openers band fertilizer and paired rear seed openers straddle a fertilizer band. All openers are staggered double-disk (USDA-ARS photo).

be developed for most cultivated drylands. We realize that development of no-tillage systems may be easier in a developed country with mechanized equipment and large sprayers. Yet, no-tillage residue management principles work just as well where weeds are controlled by slashing and hoeing and seeds are planted in holes punched with a primitive farming implement. The adaptation of no-tillage farming is limited only by the ingenuity and inventiveness of man.

Most limitations on the adaptability of no-tillage systems to dryland farming are soil related. Soil properties favorable to no-tillage are (1) coarse-textured surface or a self-mulching clay soil with high initial infiltration, (2) low susceptibility to compaction and crusting, (3) good internal drainage, (4) high biological activity, and (5) friable consistency over a wide range of moisture contents. When these conditions are present, the need for mechanical soil tillage is minimized (Lal, 1986).

Structurally inactive soils, defined as soils that contain less than 20% clay, have negligible shrink-swell characteristics and require some mechanical tillage for seedbed preparation (Lal, 1986); thus, they are not well adapted to no-tillage farming. Permanent improvement of soil structure and water transmission characteristics of these structurally inactive soils depends on improving organic matter content through improved residue management. Once organic matter content is increased, mechanical tillage may not be as important as it is now to these degraded soils (Lal, 1986).

Most no-tillage failures result from the inability to obtain an adequate plant density because of a compacted seed zone or poor seed-soil contact resulting from the lack of proper equipment for seeding through a mulch.

Climate can also affect adaptation of no tillage. Primary tillage is deemed crucial for successful continuous cropping of SAT Alfisols in India. These soils undergo severe hardening during the dry season, and tillage is required to create a favorable zone for root penetration and for rainfall infiltration (El-Swaify et al., 1985). Successful no-tillage crop production systems have been developed on humid Alfisols in Africa; but as in India, poor soil surface conditions resulting from a long dry season and inadequate residues restrict the adaptation of no tillage on Alfisols in semiarid Africa (Lal, 1986).

c. Equipment

Equipment requirements for no tillage are minimal; however, a well-calibrated sprayer for herbicide application and a planter capable of penetrating residues and obtaining satisfactory plant emergence are required. Sprayers were discussed in the reduced-tillage section. The same sprayers used for reduced-tillage can be used for no tillage.

Most of the planting equipment requirements for no-till are the same as discussed for reduced tillage. Row planters may use fluted or rippled coulters to cut the residue and make initial soil penetration (see Fig. 21). Where coulters are used, adequate weight must be provided for soil penetration. About 180 kg per coulter is needed to ensure adequate penetration. Staggered double-disk openers

perform well in no-till and will penetrate through hard surface soil conditions without coulters (see Fig. 22) (Allen, 1985). Some no-till planters clear a narrow band of residue ahead of the planter with shovels or disk furrowers.

No-till drills (Fig. 23a), as well as air-seeders, can be used for seeding. Heavy no-till drills have been developed in the northwestern United States for seeding small grains and banding fertilizer between "paired rows." The paired rows are about 13-cm apart, with a 38-cm interval between pairs. The drills have double-disk openers for applying seed and fertilizer and are weighted for soil penetration (Fig. 23b). By using the heavy no-till drills, annual crops of spring wheat can be produced with soil water accumulated from snow trapped in stubble rather than with the former practice of fallowing a year between crops to accumulate sufficient soil water for the succeeding crop.

d. Advantages

Many advantages can be listed for no-tillage systems in comparison with clean-tillage and some reduced-tillage systems. These include the following:

1. Improved control of wind and water erosion (Woodruff, 1972; Griffith et al., 1977; Rockwood and Lal, 1974; Osuji et al., 1980; El-Swaify et al., 1985; Lal, 1976a).
2. Improved water conservation through reduced evaporation or improved soil physical properties (Ketcheson, 1977; Wicks and Smika, 1973; Smika and Wicks, 1968; Harrold and Edwards, 1972; Rockwood and Lal, 1974; Lal, 1976b; Unger and Phillips, 1973; Unger and Stewart, 1983; Unger and Wiese, 1979).
3. Equal or higher crop yields (Aase and Siddoway, 1980; French and Riveland, 1980; Smika and Wicks, 1968; Rai and Yadav, 1979; Unger and Wiese, 1979).
4. Reduced energy inputs due to fewer operations and less intensive tillage (Allen et al., 1977; Robertson and Mokma, 1978; Dickey and Rider, 1981; Griffith and Parsons, 1980; Allen et al., 1981).
5. Reduced labor inputs for mechanized systems (Dickey and Rider, 1981).
6. Reduced equipment inventories and less wear and tear on tractors and equipment because fewer operations are performed (Harman and Wiese, 1985; Unger, 1984).
7. Improved net returns (Harman and Wiese, 1985; Unger and Wiese, 1979; Windsor, 1984).
8. Reduced soil temperatures during hot seasons (Maurya and Lal, 1981; Lal, 1976a; McCowen et al., 1985; Allen et al., 1975; Unger, 1978).
9. Increased biotic activity (Lal, 1986; Yu et al., 1981).

e. Disadvantages

No tillage has some disadvantages compared to clean-tillage and some reduced-till systems. These disadvantages include the following:

1. Reduced soil water storage and lowered crop yields with limited residues or ineffective weed control (Hadas et al., 1980; Hakini and Kachru, 1976; Woodruff, 1972; De Datta et al., 1979; Kang et al., 1980).
2. Reduced yields on poorly drained or poorly aerated soils (Baeumer and Bakermans, 1973).
3. Increased surface compaction, crusting, and reduced infiltration where the amount of residue is low (O. R. Jones, 1986, unpublished data; Sherif et al., 1982; Willcocks, 1981, 1984).
4. Delayed planting of summer crops in temperate climates due to slower soil warming (Unger and Stewart, 1976; Triplett and Van Doren, 1977).
5. Increased use of chemicals, which may increase capital requirements and reduce profits, particularly in relation to labor intensive, manual type systems of weed control.
6. Shifts in weed species with continued use of herbicides (Phillips, 1969; Wiese and Staniforth, 1973; Richey et al., 1977).
7. Adverse effects on adjacent crops with herbicide drift of phenoxy and other contact herbicides (Unger, 1984).
8. Lack of suitable sprayer equipment or prohibitively high cost, particularly in developing countries.
9. Remote and limited water supplies, which may restrict the use of herbicides in small-scale operations in some semiarid areas.
10. Increased nitrogen deficiency, possibly due to lower nitrogen mineralization and increased immobilization (Kang et al., 1980; Fox and Bandel, 1986).
11. Restricted selection of crops grown in rotations, intercropping, or mixed cropping with use of herbicides.

IV. Summary and Needs

Tillage is performed in dryland crop production to control weeds, improve soil physical structure, prepare a seedbed, and improve soil and water conservation. Many factors affect tillage system selection, including climate, crop to be grown, soil characteristics, the economic level and preference of the producer, social influences, and government policy.

Tillage systems described were clean-, stubble-mulch, reduced-, and no-tillage systems. Each has limitations to adaptations and advantages and disadvantages that apply to specific crops and soils.

An emerging trend is toward less intensive tillage with some type of reduced-tillage system to maintain crop residues on the soil surface for improved soil and water conservation. With reduced tillage, herbicides are often used to control weeds, and tillage is performed to prepare a seedbed or improve soil physical properties. In low rainfall areas with marginal water supplies, reduced-tillage rather than no-tillage systems are better adapted because residue production is limited and may not be sufficient to achieve satisfactory protection of the soil surface from raindrop impact. When rainfall is greater and adequate residues can

be produced to provide soil surface protection against crusting and compaction, no-tillage systems are effective. When residues are removed for fuel or by grazing, tillage becomes necessary to reduce erosion potential and prepare seedbeds.

Although specialized seeding equipment may be required for reduced and no-tillage systems, equipment inventories and overall costs can be lower. Knapsack sprayers and human-powered controlled droplet applicators make herbicide application possible on small-scale operations; thus, reduced- and no-tillage can be adapted to small farms in developing countries as well as to large mechanized farms in developed countries.

Our greatest need is to develop improved reduced- or no-tillage systems that are adapted to low rainfall areas where residue production is limited or residues are grazed or removed for other purposes.

References

Aase, J.K., and F.H. Siddoway. 1980. Stubble height effects on seasonal microclimate, water balance, and plant development of no-till winter wheat. Agric. Meteorol. 21:1–20.

Allen, R.R. 1985. Reduced tillage – Energy systems for furrow irrigated sorghum on wide beds. Trans. Am. Soc. Agric. Eng. 28:1736–1740.

Allen, R.R. 1988. Performance of three wheat seeders in conservation tillage residue. Trans. Am. Soc. Agric. Eng. 31:191–196.

Allen, R.R., and C.R. Fenster. 1986. Stubble mulch equipment for soil and water conservation in the Great Plains. J. Soil Water Conserv. 41:11–16.

Allen, R.R., B.A. Stewart, and P.W. Unger. 1977. Conservation tillage and energy. J. Soil Water Conserv. 32:84–87.

Allen, R.R., J.T. Musick, F.O. Wood, and D.A. Dusek. 1975. No-till seeding of irrigated sorghum double cropped after wheat. Trans. Am. Soc. Agric. Eng. 18:1109–1113.

Allen, R.R., J.T. Musick, P.W. Unger, and A.F. Wiese. 1981. Soil-, water-, and energy-conserving tillage – Southern Plains. *In* Proc. Am. Soc. Agric. Eng. Conf. on Crop Production with Conservation in the 80's. Chicago, Ill., pp. 94–101. Am. Soc. Agric. Eng., St. Joseph, Mich.

Anderson, D.T. 1968. Field equipment needs in conservation tillage methods. *In* Conservation Tillage in the Great Plains, Proc. of a Workshop, Lincoln, Nebraska. Great Plains Agric. Council Publ. No. 32.

Baeumer, K., and W.A.P. Bakermans. 1973. Zero-tillage. Adv. Agron. 25:77–123.

Behrens, P., and D.C. Kemp. 1983. A new pull-along sprayer for herbicides. Rural Development Technology Conf., Bulawayo.

Bilbro, J.D., and D.W. Fryrear. 1983. Residue management and cultural practices for a semiarid region. J. Soil Water Conserv. 38:312–314.

Bradfield, J.M., and R.W. Blanchar. 1977. Profile modification of a Fragiudalf to increase crop production. Soil Sci. Soc. Am. J. 41:127–131.

Burnett, E., and V.L. Hauser. 1967. Deep tillage and soil-plant-water relationships. *In* Tillage for Greater Crop Production Conf. Proc., pp. 47–52. Am. Soc. Agric. Eng., St. Joseph, Mich.

Burwell, R.E., R.R. Allmaras, L.L. Sloneker. 1966. Structural alteration of soil surfaces by tillage and rainfall. J. Soil Water Conserv. 21:61–63.

Cairns, R.R., and W.E. Bowser. 1977. Solonetzic soils and their management. Canada Dept. Agric. Publ. 1391.

Campbell, R.B., D.C. Reicosky, and C.W. Doty. 1974. Physical properties and tillage of Paleudults in the southeastern Coastal Plains. J. Soil Water Conserv. 29:220-224.

Cannell, G.H., and H.E. Dregne. 1983. Regional setting. *In* Dryland Agriculture. H.E. Dregne and W.O. Willis (eds.). pp. 3-17. Am. Soc. Agron. Monogr. No. 23. Am. Soc. Agron., Madison, Wisc.

Carpenter, N.R. 1980. Development of rainfed areas in the Near East: A proposal combining government, policy, institutional organizations, technical, social and economic components into a developed system for rainfed areas. *In* Rainfed Agriculture in the Near East and North Africa, pp. 350-355. Proc. FAO Regional Seminar, Amman, Jordan, May 1979. Rome: FAO.

Clark, R.N., and O.R. Jones. 1981. Furrow dams for conserving rainwater in a semiarid climate. *In* Proc. Am. Soc. Agric. Eng. Conf. on Crop Production with Conservation in the 80's. Chicago, Ill., pp. 198-206. Am. Soc. Agr. Eng., St. Joseph, Mich.

Constantinesco, I. 1976. Soil conservation for developing countries. FAO Soils Bull. 30. Rome: FAO.

De Datta, S.K., F.R. Bolton, and W.L. Lin. 1979. Prospects for using minimum and zero tillage in tropical lowland rice. Weed Res. 19:9-15.

Dickey, E.C., and A.R. Rider. 1981. Eastern Nebraska row crop tillage systems. *In* Proc. Am. Soc. Agric. Eng. Conf. on Crop Production with Conservation in the 80's. Chicago, Ill., pp. 85-93. Am. Soc. Agr. Eng., St. Joseph, Mich.

Doran, J.W., and J.F. Power. 1983. The effects of tillage on the nitrogen cycle in corn and wheat production. *In* Nutrient Cycling in Agricultural Ecosystems. R. Lowrance et al. (eds.). pp. 441-445. Univ. Georgia, Coll. Agric. Spec. Publ. No. 23. Athens, Ga.

Doty, C.W., R.B. Campbell, and D.C. Reicosky. 1975. Crop responses to chiseling and irrigation in soils with a compact A2 horizon. Trans. Am. Soc. Agric. Eng. 18:668-672.

Eck, H.V., and H.M. Taylor. 1969. Profile modification of a slowly permeable soil. Soil Sci. Soc. Am. Proc. 33:779-783.

Eck, H.V., T. Martinez, and G.C. Wilson. 1977. Alfalfa production on a profile modified slowly permeable soil. Soil Sci. Soc. Am. J. 41:1181-1186.

El-Swaify, S.A., P. Pathak, T.J. Rego, and S. Singh. 1985. Soil management for optimized productivity under rainfed conditions in the semi-arid tropics. *In* Advances in Soil Science. B.A. Stewart (ed.). 1:1-64.

FAO. 1977. Introduction. *In* Soil Conservation and Management in Developing Countries, pp. 1-2. FAO Soils Bull. 33. Rome: FAO.

FAO. 1978a. Soil erosion by wind and measures for its control on agricultural lands. FAO Agric. Devel. Paper No. 71. Rome: FAO.

FAO. 1978b. Soil erosion by water: Some measures for its control on cultivated lands. FAO Agric. Devel. Paper No. 81. Rome: FAO.

Fenster, C.R. 1973. Stubble mulching. *In* Conservation Tillage, pp. 202-207. Soil Conserv. Soc. Am., Ankeny, Iowa.

Fenster, C.R. 1977. Conservation tillage in the Northern Plains. J. Soil Water Conserv. 32:37-42.

Fenster, C.R., and T.M. McCalla. 1971. Tillage properties in western Nebraska with a wheat-sorghum-fallow rotation. Agric. Exp. Stn. SB 515, Univ. of Nebraska, Lincoln.

Fisher, C.E., and E. Burnett. 1953. Conservation and utilization of soil moisture. Texas Agric. Exp. Stn. Bull. B-767.

Fosbrooke, H.A. 1974. Socio-economic aspects of shifting cultivation. *In* Shifting Cultivation and Soil Conservation in Africa, pp. 72–77. FAO Soils Bull. 24. Rome: FAO.

Fox, R.H., and V.A. Bandel. 1986. Nitrogen utilization with no-tillage. *In* No-Tillage and Surface-Tillage Agriculture—The Tillage Revolution. M.A. Sprague and G.B. Triplett (eds.). 117–148. New York: John Wiley & Sons.

French, E.W., and N. Riveland. 1980. Chemical fallow in a spring wheat-fallow rotation. North Dakota Farm Res. 38(1):12–15.

Griffith, D.R., and S.D. Parsons. 1980. Energy requirements for various tillage-planting systems. Purdue Univ. Coop. Ext. Serv. Publ. (Tillage) ID-141.

Griffith, D.R., J.V. Mannering, and W.C. Moldenhauer. 1977. Conservation tillage in the eastern Corn Belt. J. Soil Water Conserv. 30:20–28.

Hadas, A., D. Wolf, and E. Stibbe. 1980. Tillage practices and crop response—Analyses of agro-ecosystems. Agro-Ecosystems 6:235–248.

Hakimi, A.H., and R.P. Kachru. 1976. Response of barley crop to different tillage treatments on calcareous soil. J. Agric. Eng. Res. 21:399–403.

Halvorson, A.D., and A.L. Black. 1974. Saline-seep development in dryland soils of northeastern Montana. J. Soil Water Conserv. 29:77–81.

Harman, W.L., and A.F. Wiese. 1985. Economic appraisal of reduced-tillage practices. *In* Weed Control in Limited-Tillage Systems. A.F. Wiese (ed.). pp. 282–297. Champaign, Ill.: Weed Sci. Soc. Am.

Harper, J., and O.H. Brensing. 1950. Deep plowing to improve sandy land. Oklahoma Agric. Exp. Stn. Bull. B-362.

Harrold, L.L., and W.M. Edwards. 1972. A severe rainstorm test of no-till corn. J. Soil Water Conserv. 27:30.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1983. The animal-drawn wheeled tool carrier. ICRISAT Info. Bull. 8. Patancheru, AP 502 324, India.

Johnson, W.C., and R.G. Davis. 1972. Research on stubble-mulch farming of winter wheat. U.S. Dept. Agric., Agric. Res. Serv. Conserv. Res. Rpt. No. 16. Washington, DC: U.S. Government Printing Office.

Jones, O.R., and R.N. Clark. 1987. Effects of furrow dikes on water conservation and dryland crop yields. Soil Sci. Soc. Am. J. 51:1307–1314.

Kang, B.T., K. Moody, and J.O. Adesina. 1980. Effects of fertilizer and weeding in no-tillage and tilled maize. Fertilizer Res. 1:87–93.

Ketcheson, J. 1977. Conservation tillage in eastern Canada. J. Soil Water Conserv. 32: 57–60.

Klocke, N.L. 1979. No-till drills for fall seeding small grains. ASAE Paper No. 79-1023. Am. Soc. Agric. Eng., St. Joseph, Mich.

Lal, R. 1976a. No-tillage effects on soil properties under different crops in western Nigeria. Soil Sci. Soc. Am. J. 40:762–768.

Lal, R. 1976b. Soil erosion in Alfisols in western Nigeria. II. Effects of mulch rates. Geoderma 16:377–387.

Lal, R. 1986. No-tillage and surface-tillage systems to alleviate soil-related constraints in the tropics. *In* No-Tillage and Surface-Tillage Agriculture—The Tillage Revolution. M.A. Sprague and G.B. Triplett (eds). pp. 261–317. New York: John Wiley & Sons.

Lemon, E.R. 1956. The potentialities for decreasing soil moisture evaporation loss. Soil Sci. Soc. Am. Proc. 20:120–125.

Lessiter, F. (ed.). 1982. 1981/1982 no-till farmer acreage survey. No-Till Farmer 10(3):5.

Lyles, L., L.J. Hagen, and E.L. Skidmore. 1983. Soil conservation: Principles of erosion by wind. *In* Dryland Agriculture. H.E. Dregne and W.O. Willis (eds). pp. 177–188. Am. Soc. Agron. Monogr. No. 23. Am. Soc. Agron., Madison, Wisc.

Massoud, F.I. 1975. Physical properties of sandy soils in relation to cropping and soil conservation practices. *In* Sandy Soils, FAO Soils Bull. 25. Rome: FAO.

Mathers, A.C., G.C. Wilson, A.D. Schneider, and P. Scott. 1971. Sugarbeet response to deep tillage, nitrogen, and phosphorus on Pullman clay loam. Agron. J. 63:474–477.

Maurya, P.R., and R. Lal. 1981. Effects of different mulch materials on soil and on root growth and yield of maize and cowpea. Field Crops Res. 4:33–45.

McCowen, R.L., R.K. Jones, and D.C.I. Peake. 1985. Evaluation of a no-till tropical legume ley-farming strategy. *In* Agro-Research for the Semiarid Tropics. R.C. Muchow (ed.). pp. 450–472. Australia: Univ. Qld. Press.

Moody, K. 1974. Weeds and shifting cultivation. *In* Shifting cultivation and Soil Conservation in Africa, pp. 155–166. FAO Soils Bull. 24. Rome: FAO.

Morrison, J.E., Jr. 1978. No-tillage experimental planter performance and depth regulation evaluation. Trans. Am. Soc. Agric. Eng. 21:602–604, 609.

Musick, J.T., and D.A. Dusek. 1975. Deep tillage of graded-furrow-irrigated Pullman clay loam. Trans. Am. Soc. Agric. Eng. 18:263–269.

Osuji, G.E., O. Babalola, and F.O. Aboaba. 1980. Rainfall erosivity and tillage practices affecting soil and water loss on a tropical soil in Nigeria. J. Environ. Mgmt. 10:207–217.

Papendick, R.I., and D.E. Miller. 1977. Conservation tillage in the Pacific Northwest. J. Soil Water Conserv. 32:49–56.

Phillips, W.M. 1969. Dryland sorghum production and weed control with minimum tillage. Weed Sci. 17:451–454.

Pumphrey, F.V. 1975. Seed drills, how they are used and why. USAID/Oregon State Univ. Team, Ankara, Turkey.

Radke, J.K. 1982. Managing early season soil temperatures in the northern corn belt using configured soil surfaces and mulches. Soil Sci. Soc. Am. J. 46:1067–1071.

Rai, R.N., and Y.S. Yadav. 1979. Effect of tillage practices on yield of rainfed wheat in Doon Valley. Indian J. Agron. 24:72–77.

Rasmussen, W.W., G.C. Lewis, and M.A. Fosberg. 1964. Improvement of the Chilcott-Sebree slick spot soils in southwestern Idaho. U.S. Dept. Agric., Agric. Res. Serv. 41-91. Beltsville, Maryland.

Richey, C.B., D.R. Griffith, and S.D. Parsons. 1977. Yields and cultural energy requirements for corn and soybeans with various tillage-planting systems. Adv. Agron. 29: 141–182.

Robertson, L.S., and D.L. Mokma. 1978. Crop residue and tillage considerations in energy conservation. Michigan State Univ. Coop. Ext. Serv. Bull. E-1123.

Rockwood, W.G., and R. Lal. 1974. Mulch tillage: A technique for soil and water conservation in the tropics. Span 17:77–79.

Sandoval, F.M., J.J. Bond, and G.A. Reichman. 1972. Deep plowing and chemical amendment effect on a sodic claypan soil. Trans. Am. Soc. Agric. Eng. 15:681–684, 687.

Sherif, S., M.S. Chaudhry, and S. Khan. 1982. Dryland wheat production in the western part of Libya. II. Subsoiling and its residual effects. Libyan J. Agric. 11:23–30.

Smika, D.E., and G.A. Wicks. 1968. Soil water storage during fallow in the Central Great Plains as influenced by tillage and herbicide treatments. Soil Sci. Soc. Am. Proc. 32:591–595.

Smith, E.S., D.H. Vaughn, J.V. Perumpral, and P.H. Reid. 1983. Soybean response to various tillage and planting systems. Am. Soc. Agric. Eng. Paper No. 83-1524. Am. Soc. Agric. Eng., St. Joseph, Mich.

Triplett, G.B., Jr., and D.M. Van Doren, Jr. 1977. Agriculture without tillage. Sci. Am. 236(1):28-33.

Trouse, A.C., Jr. 1978. Physical conditions of soil affecting no-tillage techniques. Proc. First Ann. Southeastern No-Till Systems Conf., Univ. Georgia Spec. Publ. No. 5, pp. 30-36.

Unger, P.W. 1978. Straw-mulch rate effect on soil water storage and sorghum yield. Soil Sci. Soc. Am. J. 42:486-491.

Unger, P.W. 1982. Surface soil physical properties after 36 years of cropping to winter wheat. Soil Sci. Soc. Am. J. 46:796-801.

Unger, P.W. 1984. Tillage systems for soil and water conservation. FAO Soils Bull. 54, Rome: FAO.

Unger, P.W., and A.F. Wiese. 1972. No-tillage research in the Panhandle of Texas. Proc. No-Tillage Systems Symp., Columbus, Ohio, pp. 103-107. Ohio State Univ., Columbus, Ohio.

Unger, P.W., and R.E. Phillips. 1973. Soil water evaporation and storage. *In* Conservation Tillage, The Proc. of a Natl. Conf. Ankeny, Iowa: Soil Conserv. Soc. Am.

Unger, P.W., and B.A. Stewart. 1976. Land preparation and seedling establishment practices in multiple cropping systems. *In* Multiple Cropping. R.I. Papendick, P.A. Sanchez, and G.B. Triplett (eds.). pp. 255-273. Spec. Publ. No. 27, Madison, Wis: Am. Soc. Agron.

Unger, P.W., and B.A. Stewart. 1983. Soil management for efficient water use. *In* Limitations to Efficient Water Use in Crop Production. H.M. Taylor, W.R. Jordan, and T.R. Sinclair (eds.). pp. 419-460. Madison, Wis.: Am. Soc. Agron.

Unger, P.W., and A.F. Wiese. 1979. Managing irrigated winter wheat residues for water storage and subsequent dryland grain sorghum production. Soil Sci. Soc. Am. J. 43:582-588.

USDA. 1954. Diagnosis and improvement of saline and alkali soils. Handbook No. 60, U.S. Dept. Agriculture. Washington, D.C.: U.S Government Printing Office.

Wicks, G.A. 1986. Substitutes for tillage on the Great Plains. *In* No-Tillage and Surface-Tillage Agriculture—The Tillage Revolution. M.A. Sprague and G.B. Triplett (eds.). pp. 183-196. New York: John Wiley & Sons.

Wicks, G.A., and D.E. Smika. 1973. Chemical fallow in a winter wheat-fallow rotation. J. Weed Sci. Soc. Am. 21:97-102.

Wiese, A.F., and D.W. Staniforth. 1973. Weed control in conservation tillage. *In* Conservation Tillage, The Proc of a Natl. Conf., pp. 108-114. Ankeny, Iowa: Soil Conserv. Soc. Am.

Wiese, A.F., and E.W. Chenault. 1987. Controlling weeds and volunteer crops during fallow periods. Texas Agric. Exp. Sta. Bull. 1568.

Wilkins, D.E., G.A. Muilenburg, R.R. Allmaras, and C.E. Johnson. 1983. Grain drill opener effects on wheat emergence. Trans. Am. Soc. Agric. Eng. 26:651-655, 660.

Willcocks, T.J. 1981. Tillage of clod-forming sandy loam soils in the semi-arid climate of Botswana. Soil & Tillage Res. 1:323-350.

Willcocks, T.J. 1984. Tillage requirements in relation to soil type in semi-arid rainfed agriculture. J. Agric. Eng. Res. 30:327-336.

Williamson, E.S., E.A. Dowding, W.G. Aanderud, G.R. Durland, F.S. Shideler, and M.S. Argabright. 1976. Conservation tillage South Dakota Coop. Ext. Serv. Pamp. EC 703.

Wilsie, C.P. 1962. Crop Adaptation and Distribution. San Francisco and London: Freeman and Company.

Windsor, T. 1984. Dryland farming for increased food production. *In* The Role of Farm Management in Food Production, pp. 217–222. Fifth Int. Farm Mgmt. Cong., Farnham, Royal, Slough, UK. Common. Agric. Bureau.

Woodruff, N.P. 1972. Wind erosion as affected by reduced tillage systems. *In* Proc. No-Tillage Systems Symp., Columbus, Ohio, pp. 5–20. Columbus: Ohio State Univ.

Yu, S.L., J.S. He, and G.H. Zhang. 1981. Study on the effect of mulching groundnuts with plastic film on soil fertility and activity of microflora. Zhongguo Youliao No. 3, 50–52.

Zingg, A.W., and C.J. Whitfield. 1957. A summary of research experience with stubble-mulch farming in the western states. U.S. Dept. Agric. Tech. Bull. 1166. Washington, DC: U.S. Government Printing Office.

Fertility Management and Nutrient Cycling*

J.F. Power

I. Introduction 131
II. Principles Relating Water and Nutrient Availability 132
A. Law of the Limiting 132
B. Inputs into Dryland Agriculture 133
III. Water Deficits 135
A. Soil Chemistry 135
B. Soil Microbiology 137
C. Plant Growth and Nutrient Availability 138
IV. Management Practices 140
A. Tillage and Residue Management 141
B. Cropping Systems 143
C. Cultural Practices 145
V. Conclusions 146
References 147

I. Introduction

In dryland agriculture, limited water availability is usually the factor that ultimately limits crop production. However, it is not unusual for limited availability of one or more soil nutrients to further decrease production potential. Often, the effects of water and nutrient deficiencies are additive.

Because soils used for dryland agriculture were developed under widely varying conditions, their ability to supply nutrients is highly variable. In temperate

*Contribution from Agricultural Research Service, U.S. Department of Agriculture, in cooperation with the Nebraska Agricultural Research Division.

1990 by Springer-Verlag New York Inc.
Advances in Soil Science, Volume 13

regions of North and South America, northern Asia, and eastern Africa many dryland soils are Mollisols, with a relatively deep A-horizon enriched with organic matter. These soils are often inherently fertile and respond primarily to nitrogen (N) and often to phosphorus (P) fertilizer. Dryland soils in some subtropical areas (Australia, India, southwestern Asia, parts of Africa, and South America) are often older, more weathered, and inherently less fertile. Such soils are frequently deficient in a number of the micronutrients, such as iron (Fe), copper (Cu), molybdenum (Mo), and others. Thus, dryland soils as a group cannot be categorized as being sufficient in any one or group of nutrients, as is true for soils developed under other rainfall patterns.

The purpose of this chapter is to summarize soil fertility aspects of dryland soils. This summary includes a discussion of the principles involved (especially principles somewhat unique to dryland soils), the effects of water deficits on soil processes and plant activity, and management practices suitable for controlling nutrient cycling in dryland soils. Discussions of not only the effects of nutrient cycling and availability on crop production, but also the fate of nutrients and environmental concerns are included. Primary emphasis is placed on N and P cycling and availability because deficiencies of these elements are more universal than are micronutrient deficiencies. This chapter is not intended to provide an extensive literature review but rather to outline the principles involved, providing a few specific examples to illustrate these principles. Although many of the examples are drawn from research on the dryland soils in temperate regions of North America, with which the author is most familiar, the principles usually have applications elsewhere.

II. Principles Relating Water and Nutrient Availability

A. Law of the Limiting

Liebig's "Law of the Limiting" applies to dryland soil just as it applies to other soils throughout the world. The nutrient that is relatively least available is the first nutrient to restrict potential crop production. The "Law of the Limiting" is complicated somewhat in dryland soils by the effects of water deficits on plant growth and production potential. As water availability decreases, a point comes at which water deficiency restricts plant growth to a greater extent than any nutrient deficiency. Also, water availability has a dominating effect on the availability of N, P, and other nutrients in dryland soils.

The relationship between plant responses to water and nutrient deficiencies is illustrated nicely in Figure 1, in which the responses of native perennial grasses to nitrogen fertilizer rate are shown as a function of water availability. With relatively high water availability, a very large growth response to increasing fertilizer N rate was observed. As water deficit increased, the magnitude of this response decreased. Finally, when water was very limited, dry-matter production by the grass was quite low, and little or no response to N fertilization was observed. At

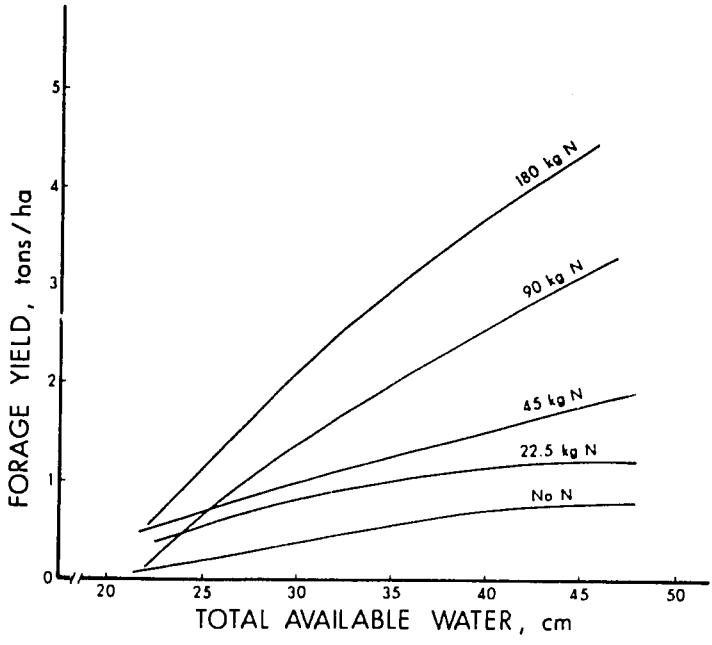


Figure 1. Effect of available water on bromegrass products at different fertilizer N rates. (Smika et al., 1965.)

this point, water availability was more limiting than was N availability. Consequently, additional N without additional water was of no benefit. Likewise, adding water without adding N produced very limited increases in plant growth.

The relationship of water and N availability to plant growth, shown in Figure 1, has been developed for a number of crops and for other nutrients. Thus, this "Law of the Limiting" might be altered to say that the most restrictive plant growth factor is the factor that first restricts growth.

B. Inputs into Dryland Agriculture

The effects of inputs into dryland farming systems on the soil environment, nutrient availability, and subsequent plant growth are shown schematically in Figure 2. For a given soil and climate input, with their inherent properties and characteristics, the producer controls the soil environment through the selection of management practices. Factors of the soil environment of most concern are air (oxygen) and water regimes, soil temperature, and substrate availability. The farmer makes and executes a series of management decisions each year—choice of tillage practices, crop residue management, irrigation and fertilization practices, crops grown and cropping sequences, manuring and green manuring, weed and pest control, harvesting technique, and others. These decisions for a given

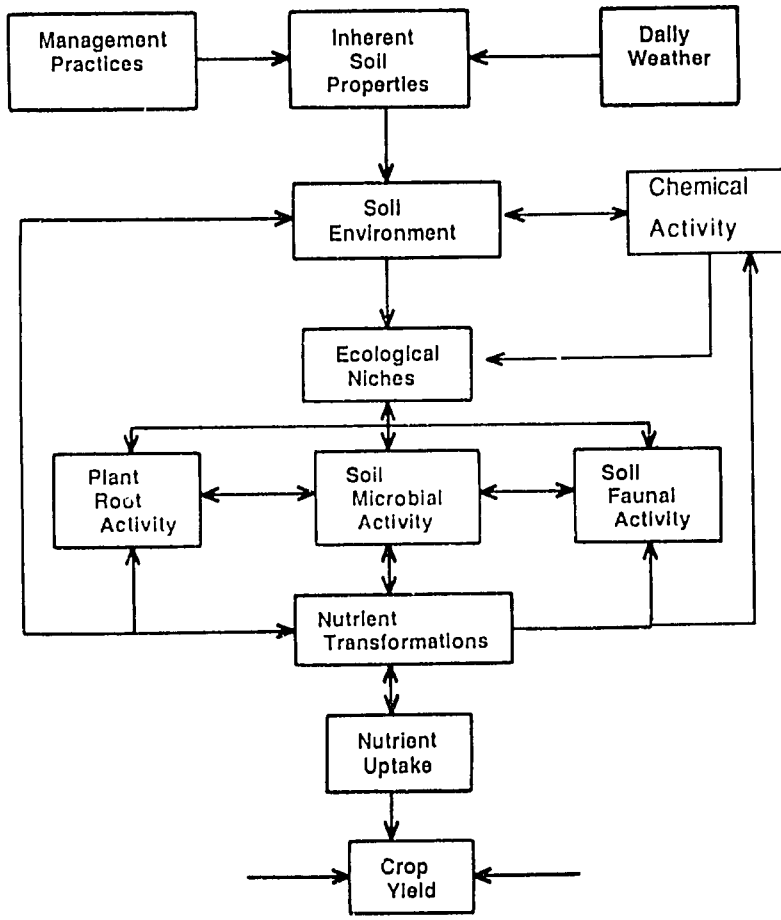


Figure 2. Flow chart relating biotic and abiotic factors to soil ecology and nutrient uptake.

soil in a given climate result in unique combinations of aeration, water availability, temperature distribution, and availability of subrates (especially soluble C for microorganisms and plant-available nutrients for plant roots).

The preceding parameters of soil environment established as a result of management decisions regulate to a large extent the chemical reactions and biological activity that occur in the soil. Chemical reactions are concerned with precipitation–solubility relations (phase changes), as well as alterations of chemical forms. For example, as the soil dries, many inorganic elements precipitate out of soil solution as solubility constants of the various salts are reached (Kissel et al., 1985).

Biological activity is concerned directly with plant root activity and microbial activity. Restricted plant root activity would, of course, have direct effects on

plant growth and productivity. Because the food chain of the macroorganisms in the soil depends primarily on microbial activity, soil environment would also have an indirect as well as direct effect on activity of macroorganisms. Soil microorganisms live and function predominantly within the pores of the soil. These pores are also occupied by the water and air contained in a volume of soil Consequently, one would expect that the better farm management decisions would be those in which water, aeration, and microbial activity are near the optimum combination for biological activity.

The chemical and biological activity of the soil regulates, to a large extent, the nature and extent of nutrient transformations that occur (see Fig. 2). As a result of drying, precipitation of certain salts usually immobilizes nutrients in forms that are not readily available to the growing crop. Likewise, changes in water and aeration regimes may result in oxidation–reduction reactions that convert certain elements from plant-available to unavailable forms (Fe, Mn, and others). Also, salt concentration of the soil solution (salinity) increases as soil water content decreases and can have subsequent effects on all biological activity by altering the osmotic potential.

Restricted biological activity resulting from a suboptimum soil environment would greatly affect the cycling and transformation of nutrients present in organic form. Nitrogen transformations and availability would be especially affected (Linn and Doran, 1984). Also, organic P, a major source of plant-available P in dryland soils, would be affected, as would Fe, Mn, Co, Cu, and other micronutrients present in plant residues and other labile organic sources, to some extent (Kissel et al., 1985). Not only would suboptimum soil environments reduce reaction rates and kinetics of transformations, but also the kind of transformation could be altered (Lindsey and Vlek, 1977). Under certain soil water and temperature conditions, for example, significant ammonia volatilization could occur while denitrification may be very significant in another environment.

Finally, as indicated in Figure 1, all factors discussed ultimately affect plant growth and activity. Soil environment, of course, directly affects plant root growth and development, nodulation, mycorrhizal infections, meristematic activity in the crown (especially for gramecous species), and so forth. Thus, the kind and magnitude of nutrient transformations that ultimately result from management decisions affect the availability of plant nutrients. Consequently, much of the discussion in this chapter focuses on the effects of management decisions on nutrient availability in dryland soils.

III. Water Deficits

A. Soil Chemistry

Water deficits affect soil chemistry primarily through their effect on the solubility and precipitation of salts and minerals in the soil. As the soil dries, the concentration of soluble salts in the soil solution increases. If this concentration

exceeds about 5 dSm^{-1} (2 to 3 dSm^{-1} on oven-dry soil basis), the osmotic potential of the soil solution may begin to affect plant water relations and subsequent growth of salt-sensitive crops adversely (Taylor, 1983). This level of salinity is not unusual in dryland soils.

As salt concentrations in the soil solution increase with soil drying, the solubility constant is approached for certain salts, which begin to precipitate. Soluble anions are predominantly bicarbonate (HCO_3^-), sulfate ($SO_4^=$), and chlorides (Cl^-), along with the cations Ca^{++}, Mg^{++}, K^+, and sometimes Na^+. The sulfate salts of these cations generally precipitate first. In many dryland soils, Ca^{++} is the predominant cation, so one of the first salts to precipitate is gypsum ($CaSO_4 \cdot 2H_2O$). If significant quantities of Ca^{++} and $SO_4^=$ are present in the soil solution, salinity hazard for such soils is usually relatively low because, when conductivity levels of the saturation extract reach about 2 to 3 dSm^{-1}, gypsum begins to precipitate. As long as there are soluble Ca^{++} and $SO_4^=$ ions in solution in equilibrium with the precipitated phase, electrical conductivity does not increase, regardless of the degree of drying. Consequently, in gypsiferous soils, electrical conductivity of the saturation extract seldom increases appreciably above 2 to 3 dSm^{-1}, a level that has little adverse effect on most dryland crop species.

If sodium (Na^+) is present in the soil in significant quantity (in excess of about 6% of the cation exchange capacity), soil structure and aggregation may begin to disintegrate, resulting in a dispersed soil. Under such conditions, hydraulic conductivity is greatly reduced, soil resistance increases, surface crusting may become severe, and water infiltration is restricted. Consequently plant growth in such sodic soils is restricted by greater water deficits, greater soil resistance, and reduced hydraulic conductivity. These adverse effects become acute when the exchangeable sodium percentage reaches about 15%, varying somewhat with soil texture and organic matter content.

In addition to the effects of water deficits on problems associated with soil salinity and sodicity, water availability also affects the rate of dissolution of certain soil minerals to some extent. In terms of geologic time, dissolution (weathering) of soil minerals often proceeds at a much slower rate and at more shallow depths for dryland soils than for those developed in more humid climates. Consequently, in dryland soils, feldspars and other potassium-rich minerals often remain intact and serve as a primary source of plant-available K.

Water deficits also directly affect availability of P (Lindsey and Vlek, 1977) and many other nutrients. Soil drying often results in the precipitation of orthophosphate ($PO_4^{\equiv}$) as various forms of calcium-phosphate. In many temperate region soils, these precipitated calcium phosphates exist predominantly in the form of octocalcium phosphates, a slightly soluble source of plant-available P. However, this mineral form exists in equilibrium not only with soluble $PO_4^{\equiv}$ ions, but also with adsorbed P and other calcium-phosphate minerals, with the equilibrium concentrations varying with soil water content, salt concentration, pH, and other related factors. Often, much of the P immobilized as octocalcium phosphate can eventually become available to plants (Kissel et al., 1985). In

certain acid soils, orthophosphate may precipitate as iron and aluminum phosphates, which are relatively insoluble and unavailable.

A third manner in which water deficits may affect chemical solubility of soil nutrients is indirectly through the effects of water deficits on plant root activity (Taylor, 1983). A highly active root system respires relatively large amounts of carbon dioxide into the soil solution, reducing the soil solution pH, and thereby altering solubility of many soil minerals. For example, the increased acidity of the soil solution increases P availability in neutral or calcareous dryland soils. Plant root hairs and other tissue often remain active for only a few days or weeks. After that, they begin to decompose, providing a supply of carbon that enhances microbiological activity within the soil. The effects of microbial activity on nutrient transformations are discussed in more detail later.

B. Soil Microbiology

Water directly affects the availability of a number of nutrients, often through its effect on microbiological processes in the soil. This is especially true of N and, to a large extent, P because most of the N and an appreciable part of the labile P in a soil are derived from the biological decomposition of organic matter (Doran and Smith, 1987). Linn and Doran (1984) have shown that such biological processes as N mineralization, nitrification, and CO_2 production increase as the percentage of the soil pores filled with water (water-filled pore space) increases to about 60% (Figure 3). At higher values, rates of these aerobic processes decrease while rates of anaerobic processes (i.e., denitrification) increase. The 60% water-filled pore space (also 60% saturation) approximates water content at field capacity for most soils. From this, then, it is apparent that, as a soil dries to below field capacity, the potential rate of conversion of organic forms of N to plant-available (inorganic) forms decreases. Consequently, the rate at which indigenous organic N is mineralized and made available for crop growth decreases as the soil dries.

Mineralization of N from organic forms to soluble nitrate (NO_3^-)N is a two-step process. First, heterogeneous groups of soil organisms hydrolyze the proteins and amino acids in the organic fraction of the soil ultimately to produce ammonium N (NH_4^+). The ammonium N is then oxidized by select groups of bacteria (*Nitrosomas*, *Nitrococcus*, *Nitrobacter*) to nitrite and then to nitrate forms (Boswell et al., 1985). Because bacteria are generally more sensitive to water deficits than are fungi, the bacteria-dependent nitrification process ($NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$) may essentially cease to operate in a dry soil, whereas the ammonification step (organic N $\rightarrow NH_4^+$), accomplished predominantly by more drought-tolerant fungi, may still proceed. For this reason, it is not unusual to find appreciable accumulations of ammonium N in dryland soils after prolonged dry periods. This ammonium N is rapidly nitrified when the soil is again exposed to an environment conducive for activity of nitrifying organisms (Power et al., 1974).

With alternative wetting and drying of a surface soil, especially in summer fallowing, appreciable denitrification can occur under some conditions. Aulakh

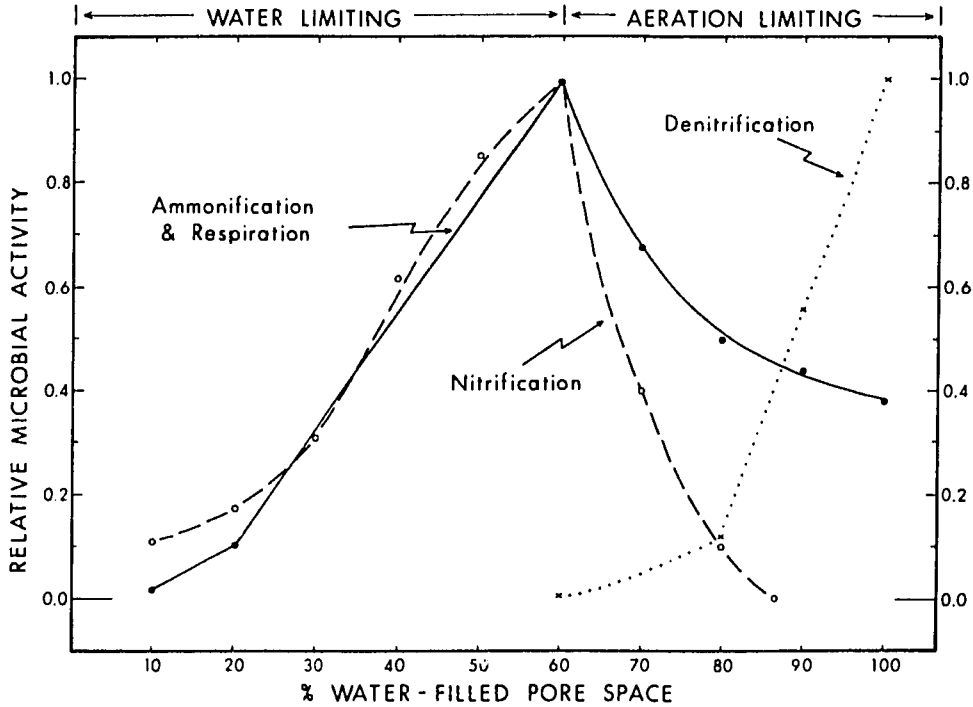


Figure 3. Relationship between several aerobic and anaerobic microbial processes and the percentage of water-filled pore space. (Linn and Doran, 1984.)

et al. (1984) showed that considerable N could be lost from a no-till summer fallow field in Saskatchewan. Temporary reduction of water-filled pore space and warm soil temperatures for a few days after a summer rain created conditions in no-till favorable for denitrification.

Water availability also has a similar effect on the rate of mineralization of organic sources of P, as well as for other nutrients present in organic forms. For many dryland soils, especially those on which manuring, green manure, reduced tillage, or other such practices are involved, organic matter may be the major source for plant-available P and for some micronutrients.

C. Plant Growth and Nutrient Availability

Plant growth (accumulation of phytomass) is a major component in the cycling and availability of nutrients. Much of the carbon fixed by photosynthesis in the green plant is the energy source for most of the microbiologically induced nutrient transformations that occur in the soil. Likewise, the organic matter in crop residues serves as a major source for replenishing various fractions

Table 1. Percent stress in smooth bromegrass resulting from N and water deficiencies

Growth period	Deficiency of N	Water	N + water
23 May–10 June	3	32	49
11 June–30 June	24	32	54
1 July–22 July	35	10	58

Source: Power (1971).

of soil organic matter, and subsequently affects aggregation, porosity and other soil properties (Doran and Smith, 1987). Gupta and Germida (1988) found that cultivation greatly reduced microbial activity and nutrient cycling in 0.75 to 1.00 mm aggregates.

Because of recurrent water deficits, plant growth on dryland soils is often less than that in less arid climates. In general, plant stresses resulting from water and nutrient deficits are additive (Table 1). Compared to well-irrigated and well-fertilized smooth bromegrass (*Bromus inermis* L.), N deficit reduced growth potential by 3, 24, and 35% for the three growth periods shown, while water deficit reduced growth potential by 32, 32, and 10%, respectively. When both water and N were deficient, growth potentials for these three periods were reduced 49, 54, and 58%, respectively—values that approximate the sum of the percentage reductions that occurred for water and N deficits separately. Halse et al. (1969) showed similar effects of N stress on growth potential of wheat (*Triticum aestivum*) in western Australia. In these examples, stress was calculated by the method of Greenwood et al. (1965):

$$S = \frac{\log M_2 - \log W_2}{\log M_1 - \log W_1} \times 100$$

where S = % stress, M_2 and M_1 = dry weight of unstressed crop, and W_2 and W_1 = dry weight of stressed crop at times t_2 and t_1, respectively.

The reduction in plant growth resulting from water stress, as indicated in Table 1, results in less nutrient uptake by the crop and, consequently, less nutrients being recycled through the crop. If crop residues are removed and not returned to the soil, then the quantity of nutrients being recycled is extremely limited, and nutrient deficiencies become more apparent (Power et al., 1986).

Recycling of nutrients is mainly a microbiological process and, consequently, depends on the rate of microbial activity. Because dryland soils are dry for a greater number of days each year than are soils in more humid regions, the microbial activity and nutrient recycling rates are therefore reduced. This reduction in rate, coupled with less crop growth and nutrient uptake, results in a much smaller volume of nutrients recycling in dryland soils than in irrigated or more humid soils.

Table 2. Organic C, total N, and organic P (kg ha^{-1}) in solum of native prairie soil and changes (%) resulting from 44 years of cultivation

Landscape segment[a]	Organic C		Total N		Organic P	
	Prairie	Change	Prairie	Change	Prairie	Change
		Sandstone				
SM	7.50	−61 [b]	0.721	−58 [b]	0.113	−57 [b]
SH	7.86	−33 [b]	0.785	−20 [b]	0.125	−20 [c]
LBS	10.50	−7 [d]	1.074	−7 [c]	0.169	+23 [b]
FS	13.05	−29 [b]	1.260	−23 [b]	0.228	−29 [b]
BBS	11.39	−39 [b]	1.145	−35 [b]	0.186	−28 [b]
BFS	14.22	−5 [d]	1.285	+4 [d]	0.215	+15 [b]
		Siltstone				
SM	9.70	−39 [b]	0.936	−35 [b]	0.131	−35 [b]
SH	10.35	+10 [d]	0.985	+14 [d]	0.122	+28 [b]
LBS-3	12.41	−56 [b]	1.254	−55 [b]	0.148	−41 [b]
FS	12.91	−40 [b]	1.246	−41 [b]	0.151	−33 [b]
TS	15.78	−34 [b]	1.488	−29 [c]	0.201	−21 [b]
		Shale				
SM	10.92	−49 [b]	1.115	−40 [b]	0.080	−16 [d]
SH	13.55	−49 [b]	1.326	−40 [b]	0.158	−44 [b]
BS	13.87	−29 [b]	1.374	−0 [b]	0.151	+5 [d]
FS	19.09	−34 [b]	2.163	−31 [b]	0.248	−13 [c]

Source: Aguilar et al. (1988).
[a] SM = summit; SH = shoulder; BS = backslope; LBS = lower backslope; BBS = back backslope; FS = footslope; BFS = back footslope, and TS = toeslope.
[b] $P < 0.10$.
[c] $P < 0.40$.
[d] Not significant at $P < 0.40$.

IV. Management Practices

Cultivation accelerates the oxidation of organic matter, resulting in more rapid decomposition of crop residues and other organic sources (Doran and Smith, 1987). Cultivation also results in greater soil organic matter losses through accelerated soil erosion. Consequently, compared to the native prairie soil, cultivated soils usually have a much smaller pool of organic matter and associated nutrients (Haas et al., 1957).

Aguilar et al. (1988) showed that these cultivation effects vary somewhat with slope position and parent material (Table 2). Cultivation for 44 years in North Dakota resulted in organic C, total N, and organic P losses as great as 61, 58, and 57%, respectively, compared to the virgin prairie soil. However, at some slope positions deposition occurred, resulting in respective gains as great as 10, 14, and 28%. While changes varied with slope position and parent material, few consistent trends were apparent. These data do illustrate, however, that the effects of

Table 3. Effect of fallow method on water content of upper 100 mm of soil for 47 days after a 40-mm irrigation

	Soil water (m^3/m^3)		
Days since irrigation	Bare fallow	Stubble mulch	No till
1	.303	.317	.303
2	.207	.263	.280
3	.237	.240	.263
4	.220	.233	.257
5[a]	.210	.240	.263
6	.207	.213	.250
11	.170	.193	.197
18	.180	.160	.170
32[b]	.163	.147	.160
47[c]	.147	.150	.143

Source: Aase and Tanaka (1987).
[a] 3 mm precipitation, day 5.
[b] 4 mm precipitation, day 24.
[c] 6 mm precipitation, day 37.

cultivation on nutrient cycling can be major and are not uniform across the landscape. Woods and Schuman (1988) reported similar observations in Wyoming.

Rasmussen and Rohde (1988) showed that stubble-mulch tillage resulted in the retention of 6 kg ha^{-1} yr^{-1} more N than occurred for bare tillage after 44 years in a wheat–fallow rotation. They also found that 18% of the fertilizer N applied during this time could be accounted for in increased soil organic N, especially in the upper 75 mm of soil. Tillage had little effect on retention of fertilizer N.

A. Tillage and Residue Management

Earlier discussions in this chapter indicated that crop residues have a major impact on potentially available nutrients for dryland soils and that the management practices employed can regulate availability of these nutrients to future crops. Crop residue management and tillage practices influence many variables that affect nutrient availability and uptake. These include effects on (a) soil water availability, (b) soil erosion control, and (c) soil environment.

Bond and Willis (1969) showed that crop residues on the soil surface slow rates of first- and second-stage evaporation of water from soil surfaces. If surfaces are not rewetted, with sufficient time, cumulative evaporation from residue-covered soil will equal that from bare soil. For dryland soils, in situations in which occasional showers periodically rewet the soil surface, these results indicate cumulative evaporation after several months of fallow for residue-covered soils is less than that for bare soils, resulting in additional water storage. If no rain is received for several months, differences in cumulative evaporation do not persist, so there is no effect of crop residues on soil water conservation (Table 3). Increasing the

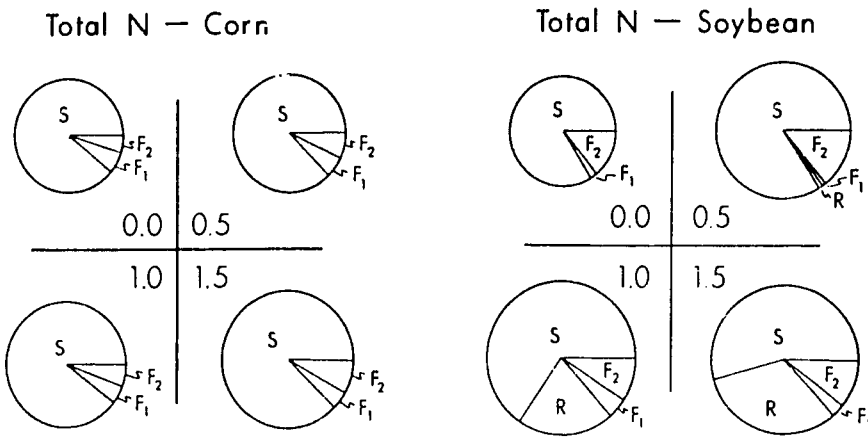


Figure 4. Effect of crop residue rates (0, 0.5, 1.0, and 1.5 times the quantity produced by previous crop) on uptake of N from soil (S), residual fertilizer (F_1), current fertilizer (F_2), and crop residue (R) by corn and soybean. (For soybean S also includes biologically fixed N_2.)

amount of crop residues on the soil surface slows the rate of drying, thereby lengthening the time period during which residue-covered soils can conserve more water than bare soils. Of course, where crop residues conserve extra soil water, increased crop yields and nutrient uptake usually result (Black, 1973; Wilhelm et al., 1986). As an example, Power et al. (1986) showed that increasing amounts of crop residues on the soil surface increased crop growth and the availability and uptake of indigenous soil organic N by both corn and soybean (Fig. 4). Likewise, recovery of N in crop residues produced by the previous year's soybean crop was also greatly increased by increasing crop residue rate.

A number of experiments at many locations have shown that soil N availability and uptake may also be enhanced by soil erosion control. Olson (1977) found that fertilizer would not restore productivity to an artificially eroded soil in South Dakota (Table 4). In a wheat-fallow rotation in Alberta, Dormarr et al. (1988) have shown similar results. Likewise, Mielke and Schepers (1986) showed that productivity of a naturally eroded Nebraska soil could be restored when 200 mm of topsoil was added, but fertilizers alone would not restore productivity.

Generally, results obtained by other scientists, at other locations, and using other techniques have all led to the same conclusions – that severe soil erosion greatly reduces soil productivity and that this productivity cannot be restored by adding any quantity of fertilizer. Maintaining crop residues on the soil surface through the use of reduced- or no-tillage practices is, of course, one of the most practical methods for controlling both wind and water erosion. In Alberta, Dormarr et al. (1988) showed that wheat yields of artificially eroded soil could be restored by application of both fertilizers and feedlot manure.

Table 4. Corn yields (μg ha^{-1}) as affected by depth of topsoil removal and fertilizer treatment, 7-year average

Fertilizer (kg ha^{-1})		Depth of Topsoil Removal (cm)		
N	P	0	30	45
56	21	3.1	2.2	2.5
112	21	3.8	2.8	2.7
168	42	4.3	3.0	2.7

Source: Olson (1977).

Dryland soil management systems in which crop residues are removed or burned ultimately lead to severe soil deterioration and loss of productivity. It is recognized that crop residues are the prime source of fuel in many dryland regions, especially in tropical and subtropical areas. This situation creates some very undesirable scenarios. In many such regions, research is in progress to develop practices in which special crops are produced to meet fuel needs. Also, much effort is being spent to develop management systems that will control the grazing of crop residues by sheep and goats, thereby leaving these residues in place for soil building.

Because of reduced evaporation from residue-covered soils, soil water regimes in such soils are usually much more favorable for biological activity than in bare soils. Likewise, the insulating effect of crop residues, coupled with the greater soil water content, results in less adverse effects of high air temperatures and wind movement on biological activity. As was discussed earlier, the more nearly optimum the soil environment, the greater the microbial activity, nutrient transformations, and potential crop yields.

B. Cropping Systems

Because of limited precipitation in many dryland areas, fallowing is frequently employed to increase soil water storage so that a crop can be produced successfully on the stored soil water plus expected precipitation. In temperate regions, this often means one crop produced every 2 years. In areas with monsoon-type precipitation patterns, a crop is often produced during the dry season on soil water stored during the wet season.

Various types of fallow are used to conserve soil water. In some regions, non-cropped fields are allowed to produce weeds, which are often used for grazing and forage. Weedy fallow seldom enhances soil water storage, so this practice generally has very limited use for water conservation. In such instances, weeds are an essential component in associated grazing systems, even though the following grain crop will suffer from water stress. Where weeds are controlled during fallow with tillage or herbicides, the crop–fallow system is often highly

efficient for grain production. As much as 50% of the precipitation received during fallow may be stored in the crop root zone (Unger and McCalla, 1980).

Because of the relatively high water conservation efficiency of some fallow practices, it is sometimes possible to produce two crops between fallow periods. As an example, in the Great Plains of the United States, a rotation of wheat–sorghum–fallow can successfully replace a wheat–fallow rotation when weed growth is controlled primarily with herbicides (ecofallow). Likewise, particularly in areas that may receive some winter precipitation as snow, crop residues and vegetative barriers (tall grass or shrub borders) are sometimes used to hold snow in place, thereby increasing potential for soil water storage and reducing the need for fallow (Black and Siddoway, 1976).

Cropping sequences may consist of various types of short- or long-term rotations or of monocultures. Monocultures of grain crops are very common in many regions. Short-term rotations may include such systems as wheat–sorghum, wheat–rice, or cover crops or green manures used with a grain crop. Longer-term rotations often consist of a definite cropping cycle involving several crops (one of which is often a legume). The ley systems in Australia are an example in which several years of a pasture legume are rotated with several years of wheat production. As much as 50% of the N in the legume residue remains in the soil organic N pool 2 years after incorporation (Amato et al., 1984). Intercropping is another system that is sometimes employed to produce two crops simultaneously.

All of these cropping systems have their unique effects on nutrient availability and cycling. While grain monocultures provide a relatively stable rate of recycling of nutrients, pest populations (weeds, insect, and disease) may build up to the extent that production is seriously affected. Also, monocultures of grain crops often lead to more severe soil losses through erosion, which ultimately may affect nutrient availability. Rotations break up pest cycles and also provide better soil erosion protection than do monocultures. Rotations containing a legume may potentially increase the amount of N recycled through crop residues (Boswell et al., 1985); however, if the seed of a grain legume is harvested, there is often little, if any, net addition of N to the ecosystem (Heichel and Barnes, 1984). In addition, for dryland soils, a deep-rooted legume such as alfalfa or sweetclover often depletes subsoil water to such an extent that grain crops that follow in a rotation suffer severely from water stress (Haas et al., 1957). Thus, the legume may increase soil organic N content, but still reduce yields of the grain crop.

Which legume cultivar should be used with dryland cropping is difficult to determine because of variability in legume cultivar characteristics and temporal and spatial variations in soils and climates in dryland regions. A recent symposium on the use of legumes in conservation tillage systems (Power, 1987) provides a number of reports on this subject. In Saskatchewan, Brewer et al. (1988) reported that N_2 fixation by lentil, pea, and faba bean decreased 5.3, 7.6, and 10.5 kg ha^{-1}, respectively, for each centimeter reduction in water use, with maximum fixation from faba bean.

C. Cultural Practices

Various cultural practices used for production of dryland crops also affect nutrient availability and uptake. These include such factors as plant population and geometry, fertilizer practices, tillage, and cropping system. The effects of tillage and cropping systems were addressed earlier in this chapter.

Generally, plant populations used for dryland soils are lower than those used for better watered soils. Reducing the leaf area, and subsequently the potential transpiration rate, is commonly achieved for dryland agriculture by reducing planting rate. If this precaution is not taken, grain crops frequently produce excess vegetative growth, depleting soil water reserves to such an extent that insufficient available water remains for grain fill. Reducing plant populations limits potential dry-matter production and nutrient uptake, thereby reducing demands on the soil to provide nutrients. However, because there is less crop growth, fewer nutrients are returned in crop residues, resulting in less nutrient recycling.

Reduction of vegetative growth can sometimes be achieved by using semidwarf varieties of crop plants. Within the last 20 years, we have seen widespread introduction of semidwarf wheat and sorghum cultivars for use on dryland. This change in production practices likewise often reduces potential dry-matter production and nutrient uptake.

Planting geometry may also be altered to some extent to reduce evaporation losses and improve grain yields. In a survey of research results on the effects of row spacing on soybean production, Alessi and Power (1982) concluded that narrowing row spacing increased early season leaf area, resulting in more water stress during grain fill. For dryland cropping, this increased water stress could result in lower grain yield. Thus, for dryland production, N uptake and recycling would be less for the narrow (15 cm) row spacing than for wider rows.

Fertilizer practices greatly affect nutrient cycling and availability (Power, 1983; Rasmussen and Rohde, 1988). Because of frequent dry periods, placement of soluble fertilizers with the seed is extremely hazardous in dryland soils. Seldom should more than 15 kg N/ha be applied with the seed—higher rates result in high osmotic potentials near the germinating seed. For oil crops, applying no fertilizer N with the seed is usually recommended; however, up to 20 to 30 kg P/ha can be applied with the seed because of the considerably lower solubility of most P fertilizers. Tanaka and Aase (1989) reported that P availability was particularly critical for an eroded soil.

In dryland soils, the surface layers often remain dry for a major part of the growing season. Such a condition might suggest that fertilizers should be placed deeper to be in the region of the active root zone for more of the growing season. However, research using P^{32}-tagged fertilizers in eastern Montana showed that, during brief periods when the surface soil was moist after infrequent showers, the wheat took up sufficient P^{32} to meet growth requirements for some time (Power et al., 1961). These results help explain why deep placement of P fertilizers in dryland soils frequently fails to show any advantage.

Timing of fertilizer application could also affect nutrient cycling (Boswell et al., 1985). Often, applying N fertilizers near the time of maximum N uptake rate of the crop results in the most efficient uptake of the fertilizer. At the other extreme, applying N to winter wheat at planting often results in relatively poor use of the fertilizer N. Frequently, larger percentages of fall-applied N are lost from the soil than occurs for application near the tillering stage. In some instances, in an extremely dry situation, some of the N may be lost by ammonia volatilization (unless nitrate only sources are used). Or if an unusually wet winter is experienced, nitrates could be lost by leaching. Available information also indicates that, frequently, even in dryland soils, about 20% of the N applied may be lost by denitrification.

Fertilizer sources are, of course, a major variable in determining nutrient cycling. Most dryland experiments show that ammonium nitrate is usually one of the most efficient N sources for dryland crops (Boswell et al., 1985). At the other extreme, these experiments often show that urea is the least efficient form of N fertilizers. One must exercise considerable caution when using urea on dryland to avoid excessive losses by ammonia volatilization. Most dryland soils are neutral to calcareous at the surface and are often relatively dry except after intermittent showers. Especially when surface-broadcast, these conditions are near optimum for ammonia volatilization from urea. By concentrating the urea (liquid or solid) in a band or pellets, surface contact is reduced, reducing volatilization. Injecting or incorporating urea beneath the soil surface is by far the best way in which to apply this material to dryland soils (Doran and Smith, 1987).

V. Conclusions

In this chapter, a number of factors affecting nutrient cycling, availability, uptake, and losses from dryland soils have been discussed. The uniqueness of associated processes as they operate in dryland soils has been pointed out. As mentioned frequently in this chapter, the overwhelmingly unique characteristic of dryland soils that affects almost all processes is that of a water-deficient environment. Thus, in dryland soils (compared to better-watered soils), we experience less vegetative growth, smaller quantities of nutrients taken up and returned to the soil, greater hazards of loss by erosion, and greater problems with salinity and volatilization of ammonia. At the other extreme, dryland soils sometimes experience many of the phenomena associated with more humid environments—periods of excess water resulting in denitrification, leaching, water erosion, and related phenomena. Often, a dryland soil experiences limited periods of both excess water and severe water deficits within the same growing season, affecting nutrient cycling processes accordingly.

Good management of dryland soils mandates the use of practices that reduce evapotranspiration losses to the greatest extent possible, especially during vegetative periods of growth. Thus, a good dryland farmer strives to keep as much residue cover on the soil as possible to reduce evaporation and runoff

losses, as well as loss of nutrients through soil erosion. Such a farmer also times planting, cultivating, fertilizing, and other production practices to use most efficiently the limited water supply available. This farmer uses planting rates, row spacings, and cultivars that save as much water as possible for the grain-fill period. Likewise, such an individual controls fertilizer practices to avoid excessive vegetative growth, thereby reducing water stress during grain fill. However, if these practices are effective in conserving more water and, subsequently, providing greater potential for crop growth, the farmer must recognize that more available nutrients will be needed to support this increased growth. Integrating all of these variables into a productive farming enterprise is the mark of the successful dryland farmer.

References

Aase, J.K., and D.L. Tanaka. 1987. Soil water evaporation comparisons among tillage practices in the Northern Great Plains. Soil Sci. Soc. Am. J. 51:436-440.

Aguilar, R., E.F. Kelly, and R.D. Heil. 1988. Effects of cultivation on soils in Northern Great Plains rangeland. Soil Sci. Soc. Am. J. 52:1081-1085.

Alessi, J., and J.F. Power. 1982. Effects of plant and row spacing on dryland soybean yield and water-use efficiency. Agron. J. 74:851-854.

Amato, M., R.B. Jackson, J.H.A. Butler, and J.N. Ladd. 1984. Decomposition of plant material in Australian soils. II. Residual organic C^{14} and N^{15} from legume plant parts decomposing under field conditions. Austr. J. Soil. Res. 22:331-341.

Aulakh, M.S., D.A. Rennie, and E.A. Paul. 1984. Gaseous nitrogen losses from soils under zero-till as compared with conventional tillage-management systems. J. Environ. Qual. 13:130-136.

Black, A.L. 1973. Soil properties associated with crop residues in a wheat-fallow rotation. Soil Sci. Soc. Am. Proc. 37:943-946.

Black, A.L., and F.H. Siddoway. 1976. Dryland cropping sequences with a tall wheatgrass barrier. J. Soil Water Cons. 31:101-105.

Bond, J.J., and W.O. Willis. 1969. Soil water evaporation: Surface residue rate and placement effects. Soil Sci. Soc. Am. Proc. 33:445-448.

Boswell, F.C., J.J. Meisinger, and N.L. Case. 1985. Production, marketing, and use of nitrogen fertilizers. *In* O.P. Engestad (ed.). Fertilizer Technology and Use. pp. 229-292. Madison, Wisc.: Soil Sci. Soc. Am.

Bremer, E., R.J. Rennie, and D.A. Rennie. 1988. Dinitrogen fixation of lentil, field pea, and fababean under dryland conditions. Can. J. Soil Sci. 68:553-562.

Doran, J.W., and M.S. Smith. 1987. Organic matter management and utilization of soil and fertilizer nutrients. In: R.F. Follet, J.W.B. Stewart, and C.V. Cole (eds.). Soil Fertility and Organic Matter as Critical Components of Production Systems. pp. 53-72. Spec. Publ. No. 19. Madison, Wisc.: Soil Sci. Soc. Am.

Dormarr, J.F., C.W. Lindwall, and G.C. Kozub. 1988. Effectiveness of manure and commercial fertilizer in restoring productivity of an artificially eroded dark brown chernozemic soil under dryland conditions. Can J. Soil Sci. 68:669-679.

Greenwood, E.A.N., D.W. Goodall, and Z.V. Titmanis. 1965. The measurement of nitrogen deficiency in grass swards. Plant and Soil 23:97-103.

Gupta, V.V.S.R., and J.J. Germuda. 1988. Distribution of microbial biomass, and its

activity in different soil aggregate size classes as affected by cultivation. Soil Biol. Biochem. 20:777–786.

Haas, H.J., and C.E. Evans, and E.F. Miles. 1957. Nitrogen and carbon changes in Great Plains soils as influenced by cropping and soil treatment. USDA Tech. Bull. No. 1164. Washington, D.C.: U.S. Government Printing Office.

Halse, N.J., E.A.N. Greenwood, P. Lapins, and C.A. Boundy. 1969. An analysis of the effects of nitrogen deficiency on the growth and yield of a Western Australia wheat crop. Aust. J. Agric. Res. 20:987–998.

Heichel, G.H., and D.K. Barnes. 1984. Opportunities for meeting crop nitrogen needs from symbiotic nitrogen fixation. In: D.F. Bezdicek (ed.). Organic Farming: Current Technology and Its Role in a Sustainable Agriculture. Spec. Publ. No. 46. Madison, Wisc.: Amer. Soc. Agron. pp. 49–59.

Kissel, D.E., D.H. Sander, and R. Ellis, Jr. 1985. Fertilizer-plant interactions in alkaline soils. In: O.P. Engelstad (ed.). Fertilizer Technology and Use. Madison, Wisc.: Soil Sci. Soc. Am. pp. 153–196.

Lindsey, W.L., and P.L.G. Vlek. 1977. Phosphate minerals. In: J.B. Dixon and S.B. Weed (eds.). Minerals in Soil Environments. Madison, Wisc.: Soil Sci. Soc. Am. pp. 639–672.

Linn, D.M., and J.W. Doran. 1984. Aerobic and anaerobic microbial populations in no-till and plowed soils. Soil Sci. Soc. Am. J. 48:794–799.

Mielke, L.N., and J.S. Schepers. 1986. Plant response to topsoil thickness on an eroded loess soil. J. Soil Water Cons. 41:59–63.

Olson, T.C. 1977. Restoring the productivity of a glacial till soil after topsoil removal. J. Soil Water Cons. 32:130–132.

Power, J.F. 1971. The evaluation of water and nitrogen stresses on bromegrass growth. Agron. J. 63:726–728.

Power, J.F. 1983. Soil management for efficient water use: Soil fertility. In: H.M. Taylor, W.R. Jordan, and T.R. Sinclair (eds.). Limitations to Efficient Water Use in Crop Production. Madison, Wisc.: pp. 461–470.

Power, J.F. (ed.) 1987. The Role of Legumes in Conservation Tillage Systems. Ankeny, Iowa: Soil Cons. Soc. Am.

Power, J.F, J.J. Bond, F.M. Sandoval, and W.O. Willis. 1974. Nitrification in Paleocene shales. Science 1983:1077–1079.

Power, J.F., J.W. Doran, and W.W. Wilhelm. 1986. Uptake of nitrogen from soil, fertilizer, and crop residues by no-till corn and soybean. Soil Sci. Soc. Am. J. 50:137–142.

Power, J.F., G.A. Reichman, and D.L. Grunes. 1961. The influence of phosphorus fertilization and moisture on growth and nutrient adsorption by spring wheat: II Soil and fertilizer P uptake in plants. Soil Sci. Soc. Am. Proc. 25:210–213.

Rasmussen, P.E., and C.R. Rohde. 1988. Long-term tillage and nitrogen fertilization effects on organic nitrogen and carbon in a semiarid soil. Soil Sci. Soc. Am. J. 52:1114–1117.

Smika, D.E., H.J. Haas, and J.F. Power. 1965. The effects of moisture and nitrogen fertilizer on growth and water use by native grass. Agron. J. 57:483–486.

Tanaka, D.L., and J.K. Aase. 1989. Influence of topsoil removal and fertilizer application on spring wheat yields. Soil Sci. Soc. Am. J. 53:228–232.

Taylor, H.M. 1983. Managing root systems for efficient water use: An overview. In: H.M. Taylor, W.R. Jordan, and T.R. Sinclair (eds.). Limitations to Efficient Water Use in Crop Production. Madison, Wisc.: Am. Soc. Agron. pp. 87–114.

Unger, P.W., and T.M. McCalla. 1980. Conservation tillage systems. Adv. Agron. 33:1–58.

Wilhelm, W.W., J.W. Doran, and J.F. Power. 1986. Corn and soybean yield response to crop residue management under no-tillage production systems. Agron. J. 78:184–189.

Woods, L.E., and G.E. Schuman. 1988. Cultivation and slope position effects on soil organic matter. Soil Sci. Soc. Am. J. 53:1371–1376.

Water-Use Efficiency*

B.A. Stewart and J.L. Steiner

I. Introduction 151
II. Seeding Rate and Planting Geometry 152
III. Crop Calendars 155
IV. Crop Selection and Germplasm Enhancement 164
V. Water Management 166
VI. Soil Fertility 168
VII. Research Needs for Improved Water-Use Efficiency 169
References 170

I. Introduction

Dryland farming is a rainfed crop production system in which the major limitation is a deficiency of water. Therefore, a major focus of dryland cropping systems is increasing efficiency of water use. Relatively few, but very important, principles underlie the farming practices that can lead to efficient water use. A maximum proportion of available water should be used for transpiration with minimum losses to evaporation, drainage, and runoff. Basically, that involves maintaining soil characteristics favorable to rapid infiltration of precipitation and retaining the water in the soil profile, cropping at a time and with a rooting intensity appropriate to use both seasonal precipitation and stored soil water, and establishing and extending a crop canopy as long as practical to minimize evaporation.

Considerable research has been done on water-use efficiency, and many papers and reviews have been written. The subject was thoroughly covered in a recent

*Contribution from USDA, Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, Texas.

1990 by Springer-Verlag New York Inc.
Advances in Soil Science, Volume 13

Previous Page Blank

book edited by Taylor et al. (1983). In spite of the many writings on the subject, there is great confusion over the use of the term *water-use efficiency*. Therefore, before we discuss specific practices and systems that can affect water-use efficiency, it is important to define the term within the context that it will be used in this review. "Water-use efficiency" (WUE) has been used by researchers to describe vastly different processes, ranging from plant physiologists reporting gas exchange by individual leaves for a few minutes to agronomists measuring grain yield response to irrigation treatments for an entire season. Sinclair et al. (1984) tried to clarify the significant variables that are common and different among various users. They defined WUE as a ratio of biomass accumulation, expressed as carbon dioxide assimilation (A), total crop biomass (B), or crop grain yield (G) to water consumed expressed as transpiration (T), evapotranspiration (ET), or total water input to the system (I). The time scale for defining water use can be instantaneous (i), daily (d), or seasonal (s). They suggested that water-use efficiency be written symbolically as a function of these three variables. For example, WUE(G,ET,s) would refer to the ratio of grain yield to evapotranspiration measured over the defined season, and WUE(A,T,i) would refer to the ratio of carbon dioxide assimilation to transpiration for an instantaneous observation. This format is used throughout this discussion.

Sinclair et al. (1984) listed five options for improving water-use efficiency relating to (1) biochemical alterations, (2) stomatal physiology, (3) alteration of the cropping environment, (4) improved harvest index, and (5) increased proportion of transpired water. They concluded, however, that most of these alternatives have serious limitations or drawbacks. In their summary, they stated "For water-limited environments, a greater potential apparently exists for improving water-use efficiency. But the reality remains that without additional water, these areas cannot be expected to become regions of high crop yields. Irrigation and full exploitation of humid climates are seemingly of highest priority in attempting to increase food production in view of the conservative nature of crop water-use efficiency." Although we agree in principle with their conclusion, it is also a reality that an increasing portion of the world's future food grains will have to be produced in water-deficient areas because of an expanding population in these areas. Because water resources for irrigation are often not available, costs for developing new irrigation projects are rapidly increasing, and high costs are associated with irrigated agriculture in general, people in many regions of the world will depend largely on dryland agriculture for their subsistence. In our presentation, we will primarily discuss practices that relate to the last three options presented by Sinclair et al. (1984).

II. Seeding Rate and Planting Geometry

In dry climates, annual cereals such as wheat (*Triticum aestivum* L.), as well as summer row crops like grain sorghum [*Sorghum bicolor* (L.) Moench], are generally seeded at relatively low rates. This is done with the expectation that wider

spacing of the plants will lead to water being conserved for use in the later part of the season, thereby increasing the harvest index (ratio of grain weight to total plant weight) and resulting in higher grain yields. There is ample evidence that wider spacing of plants will increase harvest index (Steiner, 1986). However, corresponding grain yield increases do not always occur because total dry matter production is often lower when plant density is lowered. The lower total dry matter production is generally due to less soil water extraction by the low-plant-density crop. Choosing the optimum plant population and width of row spacing continues to be one of the most difficult challenges for dryland producers. Either too high or too low plant densities can reduce grain yields because high densities use too much of the available soil water early in the season, and low densities do not fully exploit the available soil water for the complete season.

In general, stored soil water is more fully utilized at higher plant densities, resulting either from higher plant populations or decreased row spacings. The data in Table 1 clearly show that either increasing plant density or decreasing the width between rows resulted in increased soil water extraction by grain sorghum, and this was particularly true between times of emergence and heading. Although more water was available in the wide rows or low plant population treatments for use during the period between heading and maturity, much of this potential gain was lost because the water was not fully extracted. The yield data from the study (Steiner, 1986) showed that the highest population significantly reduced grain yield because of a severe decrease in harvest index, but there was no difference in grain yields between the low and medium populations because the total dry matter yield of the medium population treatment was increased enough over that of the low population treatment to offset the slightly higher harvest index for the low population treatment. Brown and Shrader (1959) also found that increasing plant populations resulted in greater extraction of stored soil water by grain sorghum.

The data in Table 2 are somewhat similar to that discussed earlier in that the low-density seeding of wheat extracted less soil water than the medium density. However, these data saggest that when the seeding density is exceptionally high, soil water extraction can also be reduced, presumably because the crop dries out the upper part of the soil profile before an adequate root system can be established. In this latter example, the plant density in the high treatment was almost 24 times greater than the low-density treatment. The grain yields (Walter and Barley, 1974) were 280, 420, and 370 g m^{-2} for the L, M, and H plant densities, respectively. This again illustrates that densities either too high or too low can reduce yields significantly and also influence the amount of water extracted from the soil. Walter and Barley (1974) concluded that, irrespective of seeding rate, the crop failed to withdraw water efficiently from the lower part of the root zone. Comparison of the observed and theoretically attainable rates of uptake of the deeper water led them to suggest that after anthesis, at high rates of seeding, the major resistance to the extraction of the deeper water was located in the soil. At the lowest rate of seeding, the major resistance appeared to have been located within the root system.

Table 1. Effect of plant population and row spacing on dry matter yield, harvest index and deep (>0.9 m) and shallow (<0.9 m) soil water extraction by grain sorghum. Bushland, Texas, 1983[a]

			Soil water extraction								
	Total dry matter	Harvest	Emergence to heading (mm)			Heading to maturity (mm)			Total season (mm)		
	(Mg ha^{-1})	index	≤0.9 m	>0.9 m	Total	≤0.9 m	>0.9 m	Total	≤0.9 m	>0.9 m	Total
38[b]	5.3	0.38	75	11	86	30	19	49	105	30	135
76L	5.7	0.45	59	9	68	44	11	55	103	20	123
38M	6.4	0.39	85	15	100	27	21	48	112	36	148
76M	6.1	0.34	67	14	81	46	6	52	113	20	133
38H	6.2	0.25	98	17	115	28	14	42	126	31	157
76H	6.0	0.28	73	7	80	37	17	54	110	24	134

[a] From unpublished data, J.L. Steiner.
[b] L, M, H = low, medium, and high plant populations corresponding to 6.9, 13.1, and 18.6 plants m^{-2}, respectively; 38 and 76 represent 0.38- and 0.76-m spacing between rows, respectively.

Table 2. Evapotranspiration and soil water extraction by wheat in Australia[a]

Plant density	Evapotranspiration (mm) 0–54 days	55–91 days	92–140 days	141–154 days	Total	Soil water extraction
L[b]	64	74	186	15	339	76
M	49	126	181	20	376	113
H	54	109	191	7	361	98

[a]Calculated from data in Table 1, Walter and Barley (1974).
[b]L, M, H = 20, 90, and 470 seedlings m^{-2}, respectively.

Although the examples cited clearly show that both the harvest index and amount of soil water extracted can be affected by crop geometry, the data suggest that there is a fairly wide range before grain yields are seriously affected. The best approach seems to be to select a moderate combination of row width and plant populations, and only in extremely dry years or extremely wet years is there a significant loss in grain yield. Based on many studies at our laboratory, a spacing of 0.75 to 1 m between rows and a population of 6 to 10 plants m^{-2} appears satisfactory for dryland grain sorghum production in the southern high plains of the United States.

III. Crop Calendars

Traditional cropping patterns have evolved, in part, to match the growing patterns of common crops to average climatic patterns. However, many other factors besides climatic limitations to growth have determined the evolution of commonly used crop calendars, such as labor limitation, conflicting demands for inputs, unavailability of desirable crops or genotypes, lack of markets, and others. If these constraints can be alleviated, then crop calendars can be designed to more efficiently exploit the climatic potential. Objectives of designing an efficient crop calendar might include shifting cropping seasons to cooler, more humid periods of the year to improve the transpiration efficiency, sowing to avoid probable stress periods during anthesis of the crop, or manipulating the ratio of early-season to late-season water use.

A system developed at the International Crops Research Institue for the Semi-Arid Tropics for deep Vertisols in India (El-Swaify et al., 1985) greatly improves water-use efficiency. Traditionally, farmers crop these soils only during the post-monsoon season on soil water stored in the profile. This system involves little economic risk, but the soil is left bare and unprotected from highly erosive rains during the monsoon season. The improved watershed-based system allows both rainy season and post-rainy season cropping of Vertisols in medium to high and dependable rainfall areas—that is, those receiving 750 to 1250 mm per year with more than 70% probability that 10 mm per week of rain will be received for half

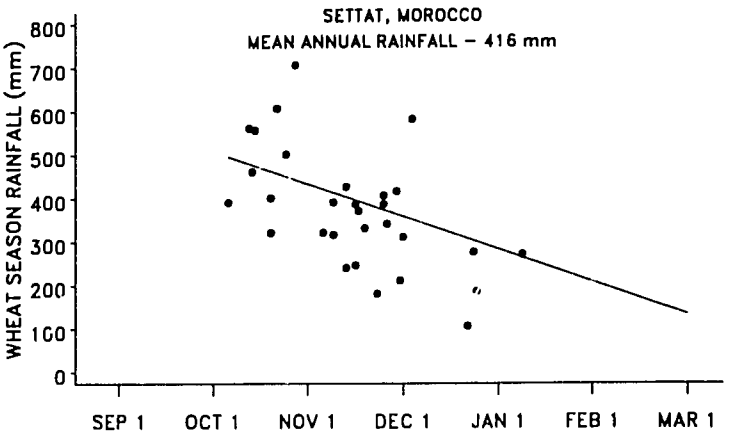


Figure 1. Decline of wheat season rainfall with late onsets of rainy seasons (adapted from Stewart, 1989a).

the weeks of the rainy season (Virmani et al., 1978). This system greatly increases water-use efficiency and crop yields while significantly reducing soil erosion.

Crops that are under stress have been reported to have a lower carbon-to-water flux rate on an instantaneous basis. These reports were based on studies using micrometeorological techniques over soybeans (Baldocchi et al., 1985) and a leaf chamber technique on sorghum (Steiner, 1987). The efficiency of conversion of intercepted energy to dry matter was reduced by 24% in pearl millet (*Pennisetum typhoides*), which was grown under water-stressed, high-vapor-pressure deficit conditions, compared to well-watered, low-vapor-pressure deficit conditions (Squire et al., 1986), also indicating a reduced water-use efficiency under stress conditions. Because the efficiency with which water is used decreases when plants undergo stress, it is important to develop crop calendars that minimize the risks of crop stress.

An example of using historical data to reduce the risk of farming in a highly variable climate was developed by Stewart (1985), who identified correlations between the date of onset of the rainy season to total seasonal rainfall in the monsoon climate of eastern Africa, which allows a farmer to determine fairly early in the growing season the probable conditions for that year's crop. Analysis of climatic records from the Mediterranean climatic zone in North Africa (Stewart, 1989a), the Near East (Stewart, 1989b), and India (Stewart, 1988) show that the technique has promise for a wide geographic range. The data in Figure 1 from Morocco illustrate the decline of growing season rainfall with late onset of the rainy season. Stewart (1985) developed the "response farming" system around the concept that decisions on choice of crop, plant populations, mineral fertilizers, and other inputs should be based on the beginning date of the rainy season. Early onset indicates increased probability of higher total rainfall; so longer season crops, higher plant populations, and higher rates of mineral fertilizers

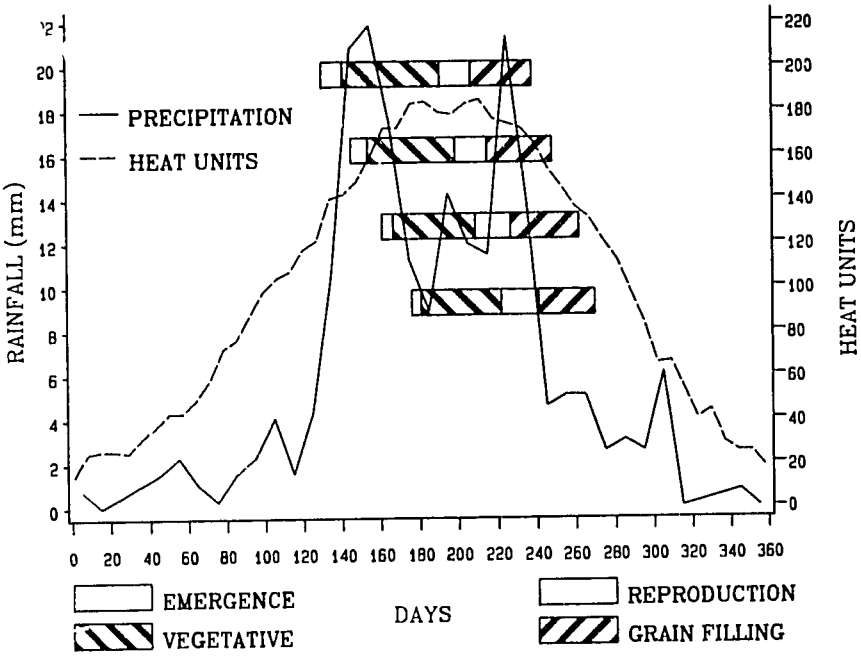


Figure 2. Weekly heat units (above 0°C) exceeded in 50% of the years and 10-day precipitation amounts exceeded in 50% of the years for the USDA Conservation and Production Research Laboratory, Bushland, Texas. The boxes represent grain sorghum seeded at four different dates.

should be used. Conversely, the probability of high seasonal rainfall is very low when the rainy season begins quite late; and a different set of decisions are warranted, often the opposite of those just discussed.

A somewhat similar system, called "opportunity cropping," is used by farmers in the U.S. Great Plains. Typical cropping systems involve a fallow period to increase the soil water content before a dryland crop is planted. However, if late season rains result in favorable soil water storage levels at time of harvest, another crop might be planted without allowing for a fallow period.

In many regions, there is a wide range of possible sowing dates for most crops that are grown. In extremely variable climatic regions such as the U.S. Great Plains, it is virtually impossible to determine in short-term field trials which sowing date would provide the most favorable growth over a long period of time. A rather simple approach to matching a cropping pattern to climate is shown for grain sorghum at Bushland, Texas, in Figure 2 The solid line represents the 10-day rainfall amounts exceeded in 50% of the years, and the dashed line represents the number of weekly heat units (degrees Celsius above 0) exceeded in 50% of the years. Constraints for grain sorghum growth include cool spring and fall temperatures, late spring frosts, early fall frosts, low springtime rainfall, and

Table 3. Rainfall, average Potential Evapotranspiration (PET), and Moisture Availability Index for 95-day periods after various emergence dates for grain sorghum at Bushland, Texas (1939–1986)

	Emergence date					
	5-17	5-24	5-31	6-07	6-14	6-21
Rainfall (mm)						
Minimum observed	88	90	56	59	43	43
75% probability, >	147	164	148	138	138	144
50% probability, >	214	216	210	194	182	175
25% probability, >	273	284	262	246	223	229
Maximum observed	480	484	474	487	423	425
Averaged observed	223	228	216	208	194	191
PET[a]						
Average	715	712	708	700	690	679
Moisture Availability Index (Rainfall/PET)						
Minimum observed	.12	.13	.08	.08	.06	.06
75% probability, >	.21	.23	.21	.20	.20	.21
50% probability, >	.30	.30	.30	.28	.26	.26
25% probability, >	.38	.40	.37	.35	.32	.34
Maximum observed	.67	.68	.67	.70	.61	.63
Averaged observed	.31	.32	.30	.30	.28	.28

[a] Based on 1958–1985 climatic data using Penman Equation (Doorenbos and Pruitt, 1977).

high temperatures in midsummer. Climatic characteristics that favor grain sorghum growth are reasonably reliable rains in late May and mid-August. The rectangular boxes represent a crop of grain sorghum planted at four different times. The four divisions within each period represent the emergence, vegetative, reproductive, and grain-filling stages of crop production.

As indicated in Figure 2, grain sorghum can be seeded in the Bushland, Texas, area over a fairly wide time period. Quinby et al. (1958) reported that the favorable seeding season in the area begins about May 15 but that higher yields of grain are produced from plantings made from June 10 to June 25. They stated that it is not safe to depend on retaining sufficient soil moisture for seeding later than June 20 in the area. A study of the rainfall probabilities, however, shows that growing season precipitation is higher for early seeded grain sorghum than for late seeded grain sorghum. Table 3 shows the probabilities for rainfall for 95-day periods following various grain sorghum emergence dates. The 95-day period is the approximate time required for growth of a dryland grain sorghum crop in the southern Great Plains after emergence. The data clearly show that growing season rainfall decreases with time after about May 24. However, there is also a decrease in the seasonal potential evapotranspiration. Since both values decrease, the moisture availability index values shown in Table 3 (growing season rainfall/growing season potential evapotranspiration) do not change sharply, but

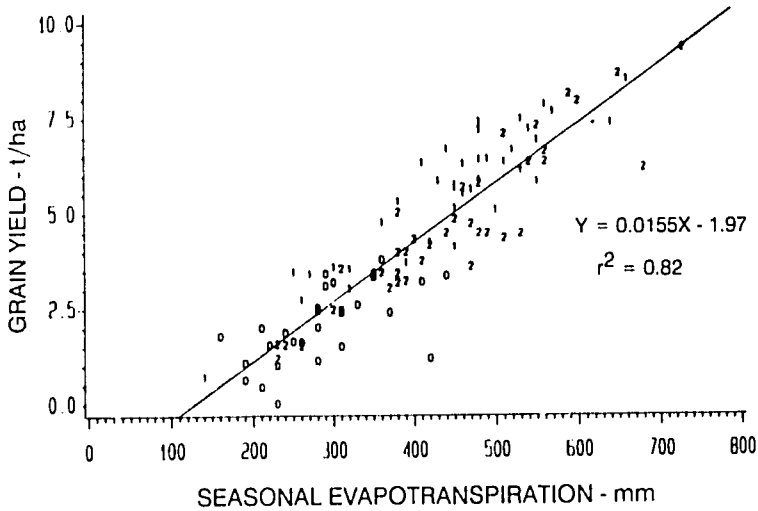


Figure 3. Relationship between yield of grain sorghum and seasonal evapotranspiration of the USDA Conservation and Production Research Laboratory, Bushland, Texas (0 – unpublished data, O.R. Jones; 1 – Musick and Dusek, 1971; 2 – Stewart et al., 1983).

there is a downward trend with delayed emergence times. This suggests that an earlier seeding date would be more desirable than a later date, which is contrary to the recommendations by Quinby et al. (1958). Current researchers in the area also favor a later seeding date (personal communication, O. R. Jones, USDA Conservation and Production Research Laboratory, Bushland, Texas). One factor that favors a later seeding date is that the plant-available stored soil water is usually increased by a delay in the seeding date. A large supply of stored available soil water is essential in most years to ensure an economic grain yield.

Figure 3 illustrates the relationship between grain yield and seasonal ET based on field results obtained from several studies over a number of years at Bushland, Texas. Based on this relationship, no grain is produced unless ET exceeds 127 mm. The rainfall probabilities presented earlier in Table 3 show that growing season rainfall for grain sorghum emerging on June 14 averages only 194 mm and that it is below 182 mm 50% of the years. The relationship clearly shows the importance of having a substantial amount of stored soil water at seeding time to supplement the growing season rainfall for supplying the water needs of the crop. The relationship shown in Figure 2 suggests that for every millimeter of ET above the threshold value of 127 mm, approximately 15 kg ha^{-1} of grain is produced. Consequently, predicted grain yields based on the relationship in Figure 2 differ greatly depending on the amount of stored soil water at seeding time. For example, if the soil water storage at seeding was essentially zero at the time of seeding, the anticipated yield of grain for grain sorghum seeded on June 14 would be less than 850 kg ha^{-1} for 50% of the years. This value was obtained by using the

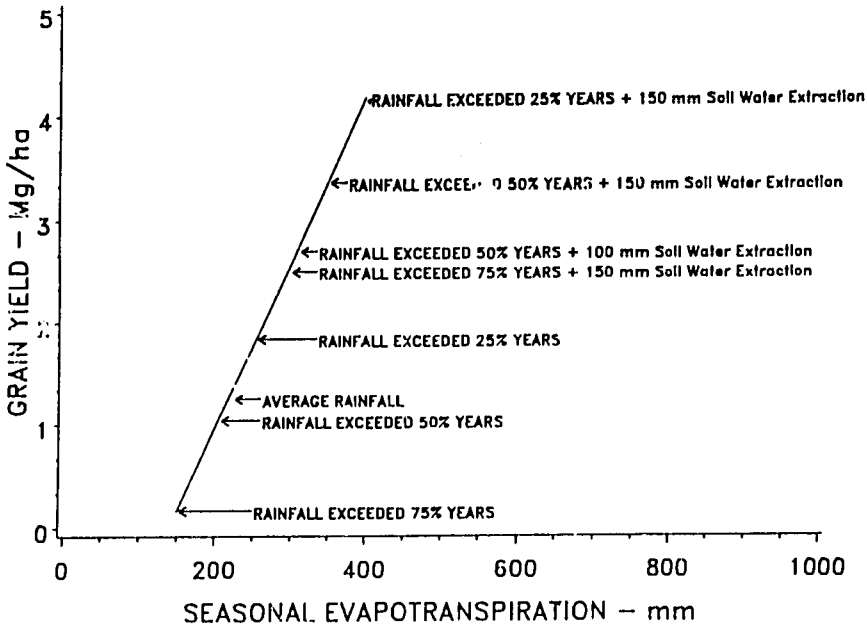


Figure 4. Anticipated sorghum grain yields for Bushland, Texas, that would be exceeded under various conditions, based on 95-day growing season rainfall probabilities beginning June 7 and assumed soil water storage at time of seeding.

182-mm rainfall probability from Table 3 and solving the relationship $Y = 0.0155X - 1.97$ shown in Figure 3.

Assuming that in addition to the growing season rainfall 100 mm of stored soil water was used for evapotranspiration, the anticipated yield would be 2400 kg ha^{-1}. Several soils of the region can store 150 mm or more of plant-available soil water in the profile, so the importance of having a high level of stored soil water at seeding time is readily apparent. Using the relationship illustrated in Figure 3 as a simple yield prediction model, reasonable yield projections for certain rainfall probabilities and stored soil water at seeding time can be made. Figure 4 illustrates the yield levels that might be exceeded under various conditions, based on 95-day growing season rainfall probabilities beginning June 7 shown in Table 3. For example, if the plant available soil water at seeding time is very low and the crop must depend entirely on growing season rainfall for meeting evapotranspiration needs, the projected yield of grain would be less than 1 Mg ha^{-1} for 50% of the years. A yield of 2 Mg ha^{-1} or greater could be anticipated only in years when the growing season rainfall was in the wettest 25% of the years. On the other hand, if sufficient soil water is stored at time of seeding to supply 150 mm of water for evapotranspiration to supplement the growing season rainfall, then a yield in excess of 2.5 Mg ha^{-1} could be anticipated 75% of the years.

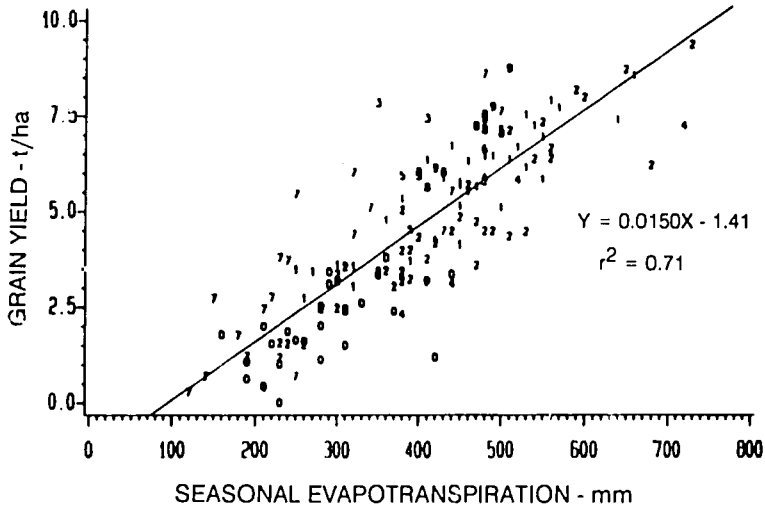


Figure 5. Relationship between yield of grain sorghum and seasonal evapotranspiration for various locations (0 – unpublished data, O.R. Jones, Texas; 1 – Musick and Dusek, 1971, Texas; 2 – Stewart et al., 1983, Texas; 3 – Owonubi and Kanemasu, 1982, Kansas; 4 – Bielorai et al., 1964, Israel; 5 – Howell and Hiler, 1973, Texas; 6 – Stewart et al., 1975, California; 7 – Seetharama et al., 1982, Compilation of India studies; 8 – Stone et al., 1978, Kansas; 9 – Chaudhuri and Kanemasu, 1982, Kansas).

The relationship between grain yield and seasonal evapotranspiration shown in Figure 5 is similar to the one shown in Figure 3. All of the data used in Figure 3 are included in Figure 5, but Figure 5 also includes data from other semiarid locations in the United States and other countries. These relationships suggest that for every millimeter of evapotranspiration, approximately 15 kg ha^{-1} of grain will be produced. The amount will, of course, vary somewhat with location and year because of the differences in climate, primarily vapor pressure deficit; but this gives a first approximation for the value of additional water used during the growing season.

The use of computer crop models holds promise for looking at the effect of seeding date on yield because this allows one to look at many years, which is simply not feasible with field experiments. We used SORKAM (Rosenthal et al., 1989), a sorghum growth model, to simulate how the seeding dates represented in Figure 2 would affect the growth and water use of grain sorghum over a 28-year climatic record at Bushland, Texas. It must be recognized, however, that in dryland farming it is not always possible to seed on a specific date. Seeding is performed when soil water contents near the surface will provide water for germination. The model was run assuming that the plant-available soil water on April 1 of each year was, in one case, 50% and, in the other case, 100% of field capacity. The preliminary and unpublished results are summarized in Table 4. The average

Table 4. Yield and water balance prediction by SORKAM Crop Model for four grain sorghum seeding dates, Bushland, Texas, 1958–1984

	May 10	May 25	June 10	June 25
	Intermediate soil water storage on April 1			
Grain yield (Mg ha^{-1}	3.4	3.4	3.5	3.5
Soil water at seeding (mm)	97	101	112	121
Growing season rainfal (mm)	264	254	235	217
Growing season potential ET (mm)	826	790	659	740
	High soil water storage on April 1			
Grain yield (Mg ha^{-1}	4.0	4.1	4.2	4.0
Soil water at seeding (mm)	177	176	181	181
Growing season rainfall (mm)	262	257	235	221
Growing season potential ET (mm)	818	788	761	743

Source: unpublished results.

yields were similar for all four seeding dates, although there was a slight trend in favor of the later seeding dates when the soil water storage on April 1 was at the intermediate level and in favor of the middle seeding dates when the soil water storage values were high on April 1. The average yields shown represent 28 individual years. The individual values for all years, seeding dates, and stored soil

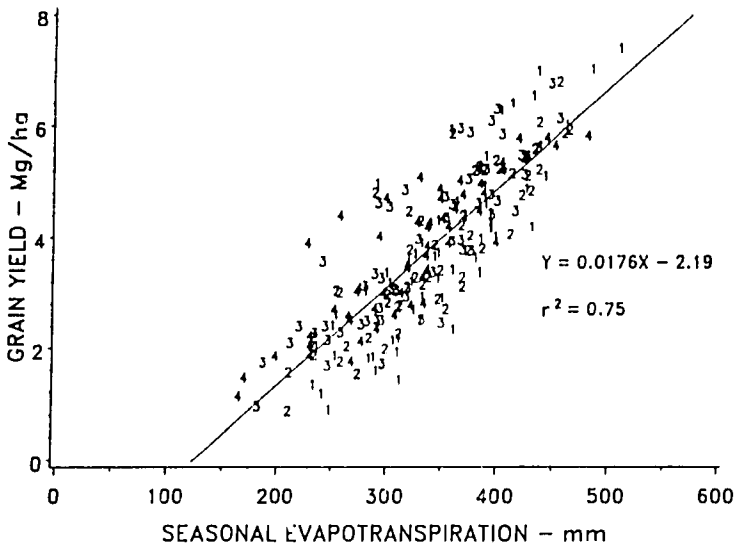


Figure 6. Relationship between sorghum grain yields and seasonal evapotranspiration simulated by SORKAM (Rosenthal et al., 1989) for 28 years of climatic data at Bushland, Texas. The model was run for four seeding dates (1 – May 10; 2 – May 25; 3 – June 10; and 4 – June 25) and two stored soil water levels for each year.

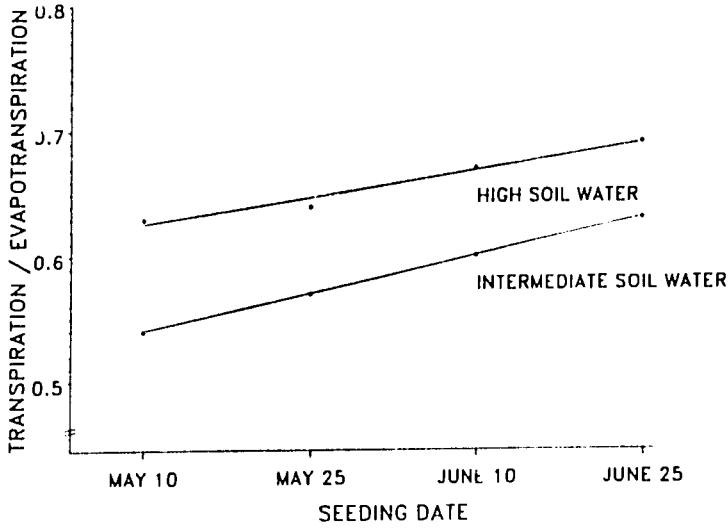


Figure 7. Simulated data showing the effects of seeding date and soil water storage at seeding time on the proportion of seasonal evapotranspiration used as transpiration.

water levels are shown in Figure 6. The grain yield values were plotted as a function of seasonal evapotranspiration values so the relationship based on the data simulated by the SORKAM model could be compared to actual field data presented earlier in Figure 3. The relationship of the simulated data, $Y = 0.0176$ ET $- 2.19$, compares very closely with the relationship of $Y = 0.0155 - 1.97$ found with the field data. This indicates that the data simulated by the model were very realistic. The 10 to 15% higher yields the model predicted are certainly reasonable and can perhaps be explained by the fact that actual yields were often reduced by insects, disease, hail, and harvest losses.

As discussed earlier in relation to Table 3, the growing season rainfall is significantly higher when grain sorghum is seeded in May than when it is seeded in June. The summary results of the model reported in Table 4 also clearly show this. There are two apparent reasons why the increase in growing season rainfall did not result in higher yields. The first is that the growing season potential evapotranspiration is also higher for early seeded grain sorghum. A second reason is that the model simulations show significant differences in the ratios of transpiration to evapotranspiration for the various seeding dates and soil water levels at time of seeding. These data, shown in Figure 7, indicate that a considerably higher percentage of the total evapotranspiration was lost as evaporation for the early than for the later seeded grain sorghum. There was also a lot higher loss from evaporation when grain sorghum was seeded into a soil with an intermediate soil water storage level than when seeded into a soil with a high soil water storage level. This suggests that plant canopies formed quicker when they were planted later in the season, particularly when seeded into a soil containing a high level of stored soil water. These

findings suggest that cultivars which grow better at lower temperatures might use the greater amounts of growing season rainfall that occur when grain sorghum is seeded early more efficiently because they would develop a plant canopy more quickly. Also, mulches that decrease evaporation from the soil surface would be very valuable (Unger et al., 1986), particularly when grain sorghum is seeded early. However, Gardner and Gardner (1983) state that mulches are of only limited effectiveness because they retard but do not eliminate evaporation. The results obtained in a field study by Unger and Jones (1981) also suggest that mulches present during the growing season have only a relatively small positive effect on reducing evaporation from the soil surface during the growing season. However, small increases in transpiration can be very important because the relationships shown in Figures 3, 5, and 6 indicate that for every additional millimeter transpiration, 15 or more kg ha^{-1} of grain is produced. The evaporation component of the evapotranspiration would be essentially contained in the intercept portion of the figures (Gardner and Gardner, 1983).

Extensive examples using sorghum illustrate the complexities of planting date analyses. A major cool season crop (winter or spring wheat) has equally complex responses to planting date. In numerous studies, delayed planting past a site-specific, optimum date has been shown to reduce grain yields by about 4 to 7% per week (Doyle and Fischer, 1979; French and Schultz, 1984a; Khalifa et al., 1977; and Thill et al., 1978). Doyle and Fischer (1979) attributed the yield reduction associated with delayed planting to reduced transpiration efficiency under the higher temperature regimes encountered later in the season. Musick and Porter (1990) attributed the yield reductions in late planted wheat to inadequate tillering and suggested that higher seeding rates could offset much of the negative impact of late seeding. In regions where stored soil water provides a major component of seasonal ET, early planting can lead to excessive depletion of soil water in the fall, resulting in crop stress during spring regrowth (Kolp et al., 1973). Knapp and Knapp (1978) reported increased winterkill of wheat planted late in the fall. However, early seeding can result in lush fall growth, making the crop susceptible to freeze damage. In areas such as the Great Plains of the United States, where winter wheat is used for cattle grazing during the vegetative growth, early planting increases the production of grazable forage.

IV. Crop Selection and Germplasm Enhancement

Many factors interact to influence the yield of a crop. It is generally recognized that crop selection and choice of cultivar are among the most important management factors. The yield potential of cultivars of some of the major crops has increased significantly over time. Sorghum, wheat, and cotton (*Gossypium hirsutum* L.), major crops grown under dryland conditions in the United States and worldwide, have been the subjects of intensive plant breeding programs. The Crop Science Society of America (Fehr, 1984) held a symposium that assessed

the genetic contributions to yield gains of sorghum, maize (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], cotton, and wheat.

From 1950 to 1980, the sorghum grain yield in the United States increased at an annual rate of 7% (Miller and Kebede, 1984). Grain yield increased by 11% from 1950 to 1960, 4% from 1961 to 1970, and 2% from 1971 to 1980. The discovery of cytoplasmic male sterility which led to hybrids, selection for disease and insect resistance, and improved cultural practices contributed to these gains. Miller and Kebede (1984) stated that harvest index (relative partitioning of assimilate to economic yield) had not changed significantly, indicating that yield gains were due to increased total biomass rather than to increased partitioning efficiency. They concluded that about 40% of the yield increase from 1950 to 1980 could be attributed to genetic improvements.

Wheat yields in the United States increased from a 3-year average for 1958 to 1960 of 1700 kg ha^{-1} to an average of 2200 kg ha^{-1} for 1978 to 1980, or 32% (Schmidt, 1984). Schmidt attributed approximately half of this yield gain to breeding. Unlike with grain sorghum, some of the yield increase for wheat has been due to an increase in the harvest index. Improved wheat cultivars have increased spike size and fertility and improved straw strength and grain-to-straw ratios.

Plant breeding will continue as a major focal point for increasing crop yields, but major breakthroughs for increasing water-use efficiency have been elusive. Blum (1979) presented a physiological basis for breeding for drought resistance in sorghum crops, which aims to maintain productivity of the crops under water-limited conditions. Blum (1983) also discussed the potential for breeding plants to produce under the constraints from a variety of environmental stresses such as drought, heat, chilling, mineral deficiencies, or toxicities. Genetic improvement that allows the crop to maintain productivity under unfavorable conditions will enhance water-use efficiency.

Van Staveren and Stoop (1985) presented an interesting analysis of fitting improved genetic sorghum lines into traditional cropping systems. Traditional systems have evolved in Burkina Faso, where farmers seed millets on dry upland slopes, sorghum on midslopes, maize on the low moist slopes, and rice (*Oryza sativa* L.) in lowlands. When introducing improved cultivars into the region, Van Staveren and Stoop (1985) concluded that no single technological package could satisfactorily replace local practices. Instead, there was a need to fit specific genetic material and practices into specific environments which exist across a toposequence in west Africa.

Heichel (1983) stated that relatively few attributes directly associated with efficiency of water use are known to be under genetic control. Stomatal size, density, and behavior, as well as depth and pattern of rooting, are heritable characteristics in a number of species. Leaf dimension, leaf angle, and crop maturity can also be controlled genetically. Therefore, breeding crops for more efficient water use is a very complex undertaking, and gains will likely be slow in coming. The most significant gains from plant breeding in the relatively short term will likely continue to be in increasing harvest index. Although the harvest index of

Table 5. Water balance for wheat–fallow–sorghum cropping system at Bushland, Texas

	Wheat	Fallow[a]	Sorghum	Fallow[a]	Total
Precipitation	256	462	241	416	1375
Evapotranspiration	329	–	286	–	615
Runoff	13	25	27	43	108
Soil water change	−86	86	−72	72	–
Evaporation		351		301	652

Sources: From O.R. Jones, personal communication, Johnson and Davis (1972).
[a]Fallow periods between crops are about 11 months.

grain sorghum has not been altered by genetics directly as in the case of wheat, it has been indirectly increased by the development of shorter-season cultivars that complete their life cycles and produce a grain crop before the available water is exhausted.

Plant breeding for disease and insect resistance, as well as for tolerance to difficult soils such as saline or high-aluminum soils (Wright, 1977), also holds promise for dryland areas. The fact remains, however, that the genetic potential of crops is generally not the first limiting factor in dryland production, and improved cultivars will not produce at their potential levels unless adequate water management and soil fertility practices are implemented.

Crop selection, in terms of both species and cultivar, should be based on the probability of rainfall and stored soil water being available to produce a satisfactory yield. Choosing a crop that matures too quickly will result in a low WUE(G,I,s) because a significant portion of the seasonal rainfall is not used. The choice of too long a crop can be even more disastrous if the water supply is depleted before the grain part of the crop can be produced, resulting in a very low harvest index.

In areas where water is occasionally stored deep in the soil profile, a deep-rooted crop may be planted periodically to extract the deep soil water. Bremner et al. (1986) showed that sunflower (*Helianthus annuus*) extracted 92% of the total available soil water in a 2-m profile, compared to 64% extracted by grain sorghum. In southern Australia, where the experiment was conducted, sunflower was recommended as an "opportunity" crop to be planted only when there is water deep in the profile.

V. Water Management

Water-use efficiency (G,I,s) can be maximized only by managing the precipitation over the entire year. Research data and farmer experience in North America suggest that four conditions are necessary to improve water conservation, crop production, and erosion control in dryland systems: (1) effective weed control; (2) maintenance of adequate surface residues to reduce evaporation, control ero-

Table 6. Net soil water gain at the end of fallow as influenced by straw mulch rates at four Great Plains locations

Location	Number of years reported	Soil water gain (cm) at various mulch rates (t/ha)			
		0	2.2	4.4	6.6
Bushland, TX	3	7.1	9.9	9.9	10.7
Akron, CO	6	13.4	15.0	16.5	18.5
North Platte, NE	7	16.5	19.3	21.6	23.4
Sidney, MT	4	5.3	6.9	9.4	10.2
Average		10.7	12.7	14.5	15.7
Gain by mulching			2.0	3.8	5.0

Source: From Greb et al., 1979.

sion, and trap snowfall in some areas; (3) retention of hard clods 1 to 8 cm in diameter on soil surface, especially when surface residues are limited, to resist wind erosion, slow runoff water, anchor mulches, provide shade, and physically protect small plants; and (4) management of soil to retain enough water in the seedbed for seed germination (Greb et al., 1979).

Even systems that successfully produce these conditions can be quite inefficient in terms of total water-use efficiency. An excellent 28-year water balance (Table 5) for a wheat-fallow-sorghum cropping system on Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll) has been compiled at Bushland, Texas (Stewart and Burnett, 1987). This cropping system produces two crops in 3 years, with 11-month fallow periods between crops. Evapotranspiration during the growing season is directly proportional to crop yields, but only 45% of the total precipitation was used in this manner. Approximately 47% of the precipitation was lost by evaporation during the fallow periods, and 8% was lost by runoff. El-Swaify et al. (1985) presented water balance data for traditional cropping systems for a Vertisol and an Alfisol at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in India. In both cases, only about 40% of the total rainfall was used for evapotranspiration during the growing season, and more than 25% was lost as runoff. An improved management system for Vertisols developed at ICRISAT (El-Swaify et al., 1985) allows both rainy season and post-rainy season cropping, thereby dramatically increasing the WUE(G,I,s).

Management practices that reduce runoff or decrease evaporation can be very beneficial for improving WUE(G,I,s). Recent studies in the Great Plains of the United States have focused on reducing tillage as a means to retain more residue on the surface and increase fallow efficiency. In some areas, complete no-till systems are practiced. The studies have clearly shown that surface residues result in more water being stored in the soil for use by crops. Table 6 summarizes the research data from four locations and shows that soil water storage during fallow increased markedly with increasing amounts of straw left on the surface as a mulch.

Increased soil water storage in dryland areas generally results in significant yield increases. In the northern Great Plains of the United States, about 16 kg ha^{-1} of wheat grain can be expected for each additional millimeter of stored soil water at seeding. Because of increased vapor pressure deficits from north to south in the Great Plains, less grain can be expected in the southern areas. About 12 kg ha^{-1} of wheat grain can be expected from an equivalent amount of stored soil water in the central Great Plains, and about 6 kg ha^{-1} of wheat grain or 15 kg ha^{-1} of sorghum grain in the southern Great Plains. The chapter in this volume on Conservation Tillage Systems by P. W. Unger discusses more fully the beneficial effect of straw mulches for increasing infiltration and decreasing evaporation.

Furrow dams, synonymous with tied ridges, can be very effective for reducing runoff, thereby increasing WUE(G,I,s). Conservation bench terraces and other water harvesting management practices can also greatly increase water-use efficiency by making a larger part of the rainfall available for crop production. Jones et al. (1985) discuss a number of these practices that efficiently conserve water for crop production.

VI. Soil Fertility

One of the keys to sound water management is adequate soil fertility to ensure the most efficient use of available water. Since evapotranspiration losses are largely controlled by meteorological conditions, seasonal ET is nearly the same whether yields are low or high. This is particularly true under dryland conditions in which all of the plant-available water is generally used by the crop. Viets (1962), in his classic review on fertilizers and the efficient use of water, concluded that in most cases when water supply is fixed, any management factor that increases yield will increase water-use efficiency because evapotranspiration is little affected by the management. The data in Figure 8 illustrate two very important points for dryland agriculture. First, added fertilizers is of no benefit unless sufficient water is available to support a response. Second, increasing plant-available water by management practices is futile unless the soil fertility problems are addressed to ensure adequate fertility to take advantage of the increased water supply. It is very important in dryland regions to identify which of these constraints is the first limiting constraint and address it initially. Then, as that constraint is alleviated, practices can be put in place to alleviate the second constraint.

There is abundant evidence that when soil fertility limits yields, the use of fertilizers will result in more grain or dry matter per unit of available water, thus increasing water-use efficiency. This increase occurs because adequate fertility stimulates early growth, thus increasing leaf surface for photosynthesis, and increases root development, often into deeper soil zones, which increases the supply of water to plants. Also, well-fertilized plants with vigorous, extensive root systems may absorb water from higher tension levels and from greater depths in the soil (Viets, 1962). Crop canopies develop at a faster rate with adequate fertility, and this leads to higher infiltration and reduced runoff because the canopy protects

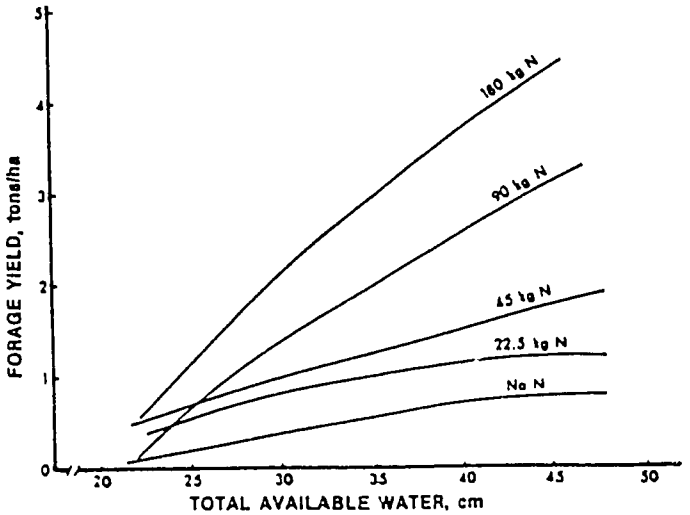


Figure 8. Effects of available water on native grass forage production with different rates of N fertilizer applied annually (adapted from Smika et al., 1965).

the soil surface from raindrop impact. Increased crop canopies can also reduce soil evaporation, thereby increasing the proportion of soil water that is used for transpiration. Proper fertilization can also hasten the maturity of many crops, thereby shortening the period crops have to draw on limited water supplies.

VII. Research Needs for Improved Water-Use Efficiency

In dryland regions, especially in many developing countries, research institutions are woefully inadequate. Too often, the resources allocated to drylands have been very minimal because primary attention has been focused on irrigated agriculture or on favorable rainfall areas. Although this past allocation of resources can be easily understood, and perhaps even justified, successful development of dryland regions occurs only after research institutions have developed technologies adapted to particular conditions in each area.

In the near term, improvements in water-use efficiency for dryland agriculture will come from implementation of proven principles of good agronomic management practices. French and Schultz (1984b) showed that the water-use efficiency of crops is reduced drastically below potential levels by such yield-limiting factors as weeds, nutrient limitations, diseases, low harvest index caused by early depletion of the soil water reserve, waterlogging, and inadequate canopy development.

In developing countries, the first priority should be to improve indigenous practices by adapting proven practices from other regions. The practices from other regions cannot be directly transferred, but the principles will apply, and the

specific practices can be altered to fit the local environment and social and economic conditions. Adaptive research coupled closely with technology transfer demonstration plots on the farmers fields are essential. The research must be conducted with equipment appropriate for the region. Research for developing areas must focus on resilient species, minimum effective input rates, low risk of failure, adequate minimum production in poor years, and diverse cropping patterns (Bay-Petersen, 1986).

Once good agronomic practices are implemented, then improved cropping systems may be possible through a better understanding of the agroclimatic potentials and limitations of a region. A first step is to conduct an agroclimatic analysis to determine the amount of water available for crop use during different parts of the year through dependable rainfall or through a soil water reservoir. Integration of agroclimatic data with detailed soil data bases is essential to take advantage of available soil water reservoirs that buffer the crop against erratic rainfall. Data are often inadequate for analyzing agroclimatology and soil resources and management practices. This inadequacy must be corrected because good data bases are essential for the development of dryland regions. An efficient cropping system should make good use of all the water available in a year, not just for part of the year; and it must be stable over a multiple-year basis (i.e., it must produce relatively stable yields under erratic climatic conditions over a period of time).

In defining the water-use efficiency of a cropping system, all economic returns must be taken into account—grain yields, contributions of the crop to animal production, and contributions of the crop to fertility needs of subsequent crops. This approach requires an improved understanding of the competing costs and benefits of different uses that can be made of a crop. It also requires improved integration of agronomic and economic analyses.

This chapter gave many examples using crop growth or yield models. These models were developed assuming that water was the primary limitation to crop growth and productivity. To use agronomic models to conduct agroclimatic analyses across a range of dryland conditions, models must be developed and tested which consider such aspects as soil limitations to crop growth, genetic differences in cultivars, water and nutrient interactions, and competition between plants of different species. Modeling is very resource intensive, so major efforts should be concentrated in international centers to avoid duplication of efforts. Good communications with regional and national programs are essential to ensure that the models produced have the necessary information to conduct required specific analyses.

References

Baldocchi, D.D., Verma, S.B., and Rosenberg, N.J. 1985. Water use efficiency in a soybean field: Influence of plant water stress. Agric. Forest Meteor. 34:53–65.

Bay-Petersen, J. 1986. New technology for low-income farmers in developing countries. Outlook on Agric. 15:110–114.

Bielorai, H., Arnon, J., Blum, A., Elkana, Y., and Ress, A. 1964. The effect of irrigation and interrow spacing on grain sorghum production. Israel J. Agric. Res. 14: 227–236.

Blum, A. 1979. Genetic improvement of drought resistance in crop plants: A case study for sorghum. In H. Mussell, and R.C. Staples, eds. Stress Physiology in Crop Plants. pp. 430–445. New York: Wiley Interscience.

Blum, A. 1983. Breeding crop varieties for stress environments. CRC Critical Rev. Plant Sci. 2:199–238.

Bremner, P.M., Preston, G.K., and Fazekas de St. Groth, C. 1986. A field comparison of sunflower (*Helianthus annuus*) and sorghum (*Sorghum bicolor*) in a long drying cycle. I. Water extraction. Australian J. Agric. Res. 37:483–493.

Brown, P.L., and Shrader, W.D. 1959. Grain yields, evapotranspiration, and water use efficiency of grain sorghum under different cultural practices. Agron. J 51:339–343.

Chaudhuri, U.N., and Kanemasu, E.T. 1982. Effect of water gradient on sorghum growth, water relations, and yield. Canadian J. Plant Sci. 62:599–607.

Doorenbos, H., and Pruitt, W.O. 1977. Crop water requirements. Irrig. Drain. Paper No. 24. FAO, United Nations, Rome, Italy.

Doyle, A.D., and R.A. Fischer. 1979. Dry matter accumulation and water-use relationships in wheat crops. Australian J. Agric. Res. 30:815–829.

El-Swaify, S.A., Pathak, P., Rego, T.J., and Singh, S. 1985. Soil management for optimized productivity under rainfed conditions in the semi-arid tropics. Adv. Soil Sci. 1:1–63, New York: Springer-Verlag.

Fehr, W.R. (ed.). 1984. Genetic Contributions to Yield Gains of Five Major Crop Plants. CSSA Spec. Pub. No. 7 Madison, Wisc.: Crop Sci. Soc. Am.

French, R.J., and Schulz, J.E. 1984a. Water-use efficiency of wheat in a Mediterranean-type environment. I. The relationship between yield, water use, and climate. Australian J. Aric. Res. 35:743–764.

French, R.J., and Schulz, J.E. 1984b. Water-use efficiency of wheat in a Mediterranean-type environment. II. Some limitations to efficiency. Australian J. Agric. Res. 35: 765–775.

Gardner, W.R., and Gardner, H.R. 1983. Principles of water management under drought conditions. In J.F. Stone and W.O. Willis, eds. Plant Production and Management Under Drought Conditions. Development in Agricultural and Managed-Forest Ecology 12. pp. 143–155. Amsterdam: Elsevier Science Publisher B.V.

Greb, B.W., Smika, D.E., and Welsh, J.R. 1979. Technology and wheat yields in the Central Great Plains: Experiment station advances. J. Soil Water Conserv. 34:264–268.

Heichel, G.H. 1983. Crop manipulation for efficient use of water: Inadvertent and intended manipulations for crop water use. In H.M. Taylor, W.R. Jordan, and T.R. Sinclair, eds. Limitations to Efficient Water Use in Crop Production. pp. 375–380. Madison, Wisc.: Am. Soc. Agron.

Howell, T.A., and Hiler, E.A. 1975. Optimization of water-use efficiency and high frequency irrigation. I. Evapotranspiration and yield relationships. Trans. Am. Soc. Agric. Eng. 18:873–878.

Johnson, W.C., and Davis, R.G. 1972. Stubble mulch farming of wheat: A history of 28 years experience at USDA Southwestern Great Plains Research Center, Bushland, Texas. USDA Agric. Res. Conserv. Report No. 16.

Jones, O.R., Unger, P.W., and Fryrear, D.W. 1985. Agricultural technology and conservation in the Southern High Plains. J. Soil Water Conserv. 40:195–198.

Khalifa, M.A., Akasha, M.H., and M.B. Said. 1977. Growth and N-uptake by wheat as affected by sowing date and nitrogen in irrigated semi-arid conditions. J. Agric. Sci., Camb. 89:35-42.

Kolp, B.J., Sackett, R.G., Bohnenblust, K.E., and Roehrkasel, G.P. 1973. Effect of rate and date of seeding Shoshoni winter wheat in soil moisture depletion. Agron. J. 65:929-930.

Knapp, W.R., and Knapp, J.S. 1978. Response of winter wheat to date of planting and fall fertilization. Agron. J. 70:1048-1053.

Miller, F.R., and Kebede, Y. 1984. Genetic contributions to yield gains in sorghum, 1950 to 1980. In W.R. Fehr, ed. Genetic Contributions to Yield Gains of Five Major Crop Plants. pp. 1-14. CSSA Spec. Pub. No. 7. Madison, Wisc.: Crop Sci. Soc. Am.

Musick, J.T., and Dusek, D.A. 1971. Grain sorghum response to number, timing, and size of irrigations in the Southern High Plains. Trans. Am. Soc. Agric. Eng. 14:401-404.

Musick, J.T., and Porter, K.B. 1990. Wheat. In B.A. Stewart and D.R. Nielsen, eds. Irrigation of Agricultural Crops. Madison, Wisc.: Agron. Mono. 30, Am. Soc. Agron., 598-638.

Owonubi, J.J., and Kanemasu, E.T. 1982. Water use efficiency of three height isolines of sorghum. Canadian J. Plant Sci. 62:35-46.

Quinby, J.R., Kramer, N.W., Stephens, J.C., Lahr, K.A., and Karper, R.E. 1958. Grain sorghum production in Texas. TX Agric. Exp. Stn. Bull. 912.

Rosenthal, W.D., Vanderlip, R.L., Jackson, B.E., and Arkin, G.F. 1989. SORKAM: A Grain Sorghum Crop Growth Model. Texas Agric. Exp. Stn. College Station, TX MP-1669.

Schmidt, J.W. 1984. Genetic contributions to yield gains in wheat. In W.R. Fehr, ed. Genetic Contributions to Yield Gains of Five Major Crop Plants. pp. 89-101. CSSA Spec. Pub. No. 7. Madison, Wisc.: Crop Sci. Soc. Am.

Seetharama, N., Mahalakshmi, V., Bidinger, F.R., and Singh, S. 1982. Response of sorghum and pearl millet to drought stress in semi-arid India. In Proc. International Symposium on Agrometeorology of Sorghum and Millet in the Semi-Arid Tropics, Patancheru, India, November 1982, pp. 159-173. ICRISAT Center.

Sinclair, T.R., Tanner, C.B., and Bennett, J.M. 1984. Water-use efficiency in crop production. BioScience 34:36-40.

Smika, D.E., Haas, H.J., and Power, J.F. 1965. Effects of moisture and nitrogen fertilizer on growth and water use by native grass. Agron. J. 56:483-486.

Squire, G.R., Marshall, B., and Ong, C.K. 1986. Development and growth of pearl millet (*Pennisetum typhoides*) in response to water supply and demand. Expl. Agric. 22:289-299.

Steiner, J.L. 1986. Dryland grain sorghum water use, light interception, and growth responses to planting geometry. Agron. J. 78:720-726.

Steiner, J.L. 1987. Radiation balance of dryland grain sorghum as affected by planting geometry. Agron. J. 79:259-265.

Stewart, B.A., Musick, J.T., and Dusek, D.A. 1983. Yield and water-use efficiency of grain sorghum in a limited irrigation-dryland system. Agron. J. 75:629-634.

Stewart, B.A., and Burnett, E. 1987. Water conservation technology in rainfed and dryland agriculture. In Wayne R. Jordan, ed. Water and Water Policy in World Food Supplies. pp. 355-359. Texas A&M Univ. Press, College Station, Texas.

Stewart, J.I. 1985. Response farming: A scientific approach to ending starvation and alleviating poverty in drought zones of Africa. In Proc. International Conference on African Agricultural Development: Technology, Ecology and Society, California State Polytechnic University, Pomona, California, May 28-June 2, 1985.

Stewart, J.I. 1988. Development of management strategies for minimizing the impact of seasonal rainfall variation. In F.R. Bidinger and C. Johansen, eds. Drought Research Priorities for the Dryland Tropics. pp. 131–150. ICRISAT, Patancheru, India.

Stewart, J.I. 1989. Mediterranean-type climate, wheat production and response farming. In Proc. Workshop on Soil, Water and Crop/Livestock Management Systems for Rainfed Agriculture in the Near East Region. Amman, Jordan, January 18–23, 1986. pp. 5–19. USAID, USDA, ICARDA, ACSAD, Jordan Ministry of Agriculture, Water Authority of Jordan, and Yarmouk University.

Stewart, J.I. 1989. Response farming for improvement of rainfed crop production in Jordan. In Proc. Workshop on Soil, Water and Crop/Livestock Management Systems for Rainfed Agriculture in the Near East Region. Amman, Jordan, January 18–23, 1986. pp. 288–306. USAID, USDA, ICARDA, ACSAD, Jordan Ministry of Agriculture, Water Authority of Jordan, and Yarmouk University.

Stewart, J.I., Misra, R.D., Pruitt, W.O., and Hagan, R.M. 1975. Irrigating corn and grain sorghum with a deficient water supply. Trans. Am. Soc. Agric. Eng. 18:270–280.

Stone, L.R., Gwin, R.E., Jr., and Dillon, M.A. 1978. Corn and grain sorghum yield and water use in response to limited irrigation. Kansas Water News 21:12–21.

Taylor, H.M., Jordon, W.R., and Sinclair, T.R., eds. 1983. Limitations to Efficient Water Use in Crop Production. Madison, Wisc.: Am. Soc. Agron.

Thill, D.C., Witters, R.E., and Papendick, R.I. 1978. Interaction of early- and late-planted winter wheat with their environment. Agron. J. 70:1041–1047.

Unger, P.W., and Jones, O.R. 1981. Effect of soil water content and a growing season straw mulch on grain sorghum. Soil Sci. Soc. Am. J. 45:129–134.

Unger, P.W., Steiner, J.L., and Jones, O.R. 1986. Response of conservation tillage sorghum to growing season precipitation. Soil and Tillage Res. 7:291–300.

Van Staveren, J. Ph., and Stoop, W.A. 1985. Adaptation to toposequence land types in West Africa and different sorghum genotypes in comparison with local cultivars of sorghum, millet, and maize. Field Crops Res. 11:13–35.

Viets, F.G., Jr. 1962. Fertilizers and the efficient use of water. Adv. Agron. 14:223–264.

Virmani, S.M., Sivakumar, M.V.K., and Reddy, S.J. 1978. Rainfall probability estimates for selected locations of semi-arid India. ICRISAT Res. Rep. 1., Patancheru, A.P., India.

Walter, C.J., and Barley, K.P. 1974. The depletion of soil water by wheat at low, intermediate, and high rates of seeding. Trans. 10th Int. Congr. Soil Sci. 1:150–158..

Wright, M.J. 1977. Plant Adaptation to Mineral Stress in Problem Soils. Spec. Pub. Cornell Univ. Agric. Exp. Stn., Ithaca, NY.

Water Erosion and Water Quality

D.K. McCool and K.G. Renard

I. Introduction 175
II. Impacts 177
A. Erosion 177
B. Water Quality 178
III. Prediction 179
A. Erosion 179
B. Water Quality 181
IV. Research Needs 182
V. Summary 183
References 183

I. Introduction

Water erosion at some level is inevitable. Geological erosion transforms rugged mountains into rounded hills and produces fertile valleys and lowlands. Only by massive engineering structures is geological erosion reduced at a point, and in terms of geological time even then it is only temporarily averted.

Accelerated erosion reflects the activity of man. It occurs because of cultivation of sloping lands or vegetation alteration caused by a concentration of domesticated animals. Generally, accelerated erosion is detrimental. It results in movement of topsoil from hillslopes to valley bottoms that may already have an adequate depth of topsoil, or to streams and reservoirs. Subsoil is usually less hospitable to plant growth than topsoil because of a lack of nutrients and lower available water-holding capacity.

Erosion was recognized as a problem in early civilizations and various attempts were made to deal with it (Bennett, 1939). Literally thousands of years of

1990 by Springer-Verlag New York Inc.
Advances in Soil Science, Volume 13

Previous Page Blank

labor were spent constructing canals, dikes, and elaborate bench terrace systems. The remnants of these can still be seen, and some are still in use in certain parts of the world.

In the United States, erosion was recognized as a severe problem within a few years of settlement. Frequently the solution for the farmer of eroded and depleted land was to abandon the property and move to a new area because new land was readily available. There were a few conservationists in the 18th and 19th centuries, but their efforts were not extensive and there was no way to communicate effectively with a large number of farmers.

It was not until the start of the 20th century that erosion in the United States received national attention. In 1930, federal appropriations were made for investigations as to causes of erosion. This and subsequent legislation established 10 soil erosion experiment stations across the country (Bennett, 1939). The need for additional emphasis on soil erosion was heightened by the drought and dust bowl period of the 1930s. Since that time, farming practices have changed dramatically, with larger, more economically efficient farming units and larger tillage and harvesting equipment. These changes in farming practices have made it difficult to use traditional erosion control practices and placed more emphasis on cultural practices such as mulching and residue management. In the late 1960s and the 1970s, reduced and no-till seeding techniques were developed, first for row crops and then for small grains.

Reduced tillage and no-till systems result in higher quantities of crop residues remaining on the surface, which reduces runoff and erosion. However, these systems generally require higher application rates of insecticides and herbicides. Thus, there is a possibility that improved erosion control associated with conservation tillage systems may lead to decreased water quality because of increased chemical usage and the accompanying greater losses in the runoff or to groundwater.

Developing nations are frequently faced with problems of severe soil erosion and depletion of the soil resource base. As they struggle to feed an increasing population, steeper and less suitable lands come under cultivation. The result is increased soil erosion, greater fluctuations in runoff, and increased sediment damage. Erosion control practices such as mulching with crop residues are often not used because of tradition, use of the residue for other purposes, insect problems, or the additional labor needed to manage the residue.

The erosion problem in some parts of the world is unrecognized or ignored, with the assumption that erosion is a problem only where it is well publicized such as in the United States or in areas where erosion-depleted soil combined with drought have caused widespread famine and suffering. In reality, it is under only the most benign climatic, topographic, and soil conditions that accelerated erosion has no potential for damaging the natural resource base.

Assessing the status of the soil resource base and its change with time is an important activity in developing as well as developed nations. These assessments are necessary to predict capability of meeting food and fiber needs of the near and distant future. Properly conducted and used, assessments can assist planners and

policy makers to make good decisions regarding land use and to design programs to control soil erosion.

The purpose of this chapter is to discuss water erosion and water quality impacts, to describe methodology to answer questions of interactions between erosion control and water quality, and to describe methodology for assessing soil erosion.

II. Impacts

A. Erosion

The effect of erosion on productivity received much attention in the United States from the 1930s through the early 1950s. Research sometimes involved topsoil scalping to simulate a severely eroded area for comparison with an adjacent noneroded area. Some researchers compared eroded phases of the soil with those with greater topsoil depth, while others initiated long-term projects to erode a plot area more naturally. Results from these studies of the detrimental impact of erosion on crop productivity were so conclusive that research emphasis was shifted to measuring erosion rates under different cropping practices, developing erosion-control practices, and predicting erosion (Meyer et al., 1985).

In the early 1980s renewed interest developed in relationships between soil erosion and productivity, largely as a result of Public Law 95-192, the Soil and Water Resources Conservation Act of 1977 (RCA). The RCA emphasized the need for better quantification of erosion-induced productivity losses, their economic impacts, and their short-term and long-term impacts on the ability of the United States to produce food, feed, and fiber. Because of different crop varieties, fertilization techniques, and tillage practices, it was not possible to extrapolate results of the earlier studies to current conditions (Williams et al., 1981). Studies linking soil erosion to productivity were undertaken. In nearly all cases, because of funding requirements and other constraints, the research was designed to be short term. These erosion/productivity concerns and the requirements of RCA also led to development of models linking soil erosion and productivity. The most widely used of these models is the Erosion-Productivity Impact Calculator (EPIC) (Williams and Renard, 1985).

In early 1983 a Symposium on Soil Erosion and Crop Productivity focused on appraisals, policies, economics, and prediction techniques (Follett and Stewart, 1985). By late 1984 sufficient current experimental data were available that a National Symposium on Erosion and Soil Productivity was held at which several researchers presented their results (ASAE, 1985). Nearly all the results showed a significant impact of soil erosion on productivity. The impact was a function of erosion rates and soil characteristics; in some cases crop yield would be changed significantly over a long period of time while in others the changes would be more rapid. Researchers in some areas found landscape position to be a factor of greater importance than topsoil depth, largely because of soil variations and moisture-holding capacity related to landscape position (Gilliam et al., 1985).

The studies cited previously all concentrated on the effect of erosion on productivity. They did not address the issue of off-site damages, such as filling of roadside ditches, reduced channel flow capacity, reservoir siltation, loss of fish habitat, aesthetic considerations, and lost recreational potential.

That off-site damages could exceed productivity losses was emphasized by Crosson (1984), who cited results of the 1977 National Resources Inventory (NRI), results from studies at the University of Minnesota, and from studies of Resources for the Future that indicated, respectively, yield losses of 8% in 50 years, 5 to 10% in 100 years, and 2 to 3% in 30 years. The annual cost of these yield losses was estimated at $40 million in 1984 and $80 million in 1985; annual costs would increase by about $40 million each year. In contrast, Crosson cited a study by the Conservation Foundation that indicated off-site damages from sediment were about $3.1 billion per year, many times the cost of the productivity losses. Since then, off-site impact has been an important consideration in nearly [illegible] il erosion studies and projects.

B. Water Quality

Surface water quality can be affected by a number of factors, the most obvious and visible being suspended sediment. However, the most troublesome are not the visible factors, but rather the invisible that render the water unsafe for livestock, irrigation, recreation, and human consumption. Water can be made unsafe by a number of chemical and biological agents. These include excess plant nutrients, animal wastes, municipal or household wastes, agricultural chemicals, and other materials.

Water quality has been a matter of a public concern for some time. In the United States, federal legislation addressing water quality appeared before 1900. The Refuse Act of 1899, the Public Health Act of 1912, and the Oil Pollution Act of 1912 all dealt with water quality. The first federal legislation having a major impact on U.S. agriculture was the Federal Water Pollution Control Act Amendments of 1972, which, among other items, addressed non-point source pollution from such sources as farm fields.

Major water quality problems of concern to agriculture are nutrients and pesticides. Nutrients make water unsafe for humans, animals, or fish when the concentration of certain forms exceeds a critical level; excessive nutrients can also accelerate eutrophication. Nitrogen has perhaps received the most attention as a threat to water quality (Wadleigh, 1968). Nitrite is the most toxic form of nitrogen, but children, young animals, and cattle convert some of the more common nitrates to nitrites in their stomachs and can develop methemoglobinemia. In 1962 the U.S. Public Health Service set an upper limit on nitrate in drinking water at 10 mg N per liter (45 ppm nitrate) (Frere, 1976).

Eutrophication, a natural process, is accelerated by the enrichment of water by excess nutrients. The ensuring luxuriant growth of algae and plants and their decay removes oxygen from the water. Rapid growth of algae is the greatest and most widespread problem in most of the United States (Frere, 1976). High levels

of nitrogen and phosphorus appear to be the nutrients accounting for most of the excessive algae growth. Frere cited Sawyer (1947), who concluded concentrations of 0.3 ppm of inorganic nitrogen and 0.015 ppm for inorganic phosphorus were levels at which eutrophication would become a problem.

On a nationwide level, fertilizer is a major and manure a minor input of nutrients to streams. The relative role of these factors may be reversed for a given area, such as those with a high concentration of livestock (Frere, 1976).

Pesticides move into surface waters with either runoff or sediment. In general, soluble compounds move with the runoff and adsorbed compounds move with the sediment. However, some very water-soluble compounds have strong irreversible adsorption to soil particles and move only with the sediment. Movement of pesticides is very complex and is a function of the soil characteristics as well as those of the pesticide itself (Caro, 1976).

Subsurface water quality is mainly impacted by mobile nutrients and pesticides, although, through cracks in initially dry soil, those forms normally associated with surface flow can also enter the groundwater. Pesticides are usually applied on or near the soil surface. Fertilizers can be surface applied, incorporated by tillage, or injected into the soil. Common application rates of N are 112 kg per hectare or more in high producing areas, but 60 kg per hectare or less in drier areas. In addition, through mineralization of organic nitrogen to nitrate, 135 kg N per hectare or more can be released in fertile soil (Frere, 1976). Similarly to movement with runoff water and sediment, movement of nutrients and pesticides into and through the soil is governed by characteristics of both the soil and the nutrient or pesticide. Soluble materials move rapidly with infiltrated water in sandy soils with more organic matter or clay, even if the soil is so well structured as to maintain high permeability. According to Caro (1976) adsorption is a better indicator of overall potential movement than solubility, because strongly adsorbed materials will not move.

III. Prediction

A. Erosion

Erosion prediction has progressed from data collection to compare practices, to simple empirical models, to complex empirical models, and most recently toward process-based models. The most widely used empirical model at present is the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1965; 1978), a predictor of long-term soil loss. Soil loss is calculated as mass per unit of area based on the product of six factors: rainfall and runoff erosivity factor, R; soil erodibility factor, K; slope length factor, L; slope steepness factor, S; crop management factor, C; and erosion control practice factor, P. Various adaptations of the USLE replaced the rainfall and runoff erosivity factor, R, with parameters designed to predict more accurately on an event basis or to predict sediment yield. The Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975)

replaced the USLE R factor with a factor based on peak rate and total runoff volume for an event in an effort to predict watershed sediment yield. Onstad and Foster (1975) developed an adaptation of the USLE for predicting soil loss from events, based on a combination of the traditional R and the MUSLE peak rate and runoff volume. The Agricultural Chemical Transport Model (ACTMO; Frere et al., 1975) was an early attempt to add a hydrologic model to erosion prediction. Both ACTMO and the Chemicals, Runoff, and Erosion from Agricultural Management Systems Model (CREAMS; Foster et al., 1980) use certain factors from the USLE along with runoff prediction techniques. CREAMS includes channel processes and is suitable for small watersheds.

A revision of the USLE, called the Revised Universal Soil Loss Equation (RUSLE) is currently being developed. It retains the use of the six factors and predicts hillslope soil loss on an average annual basis, but it has improved values of the R factor for western states in the United States, takes into account variation of soil erodibility with time, has new slope length and steepness relationships, uses a subfactor system for calculating crop management factors, and has new erosion control practice factor values developed by CREAMS technology. It is programmed and operational on a personal computer.

A number of rather complex watershed erosion–sediment yield models have been developed. In general, these models were intended for watershed-size areas and are not suited to farm planning because of the data requirements and the need for mainframe computers to solve the flow equations. Frequently these models are research oriented and intended for investigating the influence of a particular parameter on the runoff and soil erosion process. Foster (1982) compares these models and is the source of much of the following discussion. A number of the earlier models linked an erosion and sediment transport model to an existing runoff model such as the Stanford model. Examples of models using the Stanford model are those of Negev (1967), David and Beer (1975), the ARM model (Donigan and Crawford, 1976; Donigan and Davis, 1978; Fleming and Leytham, 1976). In more recent modeling efforts, the modeler has tended to develop the runoff as well as the detachment and transport relationships. Examples include Smith's model (1977), the CSU model (Li, 1977), ANSWERS (Beasley, 1977), and OPUS (Smith and Ferreira, 1986). Some models such as the Ground Water Loading Effects of Agricultural Management Systems Model (GLEAMS; Leonard et al., 1987) include components for routing infiltrated water and selected chemicals through the root zone. Inclusion of this component is essential if movement of nutrients and pesticides to groundwater is to be considered, as discussed in a following section.

In 1985 a coordinated effort was started by the Agricultural Research Service, Soil Conservation Service, Forest Service, Bureau of Land Management, U.S. Geological Survey, and other federal and state agencies to replace the USLE with a process-driven field-usable erosion/sedimentation model (Foster and Lane, 1987). The effort is called the Water Erosion Prediction Project (WEPP). The model will be available in three versions—a hillslope version for farm planning,

a watershed version, and a grid version. Target date for completion of the hillslope version was late 1989. This version will apply to hillslopes without concentrated flow channels or gullies, that is, as a replacement for the USLE. It computes interrill and rill erosion along selected landscape profiles and includes sediment deposition at energy gradient decreases or in impoundments. Gully erosion is considered only in the watershed and grid versions. WEPP includes components for climate generation, infiltration, water balance, crop growth and residue decomposition, surface runoff, and erosion. It calculates spatial and temporal variations of soil loss in continuous simulation or single-event mode.

B. Water Quality

Movement of nutrients and pesticides in surface runoff is modeled by routing the material with the water or sediment as appropriate. Because the nutrients and pesticides are more readily adsorbed to the finer soil particles, it is necessary for the erosion and transport portion of the model to be selective; that is, different particle sizes should be considered separately.

ACTMO (Frere et al., 1975) routes pesticides and nitrates with surface runoff and sediment. The pesticide option considers adsorption, breakdown, and movement. The nitrate option deals with mineralization, plant uptake, and movement. CREAMS (Knisel, 1980) uses a plant nutrient submodel with a nitrogen component that considers mineralization, nitrification, and denitrification processes. Enrichment ratios provide the basis for computing nitrogen and phosphorus movement with sediment. The pesticide component considers foliar interception, degradation, and washoff, along with adsorption, desorption, and degradation in the soil. A grid-based single-event model, the Agricultural Non-Point-Source Pollution Model (AGNPS; Young et al., 1987), uses a standard runoff prediction technique, certain factors from the USLE, and channel parameters. It predicts runoff, sediment, and nitrogen, phosphorus, and chemical oxygen demand concentrations in the runoff and in the sediment for all points in the watershed.

Movement of nutrients and pesticides to groundwater is currently accomplished by use of a leaching model coupled to the infiltration component of the main hydrologic model. Both ACTMO (Frere et al., 1975) and CREAMS (Knisel, 1980) consider nitrate leaching but not pesticide movement into and through the soil. GLEAMS (Leonard et al., 1987) deals with pesticide and metabolite movement into and through the root zone. The Leaching Estimation and Chemistry Model (LEACHM; Wagenet and Hutson, 1987) considers pesticide and metabolic movement through the root zone. The CMLS model (Nofziger and Hornsby, 1986) assumes no surface runoff and routes pesticides through the root zone for single events. Another pesticide leaching model is the Pesticide Root Zone Model (PRZM; Carsel et al., 1984; 1985), which is coupled to a hydrologic/erosion model and considers pesticide movement through the root zone.

IV. Research Needs

There is pressing need for a field-usable process-based erosion and water quality model. WEPP is targeted to meet a part of that need. However, whereas the hydrology and hydraulics are process-driven, many of the soil, biological, and cropping relationships are largely empirical, and the model may be quite sensitive to some of these components. If USLE relationships are a guide, residue effect and residue decomposition will be very important, as will crop growth and cover. Also, readily available soils information may not be in sufficient detail or may be too broad or general to enable accurate prediction of infiltration and percolation and hence of runoff, soil loss, and chemical movement.

Given that erosion at some level is associated with cultivation and livestock production, and that some soils are more susceptible to erosion damage than others, the concept of a soil loss tolerance was introduced into erosion work. The soil loss tolerance, T, is defined as the maximum soil loss, in mass per unit area, that can be sustained without productivity loss. This concept has been attacked frequently. Objections include that no firm relationship exists between topsoil depth and yield and that, in some situations, productivity is much better related to available soil water than to topsoil depth (Gilliam et al., 1985). Others feel that currently used values are based on social and economic considerations rather than on sustainability of long-term productivity (Johnson, 1987).

It is likely that, in fact, whereas one of these extreme viewpoints may be correct for a given field in one area, the other may be correct for another site at some other place. The need for a better and more complete definition is evident from the controversy that has developed around T. This controversy stresses the need for a more complete concept of erosion tolerance that includes soil formation rates, suitability of the subsoil as a medium for plant growth, depth of topsoil, and potential for off-site damage.

Predicting effects of management practices on surface water quality as well as on soil loss is essential. Inasmuch as pollutants may be either carried in solution or adsorbed to soil particles, an erosion predictor such as the USLE is inadequate to address water quality. Models must also include runoff prediction. Certainly off-site impacts are of concern, so hillside models must provide input to routing models that will consider the fate of pollutants that leave the hillslope area and enter the channel system.

Groundwater quality is very important, and is emerging in the United States as an area of great concern. Much of the domestic water supply comes from groundwater sources. Preventing groundwater contamination is much easier than dealing with it after it occurs; the latter may be impossible and is certainly uneconomical.

Soil loss and water quality models that are operational and practical must be available. Data requirements must be reasonable if the model is to be used for such purposes as farm planning. The models must be user-friendly if they are to be used by a wide range of personnel. Results obtained with the models must be realistic or they will not be accepted by field personnel. These requirements,

though essential for successful application in the United States, are even more important if the models are to be used in developing nations.

Climate and soils data are needed for the operation of all erosion and water quality models, from the USLE to the most complex. In the case of the USLE, the climate data consist of break-point precipitation data or an estimate of that data. Ideally, the period of record should be about 20 years or sufficiently long to sample the precipitation cycle. Procedures have been developed to estimate break-point data from hourly precipitation data (Istok et al., 1986).

With increasing frequency, physically based models use climate-generation techniques to develop data for operating their models. For example, the WEPP model operates on the output from a climate generator (Nicks et al., 1987). The climate generator requires about 20 years of observational data of daily precipitation and daily maximum/minimum temperature. From these data the model can be developed to disaggregate the daily precipitation estimates into hourly or shorter data estimates (Woolhiser et al., 1988), which can then be used as input to time-based infiltration technology. The climate-generation and precipitation-disaggregation technologies are still in an evolutionary phase. The large number of parameters involved in such schemes make parameter determination difficult and preclude widespread application in many locations.

V. Summary

Accelerated soil erosion has been a problem since early civilization and remains so today. Population and economic pressures are causing the cultivation of steeper and more easily damaged lands. Water quality has joined soil erosion as a major concern. Previously this was primarily a concern of industrialized nations; now it must be dealt with by all. Models exist and are being developed and improved continually to determine the effect of land management decisions. These models will assist planners and policy makers worldwide in setting and meeting erosion and water quality goals.

References

ASAE. 1985. Erosion and soil productivity. Proceedings of the National Symposium on Erosion and Soil Productivity, New Orleans, La. Dec. 10–11, 1984. St. Joseph, Mich.: American Society of Agricultural Engineers.

Beasley, D.B. 1977. ANSWERS: A mathematical model for simulating the effects of land use and management on water quality. Ph.D. thesis, Purdue University, West Lafayette, Ind.

Bennett, H.H. 1939. Soil conservation. New York and London: McGraw-Hill Book Co.

Caro, J.H. 1976. Pesticides in agricultural runoff. *In*: Stewart, B.A. (Coordinator). Control of Water Pollution from Cropland. Vol. II—An Overview. pp. 91–119. USDA-ARS. Report No. ARS-H-5-2.

Carsel, R.F., L.A. Mulkey, M.N. Lorber, and L.B. Baskin. 1985. The pesticide root zone model (PRZM): A procedure for evaluating pesticide leaching threats to ground water. Ecological Modeling 30:49–69.

Carsel, R.F., C.N. Smith, L.A. Mulkey, J.D. Dean, and P. Jowise. 1984. User's manual for the pesticide root zone model (PRZM):Release 1. EPA-600/3-84-109. Athens, Ga.: USEPA, Environmental Research Laboratory.

Crosson, P. 1984. New perspectives on soil conservation policy. Journal of Soil and Water Conservation 39(4):222-225.

David, W.P., and C.E. Beer. 1975. Simulation of soil erosion – Part I. Development of a mathematical erosion model. Transactions of the ASAE 18(1):126-129,133.

Donigan, A.S., and N.H. Crawford. 1976. Modeling non point source pollution from the land surface. EPA-600/3-76-083. U.S. Environmental Protection Agency.

Donigan, A.S., and H.H. Davis. 1978. User's Manual for Agricultural Runoff Management (ARM) Model. EPA-600/3-78-080. U.S. Environmental Protection Agency.

Fleming, G., and K.M. Leytham. 1976. The hydrologic and sediment processes in natural watershed areas. *In*: Proc. of the Third Federal Inter-Agency Sedimentation Conference. Water Resources Council, Washington, D.C. 1:232-246.

Follett, R.F., and B.A. Stewart (eds.). 1985. Soil erosion and crop productivity. Madison, Wisc.: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.

Foster, G.R. 1982. Modeling the erosion process. *In*: Haan, C.T., H.P. Johnson, and D.L. Brakensiek (eds.). Hydrologic Modeling of Small Watersheds. pp. 297-380. St. Joseph, Mich.: American Society of Agricultural Engineers.

Foster, G.R., and L.J. Lane. 1987: User requirements. USDA-water erosion prediction project (WEPP). NSERL Report No. 1. National Soil Erosion Research Laboratory, West Lafayette, Ind.

Foster, G.R., L.J. Lane, J.D. Nowlin, J.M. Laflen, and R.A. Young. 1980. A model to estimate sediment yield from field-sized areas: Development of model. *In*: Knisel, W.G. (ed.). CREAMS – A Field Scale Model for Chemicals, Runoff and Erosion from Agricultural Management Systems. Volume I: Model Documentation. Chap. 3, pp. 36-64. USDA-Science and Education Administration, Conservation Research Report No. 26.

Frere, M.H. 1976. Nutrient aspects of pollution from cropland. *In*: Stewart, B.A. (Coordinator). Control of Water Pollution from Cropland. Vol. II – An Overview. pp. 59-90. USDA-ARS. Report No. ARS-H-5-2.

Frere, M.H., C.A. Onstad, and H.N. Holtan. 1975. ACTMO, An Agricultural Chemical Transport Model. USDA-ARS-H-3. Washington, D.C.

Gilliam, J.W., D.K. Cassel, R.B. Daniels, and J.R. Stone. 1985. Interrelationships among soil erosion, landscape position and soil productivity in the North Carolina Piedmont. *In*: Erosion and Soil Productivity, Proceedings of the National Symposium on Erosion and Soil Productivity, New Orleans, LA. Dec. 10-11, 1984. pp. 75-82. St. Joseph, Mich.: American Society of Agricultural Engineers.

Istok, J.D., D.K. McCool, L.G. King, and L. Boersma. 1986. Effect of rainfall measurement interval on EI calculation. Transactions of the ASAE 29(3):730-734.

Johnson, L.C. 1987. Soil loss tolerance: Fact or myth. Journal of Soil and Water Conservation 42(3):155-160.

Knisel, W.G. (ed.). 1980. CREAMS – A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. USDA Science and Education Administration, Conservation Research Report No. 26.

Leonard, R.A., W.G. Knisel, and D.A. Still. 1987. GLEAMS: Ground water loading effects of agricultural management systems. Transactions of the ASAE 30(5):1403-1418.

Li, R.M. 1977. Water and sediment routing from watersheds. *In*: Proc. of River Mechanics Institute, chap. 9. Ft. Collins: Colorado State University.

Meyer, L.D., F.E. Rhoton, and K.G. Renard. 1985. Soil erosion-soil productivity: A look to the future. *In*: Erosion and Soil Productivity, Proceedings of the National Symposium on Erosion and Soil Productivity, New Orleans, LA. Dec. 10-11, 1984. pp. 266-277. St. Joseph, Mich.: American Society of Agricultural Engineers.

Negev, M. 1967. A sediment model on a digital computer. Technical Report 76. Department of Civil Engineering, Stanford University, Stanford, Calif.

Nicks, A.D., D.A. Woolhiser, and C.W. Richardson. 1987. Generating climate data. ASAE Paper No. 87-2541. St. Joseph, Mich.: American Society of Agricultural Engineers.

Nofziger, D.L., and A.G. Hornsby. 1986. A microcomputer-based management tool for chemical movement in soil. Applied Agricultural Research 1:50-56.

Onstad, C.A., and G.R. Foster. 1975. Erosion modeling on a watershed. Transactions of the ASAE 18(2):288-292.

Sawyer, C.N. 1947. Fertilization of lakes by agricultural and urban drainage. New England Waterworks Assoc. 61:109-127.

Smith, R.E. 1977. Field test of a distributed watershed erosion/sedimentation model. *In*: Soil Erosion: Prediction and Control. pp. 201-209. Special Publication No. 21. Ankeny, Iowa: Soil Conservation Society of America.

Smith, R.E., and V.A. Ferreira. 1986. Effect of soil hydraulic properties on root zone transport processes. *In*: Proceedings of AGU Front Range Branch Hydrology Days. pp. 123-137. Ft. Collins: Hydrology Days Publications. Colorado State University.

Wadleigh, C.H. 1968. Wastes in relation to agriculture and forestry. USDA Miscellaneous Paper No. 1065. Washington, D.C.

Wagenet, R.L., and J.L. Hutson. 1987. Leaching estimation and chemistry model. Continuum Water Resources Institute. Vol. 2. Center for Environmental Research. Ithaca, N.Y.: Cornell University.

Williams, J.R. 1975. Sediment-yield prediction with universal equation using runoff energy factor. *In*: Present and Prospective Technology for Predicting Sediment Yields and Sources. pp. 244-252. USDA, ARS-S-40. Washington, D.C.: U.S. Government Printing Office.

Williams, J.R., R.R. Allmaras, K.G. Renard, L. Lyles, W.C. Moldenhauer, G.W. Langdale, L.D. Meyer, and W.J. Rawls. 1981. Soil erosion effects on soil productivity: A research perspective. Journal of Soil and Water Conservation 36(2):82-90.

Williams, J.R., and K.G. Renard. 1985. Assessment of soil erosion and crop productivity with process models (EPIC). *In*: Follett, R.F. and B.A. Stewart (eds.). Soil Erosion and Crop Productivity. pp. 67-103. Madison, Wisc.: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.

Wischmeier, W.H., and D.D. Smith. 1965. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains. USDA, Agriculture Handbook 282. Washington, D.C.: U.S. Government Printing Office.

Wind Erosion: Mechanics, Prediction, and Control

D.W. Fryrear

I. Introduction 187
II. Basic Wind Erosion Process 188
III. Extent of Problem 189
IV. Deposition of Eroded Material 193
V. Impact on Soil Productivity 195
VI. Wind Erosion Control 195
VII. Conclusions 197
References 198

I. Introduction

Wind erosion is one of the geomorphological processes that affects our everyday lives, and in semiarid regions it influences the very future of civilization. Soil is essential to sustain mankind, but soil can be rendered infertile by the complete removal of topsoil or selected removal of soil fines by wind. The particles removed may be deposited downwind to become a part of the new landscape or may be transported to oceans where the nutrient-rich dust enhances aquatic life (Morales, 1977).

Eolian features on nearly every continent are testaments to the persistence and magnitude of wind forces and the wind's ability to shape and form the earth's surface. Although the transport capacity of the wind is much less than that of water, water erosion is restricted to the sloping land while wind erosion can remove the fine nutrient-rich particles from the soil's entire surface. The texture of the remaining soil becomes coarser, and wind erosion control becomes more difficult.

As soil erosion becomes increasingly severe, alternative methods of control compatible with farming practices must be employed.

1990 by Springer-Verlag New York Inc.
Advances in Soil Science, Volume 13

Previous Page Blank

Samuel Deane (1790), was one of the first Americans to recommend hedge fences or locust trees to control wind erosion. Drown (1824) and Hill (1824) recommended the use of 5 to 8 cm of clay to make "blowy soils" productive. This basic principle (increasing the clay content of the surface soil) is still used to control wind erosion on thousands of hectares of sandy soils in the southern Great Plains (Chepil et al., 1962). The clay in the southern Great Plains is brought to the soil surface by "deep-plowing" sandy soils with a higher clay content in the subsurface profile. The benefits from deep plowing will persist for several years, depending on the management followed (Chepil et al., 1962).

The Chinese use straw barriers in a checkerboard pattern (Xu et al., 1982), raised fences (Liu et al., 1983), or forest belts, also called shelterbelts (Dong et al., 1983), to protect railroads and highways from blowing sand. Shelterbelts stabilize sand or improve the microclimate of irrigated crops. The shelterbelts tend to keep the water table low because of their own demands for water (Walls 1982). Shelterbelts are also used in India to reduce wind velocity, erosion, and evaporation losses (Gupta et al., 1983). The success of shelterbelts depends on sufficient annual rainfall to sustain the trees, and alternate uses of the trees (lumber, pulpwood, firewood, etc.).

II. Basic Wind Erosion Process

Wind erosion has had a tremendous impact on agricultural development. Throughout history it has influenced not only the location of settlements, but the development of the soil and plant resources as well. Bagnold (1939) described the very basic processes of detachment, movement, and deposition of wind-eroded particles. Most of Bagnold's work was on sand seas of the Sahara region of North Africa. Chepil and Woodruff (1963) summarized the results of 20 years of intensive research on cultivated lands of the central Great Plains region of the United States, a region severely affected by a drought and severe wind erosion in the 1930s. Their work led to the development of a wind erosion equation (Woodruff and Siddoway, 1965) suitable for planning wind erosion control systems.

Wind erosion can occur when soil aggregates, capable of being moved by wind, are present in the surface soil, the wind velocity is sufficient to detach soil aggregates, and the soil surface is not protected with nonerodible material. As the wind velocity exceeds the threshold velocity required to initiate soil movement, individual soil aggregates become aerodynamically unstable, are injected into the wind stream, and are transported downwind. The distance traveled by the airborne particles depends on the velocity of the wind and the shape and density of the soil particles.

Some of the dislodged aggregates are too large or heavy to become airborne, but may roll along the soil surface in a transport mode called surface creep. Surface creep is usually composed of aggregates 500 to 1000 μm in diameter and comprises 5 to 25% of the total material eroded. Aggregates small enough to be injected into the wind stream, but which gravity pulls back to the soil surface,

are in a transportation mode called saltation. Upon striking the soil surface, the saltating aggregates dislodge additional aggregates. Saltating aggregates are usually 100 to 500 μm in diameter, and comprise 50 to 75% of the total eroded material. If the aggregates are very light or small, they may actually be transported great distances in a mode called suspension. Aggregates in suspension are usually 2 to 100 μm in diameter and comprise 3 to 40% of the total eroded material (Chepil and Woodruff, 1963).

III. Extent of Problem

Worldwide, wind erosion has been recognized for centuries. Deane (1790) published the first accounts of wind erosion problems in the United States. Scientists recognized the need to quantify erosion to determine the extent of the problem. Woodruff and Siddoway (1965) developed a wind erosion equation to estimate potential average annual erosion. We now have equipment to measure wind erosion in the field (Fryrear, 1986).

Actual measurements of wind erosion are scarce, but dust loads have been estimated. Junge (1977) estimated the annual dust load from the Sahara to be 60 million to 270 million tons. Hagen and Woodruff (1975) estimated the annual dust load from the Great Plains region to be 37 million to 551 million tons. Since less than 1% of the total wind-eroded material is transported in the earth's atmosphere (Gillette, 1977), the quantity of material moving from one location to another at the soil's surface is very large. The "dust bowl" days of the mid-1930s focused attention on the potential magnitude of wind erosion in the United States and the far-reaching impact of uncontrolled wind erosion. The Soil Conservation Service annually reports the quantity of land damaged by wind erosion in the United States (Table 1). Land area damaged each year varies tremendously, depending on the antecedent rainfall and cropping conditions. Similar data were not available for other countries.

In the USSR, the number of dust storms each year has been reported for various locations. The greatest number (113) was observed in Central Kara Kum at Cheshme in 1948 (Sapozhnikova, 1970). Dust storms in the USSR usually last less than 3 hours, but in May 1950, in Nebit-Dag, a dust storm lasted 73 hours, and at Aidin in November 1951 a storm lasted more than 70 hours.

Soil losses in Bikaner, India, in 1978 over a 75-day period was 615 tons per hectare, and at Chandan, India, 325 tons per hectare (Gupta et al., 1981). In south and western Australia, large areas of sandy soils have been cultivated even though the area receives 300 to 500 mm of rainfall annually. Problems are severe during crop establishment or when grazing removes the pasture residues. Additional problems arise when salt-affected soils are subjected to wind erosion and the eroded soil accumulates on less saline areas, thus deteriorating the deposit locations (Malcolm, 1983).

In Big Spring, Texas, blowing dust occurs for an average of 26 days annually (see Table 1), and the storms average 7.2 hours in duration. Fryrear (1981)

Table 1. Land damaged by wind erosion as reported by the USDA-Soil Conservation Service and number of days with blowing dust each month and year at Big Spring, Texas

Year	Land damaged, 1000 ha/yr	Month J	F	M	A	M	J	Jy	A	S	O	N	D	Yearly Total
1953	2,064	11	6	6	10	8	4	0	0	3	1	3	7	59
1954	2,226	3	9	9	1	3	1	0	0	0	0	2	3	31
1955	6,207	1	2	5	9	4	0	0	0	0	2	5	6	34
1956	3,850	2	7	10	4	0	0	1	4	1	3	1	2	35
1957	4,125	3	1	7	4	5	3	0	0	0	0	0	3	26
1958	1,571	0	3	0	6	2	1	2	0	0	0	1	1	16
1959	1,296	2	1	9	1	1	1	0	1	0	0	1	1	18
1960	1,021	2	4	5	1	4	1	0	0	0	0	2	2	21
1961	903	1	3	5	8	2	0	0	0	0	1	0	2	22
1962	589	2	3	6	1	4	6	0	0	0	0	0	0	22
1963	1,218	5	3	3	3	2	1	1	0	0	0	0	1	19
1964	1,728	4	2	6	3	4	0	0	1	0	0	2	1	23
1965	1,571	6	5	4	6	3	2	0	0	0	0	2	3	31
1966	432	6	2	9	2	0	0	0	0	2	0	0	3	24
1967	982	6	7	4	6	8	0	1	0	0	3	3	1	39
1968	471	0	1	4	4	3	1	0	0	0	3	1	4	21
1969	354	4	3	2	1	0	3	0	0	0	1	0	0	14

1970	746	3	2	1	5	4	4	0	0	1	1	2	1	24
1971	1,886	4	6	10	6	3	0	0	0	0	0	1	1	31
1972	909	1	5	1	5	0	0	0	0	1	0	2	2	17
1973	792	3	1	7	4	2	1	0	0	0	0	5	3	26
1974	1,520	4	9	6	13	3	1	2	0	1	0	1	1	41
1975	2,300	6	0	7	2	3	0	0	0	0	0	2	0	20
1976	2,495	1	5	7	6	2	0	1	0	0	0	1	1	24
1977	3,235	3	7	5	2	0	0	0	0	1	1	4	6	29
1978	1,151	1	4	4	3	2	0	0	1	0	0	1	6	22
1979	1,163	3	4	5	6	2	0	0	0	0	5	1	2	28
1980	2,064	5	2	7	5	2	0	0	0	0	0	0	0	21
1981	5,058	0	0	6	2	0	0	0	0	0	0	1	3	12
1982	2,067	3	3	5	4	0	2	1	0	0	0	2	4	24
1983	2,242	2	4	6	6	5	0	0	0	2	0	4	3	32
1984	4,990	0	6	9	14	4	1	2	1	2	2	0	0	41
1985	3,440	4	1	3	3	3	1	0	0	0	0	2	1	18
1986	3,389	3	5	8	5	4	2	0	0	0	0	1	1	29
Averages		3.0	3.7	5.6	4.8	2.7	1.0	0.3	0.3	0.4	0.7	1.6	2.2	26

Source: Fryrear, 1981.

Table 2. Total number of dust storms and total hours of dust in each dust storm rating system, from 1973 to 1979

DSRS[a]	No. of storms in each category (%)	Dust storm Average duration (h)	Yearly (hr)	Total (%)	Average wind velocity (km/hr)
1	57 (30)	5.8	47	24.4	48
2	42 (23)	6.7	40	20.8	51
3	41 (22)	7.4	43	22.4	52
4	19 (10)	8.0	22	11.5	54
5	15 (8)	8.9	19	9.9	61
6	9 (5)	12.5	16	8.3	64
7	3 (2)	10.5	5	2.7	75
Total	186 (100)		192	100	

[a]DSRS Numerical value	Dust storm description (hours listed are minimum time)
1	Light blowing dust >0.5 hr, minimum visibility 7 km
2	Light blowing dust >2 hr, minimum visibility 5 km
3	Blowing dust >4 hr, minimum visibility 1.6 km
4	Blowing dust >4 hr, minimum visibility 800 m
5	Blowing dust >4 hr, minimum visibility 400 m
6	Blowing dust >6 hr, minimum visibility 300 m
7	Heavy blowing dust >8 hr, minimum visibility 200 m
8	Heavy blowing dust >10 hr, minimum visibility 100 m
9	Severe blowing dust >24 hr, minimum visibility 50 m
10	Severe blowing dust >48 hr, minimum visibility 5 m

developed a numerical Dust Storm Rating System (DSRS) based on the reduction in visibility and duration of the storm, using the dust storm records that have been collected at Big Spring since 1953 (see Table 1). Seventy-four percent of the storms were rated No. 3 or less and constitute 68% of the total hours of blowing dust but only 11.5% of the total dust load (Table 2). The transport capacity of the wind increases as the cube of the windspeed. Although the storms with a high DSRS value are infrequent, they may contribute most of the atmospheric dust load. By rating storms, comparisons between years or changes in erosion conditions can be documented. Using the DSRS, analyses of dust storms are possible to determine the frequency distribution of storms over specified periods of time at different locations.

The major potential wind eroded areas worldwide correspond to the distribution of arid soils (Table 3). These arid-region soils constitute 31.5% of the total land of this world. The largest concentration of arid-region soils is in Africa (17.7 million ha), but the continent of Australia has the highest percentage (82.1%) of arid land (Dregne, 1976). The distribution of the arid and semiarid regions of the world is illustrated in Figure 1.

Table 3. Distribution of arid-region soils by continent, excluding polar regions

Continent	Arid-region soils	
	Area in sq. km[a]	Percentage of continent
Africa	17,660	59.2
Asia	14,405	33.0
Australia	6,250	82.1
Europe	644	6.6
North America	4,355	18.0
South America	2,835	16.2
Total	46,149	

Source: From Dregne, 1976, Table 3.1.
[a] Figures in thousands.

While severe and extensive wind erosion is readily evident in arid or semiarid regions because of the dry climate and sandy soil, high winds can cause severe erosion in humid regions as well. Robinson (1968) reported that during a 5-day period with steady winds of 32 km/h (midday winds between 48 and 64 km/h) a 60-km-square area of fen-land in Lincolnshire, England, lost 50 mm of soil.

IV. Deposition of Eroded Material

The effects of loss of the eroded material from the source area, the material passing through the atmosphere in the transport area, and depositing of eroded material at its eventual depositional point must be understood to fully appreciate the complete role of wind erosion and its impact on the environment. Once soil particles have been detached from the soil surface and transported to the troposphere by wind, gravity causes them to settle. The major depositional area is immediately downwind from the source point. In some cases the eroded material settles into bodies of water, and in these instances the depositional areas do not directly affect the soils but can have an impact on water quality. Large quantities of eroded soil in the atmosphere can alter the radiation balance and influence global weather patterns.

Ancient depositional areas now serve as important agricultural regions. The loess soils of central Europe were deposited by winds from naked moraines. China's fertile loess is windblown deposit from the now-barren Gobi Desert, and the deep loess soils in the central United States were transported by wind erosion processes. Loess deposits in Israel, the Nile Valley, and the Cape Verde Islands are the result of windblown dust from the Sahara (Matznetter 1960). McTainsh and Walker (1982) reported that dust along the west coast of Africa may have originated in the Faya Largeau region 640 km northeast of Lake Chad. Prospero et al., (1972) traced the dust plumes from West Africa across the Atlantic Ocean to South America and the West Indies.

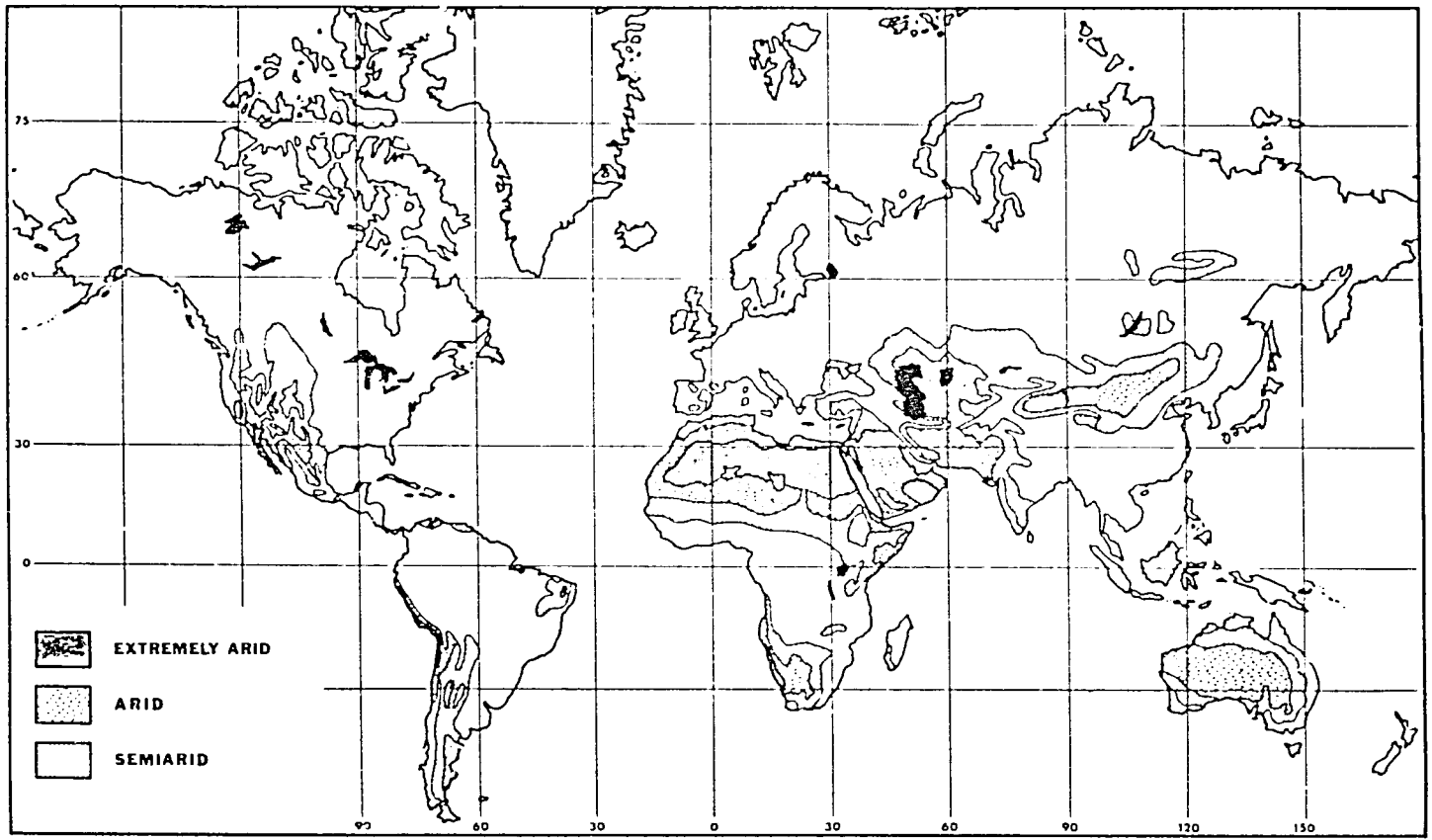


Figure 1. Arid regions of the world. Polar arid regions not shown. (From Dregne, 1976, modified from Meigs, 1953.)

V. Impact on Soil Productivity

Man cannot continue to ignore wind erosion. When the land productivity declines, insufficient food and fiber will be produced and we will be forced to deal with wind erosion. Unfortunately, by the time the problem becomes obvious, soil degradation has progressed to the point that the damage may be irreversible. The rate of the decline in productivity is related to the characteristics of the soil profile in a given climatic region. In areas where the erosion process has already stripped the soil of its fertility and water-holding capacity, crop yields are so low and erratic that further yield decline may be disastrous. Even the slightest decline in these potentially high-stress areas can be a large percentage of the yield potential. Data on the impact of wind erosion on soil productivity are now being accumulated. Lyles (1975) estimated that wheat yields in the Great Plains region of the United States is reduced 2 to 10% with the removal of 25 mm of topsoil by wind. In western Australia experiments showed a possible 2 to 7.5% reduction with wind erosion losses of 1 mm and 10 to 25% reductions with 8 mm loss of topsoil (Marsh, 1980). Natural erosion in the USSR of 5 mm reduced winter wheat yields 50%, and losses of 14 mm reduced yields 70% (Marsh, 1980). Buringh (1981), estimated that, worldwide, 50 Mha cropland is lost to wind and water erosion in a 20-year period. While the 50 Mha represents only 3.3% of the total estimated cropland in 1975, the loss of 50 Mha in 20 years is equivalent to 5 ha per minute, or about one average-size farm per minute in some parts of the developing world (Buringh, 1977). These figures illustrate that the loss of productive lands to erosion can affect an entire civilization.

VI. Wind Erosion Control

Wind erosion can be controlled by reducing wind velocity at the soil surface, roughening the soil surface, or covering the soil with nonerodible materials. The velocity of the wind at the soil surface can be reduced with standing vegetation or wind barriers (Fig. 2). The porosity of the barrier to wind flow will influence its effectiveness, but 40% porosity is recommended (Hagen, 1976). The erodibility of soils can be reduced by roughening the soil surface with tillage implements (Fig. 3) or by leaving nonerodible aggregates such as stabilized soil clods, rocks, or vegetation on the soil surface. In small-grain production areas of the United States, the major practice is to leave a portion of the crop residue on the surface. Covering even a small percentage of the soil surface with nonerodible material (Fig. 4) will reduce the soil loss of even a highly erodible soil (Fryrear, 1985). If tillage implements are used to generate the cloddy surface, additional tillage may be required after each major rainstorm to roughen the surface, depending on the soil texture. Within each area the most effective wind erosion control will use a combination of various control methods.

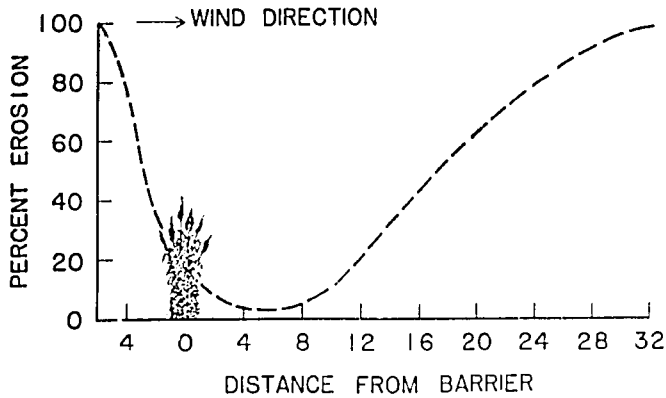


Figure 2. Influence of a 40%-porous wind barrier on wind erosion expressed as percentage of open field erosion for all winds normal to wind barrier: Wind velocity measured at 0.12 H (H = barrier height) above the soil surface. (From Hagen, 1976.)

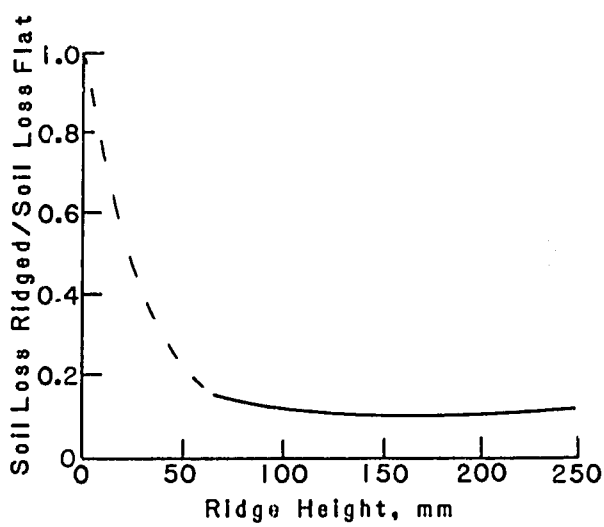


Figure 3. Relation between soil loss ratio and soil ridge roughness, K_r, with wind direction normal to ridges in the wind tunnel.

$$K_r = \frac{4\ (\text{ridge height})^2}{\text{distance between ridges}}$$

(From Fryrear, 1984.)

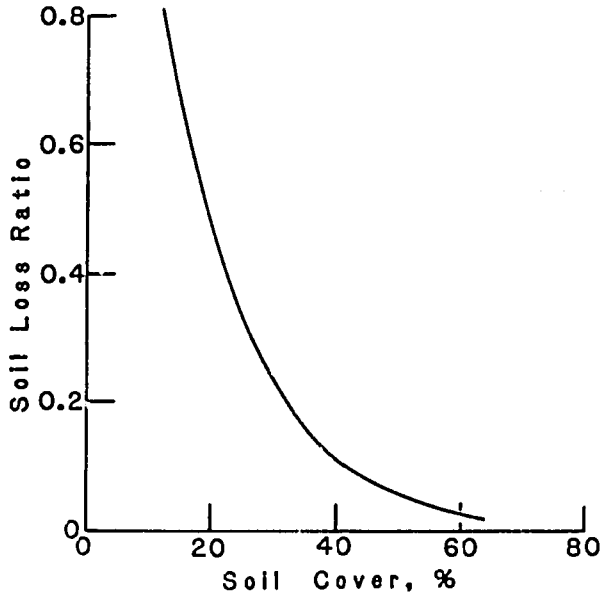


Figure 4. Relation between soil loss ratio (soil loss ratio with no cover equals 1), and percentage of soil surface covered with flat nonerodible material. (From Fryrear, 1985.)

VII. Conclusions

A study of geomorphological forms that include large expanses of loess soils, fluted rocks, and sand dunes illustrates that wind has been a significant erosion agent over long periods of time. Wind erosion continues to affect mankind and man's activities in semiarid and arid regions of the world. When we choose to ignore wind erosion, severe desertification may result. Millions of hectares of productive land are susceptible to degradation to desertlike condition. Estimates of total dust load to the atmosphere from the Sahara and the Great Plains of the United States vary from 97 million to 751 million tons per year. Individual storms may last a few minutes to several days. The limited data available suggest that severe storms with high wind velocities cause the most severe damage to soils and contribute the majority of the dust load to the atmosphere.

To reduce the impact of wind erosion on future generations, mankind must use the current knowledge of the wind erosion processes and identify opportunities to control wind erosion by using the soil, crop, and climatic resources available at each location. By using tools such as timely and effective tillage, crop residues, wind barriers, and combinations of all three and by continuing to develop more effective and efficient tools, we can minimize the hazards of wind erosion.

References

Bagnold, R.A. 1939. The Physics of Blown Sand and Desert Dunes. London: Methuen, 265.

Buringh, P. 1977. Food production potential of the world. World Dev. 5:477–485.

Buringh, P. 1981. An assessment of losses and degradation of productive agricultural land in the world. Working Group on Soils Policy, Second Meeting, Rome.

Chepil, W.S., and N.P. Woodruff. 1963. The physics of wind erosion and its control. *In* A.G. Norman, ed. Advances in Agronomy, Vol. 15, pp. 211–301. New York: Academic Press.

Chepil, W.S., E. Burnett, and E.L. Duley. 1963. Management of Sandy Soils in the Central United States. USDA Farmers' Bul. No. 2195.

Chepil, W.W., W.C. Moldenhauer, J.A. Hobbs, N.L. Nossoman, and H.M. Taylor. 1962. Deep plowing of sandy soils. USDA-ARS, Prod. Res. Rep. No. 64.

Deane, S. 1790. The New-England farmer: or, Georgical dictionary: Containing a compendious account of the ways and methods in which the most important art of husbandry is practised. Worcester, Mass.

Dong, Guangrong, Zou Guixiang, Li Changzhi, and Chen Fusheng. 1983. Preliminary observation of the efficiency of the wind-preventing and sand-resisting forest belt in the Western part of the Great Bend of the Huanghe River. J. Desert Res. 3(1):9–19.

Dregne, H.E. 1976. Soils of Arid Regions. New York: Elsevier, p. 237.

Drown, W., with the aid and inspection of Solomon Drown. 1824. Compendium of agriculture, or the farmer's guide, in the most essential parts of husbandry and gardening. Providence, R.I.

Fryrear, D.W. 1981. Southern Great Plains. Tran. ASAE 24(4):991–994.

Fryrear, D.W. 1984. Soil ridges-clods and wind erosion. Tran. ASAE. 27(2):445–448.

Fryrear, D.W. 1985. Soil cover and wind erosion. Tran. ASAE. 28(3):781–784.

Fryrear, D.W. 1986. A field dust sampler. J. Soil and Water Conserv. 41(2):117–120.

Gillette, D.A. 1977. Fine particulate emissions due to wind erosion. Trans. ASAE 20(5):890–897.

Gupta, J.P., R.K. Aggarwal, and N.P. Raikhy. 1981. Soil erosion by wind from bare sandy plains in western Rajasthan, India. Arid Envir. 4:15–20.

Gupta, J.P., and G.N. Gupta. 1981. A note on wind erosion from a cultivated field in Western Rajasthan. J. Indian Soc. Soil Sci. 29(2):278–279.

Gupta, J.P., G.G.S.N. Rao, G.N. Gupta, and B.V. Ramana Rao. 1983. Soil drying and wind erosion as affected by different types of shelterbelts planted in the desert region of Western Rajasthan, India. J. Arid Envir. 6:53–58.

Hagen, L.J. 1976. Windbreak design for optimum wind erosion control. *In*: Shelterbelts on the Great Plains. pp. 31–37. Ag. Counc. Pub. No. 78.

Hagen, L.J., and N.P. Woodruff. 1975. Particulate Loads Caused by Wind Erosion in the Great Plains. Air Pollution Control Association J. 25(8):860–871.

Hill, I. 1824. Sandy soil. Farmer's Monthly Visitor 4:7.

Junge, C. 1977. The importance of mineral dust as an atmospheric constituent. Workshop on Saharan Dust, Gotherbury, Sweden, 25–28, April 1977.

Liu, Xianwan, Lin Yuqian, He Daliang, and Chen Fusheng. 1983. A study on the experiment of the under-leading fence in wind tunnel. J. Desert Res. 3(3):25–34.

Lyles, L. 1975. Possible effects of wind erosion on soil productivity. J. Soil Water Conserv. 30:279–283.

Malcolm, C.V. 1983. Wind and Salinity as Factors in Land Degradation in Arid and Semi-arid Parts of Australia. UNESCO Seminaire Sur L'Erosion Eolienne. Djerba, Tunisia, Nov. 21-26, 1983.

Marsh, B.A. 'B. 1980. Economics of soil loss: A top priority research need Paper delivered at Int. Soil Conserv. Conf., England.

Matznetter, J. 1960. Die kapverdischen Inseln. Mitteil. Osterr. Geograph. Gesellsch. 102:1-40.

McTainsh, G.H., and P.H. Walker. 1982. Nature and distribution of Harmattan dust. Zeitschrift fur Geomorphologie. 26(4):417-435.

Meigs, P. 1953. World distribution of arid and Semiarid homoclimates. *In* UNESCO, ed., Reviews of Research on Arid Zone Hydrology, Arid Zone Res., I:203-210.

Morales, Christer 1977. Saharan Dust. New York: John Wiley & Sons.

Prospero, J.M., R A. Glaccum, and R.T. Nees. 1981. Atmospheric transport of Saharan Dust over the western equatorial North Atlantic Ocean, J. Geophysical Res. 77:5255-5265.

Robinson, D.N. 1968. Soil erosion by wind in Lincolnshire (England). E. Midland Geographer 4(6), No. 30:351-362.

Romanov, N.N. 1960. Dust storms in Central Asia. Tr. TashGU, Issue 174:198.

Sapozhnikova, S.A. 1970. A Schematic map of a number of days with dust storms in the arid zone of the USSR and adjacent territories, Tr. NIIAK, Issue 65:61-69.

Walls, James. 1982. Combating Desertification in China. UNEP Nairobi, Kenya.

Woodruff, N.P., and F.H. Siddoway. 1965. A Wind-erosion equation. Soil Sc. Soc. Am. Proc. 29:602-608.

Xu, Junling, Pei Zhangquin, and Wang Renhua. 1982. A research on the width of the protection belt of half-hidden straw checkerboard barriers. J. Desert Res. 2(3):16-22.

Methods for Removing Spatial Variability from Field Research Trials*

D.J. Mulla, A.U. Bhatti, and R. Kunkel

I. Introduction 201
II. Experimental Design 202
III. Methods of Statistical Analysis 203
IV. Explicit Trend Analysis and Removal 204
V. Comparison of Methods 206
VI. Summary 211
References 212

I. Introduction

Agronomists and soil scientists concerned with producing food and fiber or improving national food security conduct thousands of field experiments annually to determine which crop varieties, fertilizer rates, or management techniques will optimize crop yield. Because treatment differences in these experiments are often statistically not significant (Trangmar et al., 1987), making recommendations to growers is difficult or impossible.

A major source of nonsignificance is spatial correlation between closely spaced plots, which makes the comparison of treatment differences more accurate for adjacent plots than for plots separated by large distances. The source of spatial variability is often due to soil differences within the experiment. Soil differences produce an extra source of variability whose effects are not easily separated from true treatment effects.

*Scientific Paper No. 7820. College of Agriculture and Home Economics Research Center, Washington State University, Pullman, Washington. Project 0494.

© 1990 by Springer-Verlag New York Inc.
Advances in Soil Science, Volume 13

Preceding Page Blank

The purpose of this chapter is to discuss selected methods that have been used to improve the interpretation of field experiments in the presence of spatially variable soil properties. The discussion deals briefly with aspects of experimental design that are used to minimize statistical errors, with statistical techniques for separating treatment effects from error, and with selected approaches for explicit trend analysis and removal. Finally, an example is given to illustrate how the interpretation of an experiment conducted on spatially variable soil is affected by analyzing it with three different methods. The methods chosen for comparison include analysis of variance (AOV), analysis of covariance (AOC), and nearest-neighbor analysis (NNA).

II. Experimental Design

An experiment is conducted to test a hypothesis or to determine the relative outcomes of applying different treatments. To obtain significant results, the experiment must be carefully conducted so that the outcomes represent as closely as possible the effects of treatments and not the effects of some uncontrolled source of variation. Uncontrolled sources of variation, such as soil fertility trends, gradients in slope, and microclimatic differences, are undesirable and should be minimized.

Two aspects of experimental design that are important for the accurate interpretation of experiments conducted on spatially variable soils are replication and randomization. Generally, experimental designs include treatment replication to facilitate the estimation of experimental error, reduce the standard deviation of the treatment mean, and increase the range of conditions under which treatment effects are evaluated (Steel and Torrie, 1980). Many experimental designs assign treatments to plots in a random manner. Randomization ensures that experimental error estimates are unbiased. It tends to compensate for correlated errors that result when adjacent plots have yields which are more similar than yields from widely separated plots. As is shown later, however, randomization alone cannot always completely compensate for correlated errors.

Commonly, experimental designs fall into one of two broad categories depending on whether or not treatments are assigned to plots in a random or a semisystematic fashion. Designs that involve randomization include the completely random design and the randomized complete block design. Designs that assign treatments to plots in a semisystematic fashion (involving a restricted degree of randomization) include Latin square designs, split-plot designs, and nearest-neighbor designs.

The completely random design is useful for experiments conducted when no soil variability is present. This design uses no blocks, and hence no estimate of the effect of environment on yield is possible (Steel and Torrie, 1980). Randomized complete block designs require that all treatments occur once within each separate block of the experiment, and these treatments are randomized within each block. The size and location of blocks can be specified to correct for

anticipated effects of soil variability. The presence of blocks allows a correction to be made for the variability of treatments that occurs because of changes in soil properties across the experiment. Often, this soil variability is great enough to cause large variability within blocks. In this case, a large error term results and the analysis is less precise than in the case of relatively homogeneous blocks (Steel and Torrie, 1980).

An important feature of experimental design involves specifying the size and shape of plots and blocks. Results from uniformity trials have shown that the yield on small square plots is generally more variable from plot to plot than the yield on larger rectangular plots (Steel and Torrie, 1980). If an experimental design involving blocks is involved, it is generally desirable to select a block size that naturally separates the heterogeneous field into approximately square subsections that are nearly homogeneous. In practice, it is difficult to ascertain the optimum size and locations of blocks, since the patterns in soil variability are often not known in advance. Also, the soil may be so heterogeneous that blocking has no perceptible advantage.

Semisystematic experimental designs such as the Latin square (Myers, 1966) or nearest-neighbor designs (Freeman, 1979) allow the effects of systematic trends in soil fertility along rows or columns to be removed. In the Latin square and nearest-neighbor designs each treatment occurs only once in each row or column, whereas in most nearest-neighbor designs there is the additional requirement that each treatment is bordered only once by all possible combinations of pairs of the other treatments. The Latin square design is often undesirable because of the requirement that the number of rows, columns, and treatments be equal (Steel and Torrie, 1980). For experiments with a large number of treatments, the number of plots required in both the Latin square and nearest-neighbor designs may become prohibitively large.

III. Methods of Statistical Analysis

The classic method for statistical analysis of field experiments is analysis of variance (AOV). If certain basic assumptions are valid, experimental designs such as those discussed in the previous section may be analyzed using AOV. Alternatively, analysis of covariance (AOC) may be used when measurements of the spatially varying soil covariate are available. With both AOV and AOC techniques, the researcher may fail to remove the effects of soil variability completely because of one of two problems. The first problem involves the use of improper experimental design. This may include failure to randomize, insufficient replications, failure to use blocks, or improper size and shape of plots or blocks.

Alternatively, one or more of the theoretical assumptions required for using AOV or AOC may be violated. The use of AOV requires that treatment and soil effects be additive, that the experimental errors be normally distributed, that no correlation exists between errors of adjacent plots, and that a common variance exists for all treatments (Steel and Torrie, 1980). In addition to the previous

assumptions, the use of AOC requires that the regression of yield on the soil covariate is linear and independent of treatments or blocks, and that the residuals are normally and independently distributed (Steel and Torrie, 1980). An assumption made when using AOV to test the significance of treatment effects for the Latin square design is that no interaction exists between treatment, row, and column effects. In the presence of yield trends due to soil variability, the researcher should be very cautious about interpreting the results from AOV or AOC, since the assumption that experimental errors are random and uncorrelated is often violated.

IV. Explicit Trend Analysis and Removal

In most cases, it is not known before a field experiment is conducted, whether or not patterns in soil variability exist which will cause correlated errors between yields of adjacent plots. Consequently, a researcher may be faced with the task of salvaging an experiment that was improperly designed or violates one or more of the assumptions required for classical statistical analysis. In such a situation, the researcher may attempt to determine the form of the trend and remove it with one of a variety of techniques. Techniques that have been developed for this purpose include various nearest-neighbor techniques for trend removal and data analytic techniques for least-squares trend smoothing. With both methods the researcher does not necessarily have to use special designs in anticipation of an effect due to soil variability.

Least-squares smoothing techniques are beyond the scope of this discussion and will not be discussed further. The researcher interested in pursuing these methods in detail is referred to articles by Green (1985), Green et al. (1985), and Besag and Kempton (1986).

A method for nearest-neighbor adjustment of yield trends was first suggested by Papadakis (1937). Essentially, this technique involves subtracting the mean treatment yield from the yield of each plot, and subsequently using the average of the residual yields of adjacent plots in an analysis of covariance (Atkinson, 1969). Bartlett (1978) suggested an iterative approach for estimating yield trends, while Wilkinson et al. (1983) developed an improved method appropriate in situations when nonstationary trends are present.

The nearest-neighbor approach used in this chapter is an iterative method (Schwarzbach, 1984) in which treatment means are adjusted until the nearest-neighbor local trends for each treatment average to zero. The philosophy for this approach is that the unadjusted treatment means do not represent the true effect of the treatments. The true effect is best estimated by comparing yields for neighboring plots with different treatments. It is assumed that the plots are narrow in width compared to their lengths. Therefore, yield comparisons are made only for neighbors in the direction of the narrowest plot dimension.

Consider an experiment in which the yield, Y_{it}, on plot i having treatment t is affected by both treatment and soil effects. The objective of nearest-neighbor

analysis is to estimate the true treatment mean, μ_t, and the true effect of soil trend, ξ_{it}, using the linear model given by

$$Y_{it} = \mu_t + \xi_{it} + \eta_i \tag{1}$$

where η_i is the effect due to local uncorrelated errors which have zero mean and variance σ^2.

The nearest-neighbor approach to estimating true treatment means uses the iterative procedure described later, where the superscript k ($k = 1, 2, 3, \ldots$) denotes an iteration cycle. The effect of soil trend for each plot i with treatment t, ${}^k\xi_{it}$, is computed by subtracting the estimated treatment mean, ${}^k\mu_t$, from the actual plot yield, Y_{it},

$${}^k\xi_{it} = Y_{it} - {}^k\mu_t \tag{2}$$

The treatment mean for the first cycle of iteration is given by

$${}^1\mu_t = (1/m) \sum_{i \in t} Y_{it} \tag{3}$$

where m is the number of plots receiving treatment t. The value of the treatment mean on the first iteration cycle is often significantly different from the true mean due to the effect of soil variability.

Assuming that treatment and soil effects on yield are additive, it would be expected that the yields for plot i and its two neighboring plots $i - 1$ and $i + 1$ would generally give a rather accurate representation of the true relative performance of the three different treatments. This comparison would certainly be more accurate than a comparison of the yields for the three treatments from widely separated plots which are differentially affected by soil variability. The comparison of yields on neighboring plots can also be affected, to a smaller extent, by short-range variability in soil properties. Therefore, to improve the accuracy of the comparison, the nearest-neighbor method adjusts treatment means to compensate for the effect of local trends.

Nearest-neighbor differences, ${}^k\tau_{it}$, for soil trend effects on plot i and its neighboring plots, $i - 1$ and $i + 1$, are computed using the expression

$${}^k\tau_{it} = {}^k\xi_{i,t} - \frac{({}^k\xi_{i-1,t'} + {}^k\xi_{i+1,t''})}{2} \tag{4}$$

where the subscripts t' and t'' refer to the treatments on plots $i - 1$ and $i + 1$, respectively, and the ${}^k\xi$ values are computed using Eq. 2. If the local effects of soil trend are smooth and linear, the term in parentheses in Eq. 4 will equal the first term and the nearest-neighbor difference will be zero. If, however, the nearest-neighbor difference is nonzero, a comparison of yields for the three plots will not reflect the true relative performance of the treatments.

Nearest-neighbor differences for each of the m plots receiving treatment t are computed using Eq. 4 and the average value is used to update the treatment means for the next cycle of iteration using the expression

$$^{k+1}\mu_t = {}^{k}\mu_t - b\,(1/m) \sum_{i \in t} {}^{k}\tau_{it} \tag{5}$$

The constant b in Eq. 5 is typically set to a value of about .75 so that the adjustment proceeds by partial trend removal and oscillations in treatment mean are avoided.

The updated treatment means are used for a new estimate of effect of soil trend in Eq. 2, and Eqs. 4 and 5 are used to obtain the next updated value of treatment mean. The iterative process continues until the nearest-neighbor differences for all m plots receiving any treatment all average to zero. In simple terms, this means that the iterative process ends when the second term on the right-hand side of Eq. 5 is zero for all treatments.

As an illustration of this process, consider the hypothetical situation in which the average nearest-neighbor differences in Eq. 5 are positive. This can be interpreted as a situation in which the m plots receiving treatment t are, on the average, located on soil which is more fertile or productive than the soil on neighboring plots. To correct for this trend, the mean yield for treatment t is decreased using Eq. 5, thereby reducing the nearest-neighbor differences in the next cycle of iteration.

Wilkinson et al. (1983) have discussed some of the limitations of the iterated nearest-neighbor analysis. These include loss of efficiency due to yield correction using the treatment means, and upward bias in the treatment F-ratio. These limitations are, however, not usually significant unless there are substantial nonlinear trend effects in the experiment.

V. Comparison of Methods

As an example of the effect of soil variability on field experiments, consider a fertilizer experiment conducted with Russet Burbank potatoes. The experiment was conducted by Dr. R. Kunkel of Washington State University in 1971 on soil which was visually homogeneous and level. A two-factor split-plot experimental design with six blocks and 30 treatments (180 plots total) was used. The first factor, method of application, was assigned randomly to each of five strips of six plots within each block. The second factor, rate of application, was assigned randomly to each of the six plots within each strip. The five methods of applying fertilizer were broadcast, half broadcast-half banded, banded, half banded-half sidedressed, and sidedressed. The six fertilizer rates applied were 112, 224, 336, 448, 560, and 672 kg/ha of a 12% N-5.3% P-9.9% K blend fertilizer. Table 1 summarizes the treatment information. Seed pieces of Russet Burbank potato were planted in four rows per plot separated by 81.3 cm at spacings of 20.3 cm within each row. The plot dimensions were approximately 3.35-m wide and 10.06-m long and the total area of the experiment was approximately 0.61 ha.

Soil pH was measured on each plot from composite samples before planting. After harvest, the total yield and yield of U.S. grade 1 A (grade #1) potatoes was

Table 1. Description of 12% N–5.3% P–9.9% K fertilizer application treatments used in the Russet Burbank potato field experiment

Treatment #	Method of application	Rate of application (kg/ha)
1	Broadcast	112
2		224
3		336
4		448
5		560
6		672
7	1/2 Broadcast–1/2 Banded	112
8		224
9		336
10		448
11		560
12		672
13	Banded	112
14		224
15		336
16		448
17		560
18		672
19	1/2 Banded–1/2 Sidedressed	112
20		224
21		336
22		448
23		560
24		672
25	Sidedressed	112
26		224
27		336
28		448
29		560
30		672

determined for each plot. Figure 1 shows the variability of soil pH for each of the 180 plots in the experiment. Each vertical line in Figure 1 represents the average soil pH for a single plot. The variability of potato yield for each of the plots is shown in Figure 2. It can be seen from comparing the two figures that yields tend to be lower when soil pH is low than when soil pH is high. Thus, at least part of the performance in the experiment is influenced by trends in soil properties. This effect must be separated from the effect of treatments to obtain a true evaluation of treatment effects.

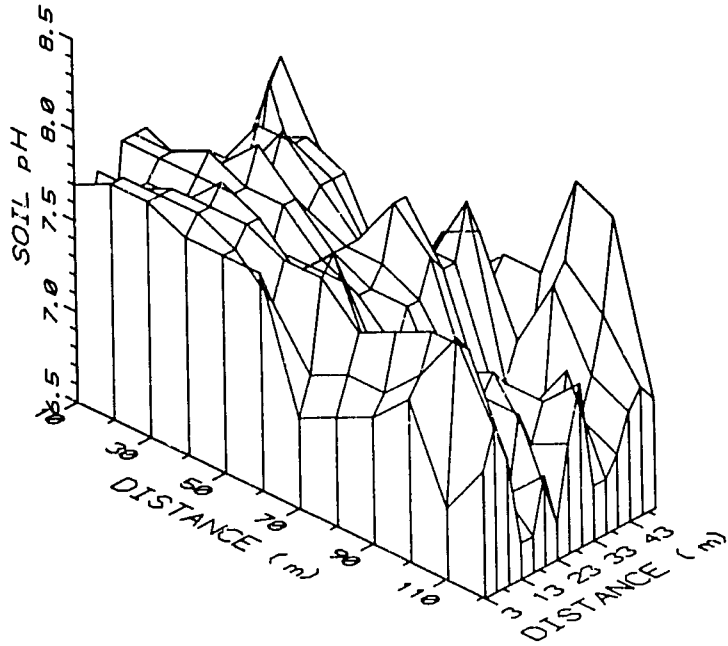


Figure 1. Three-dimensional plot of average soil pH for each of the 180 plots in the Russet Burbank field experiment.

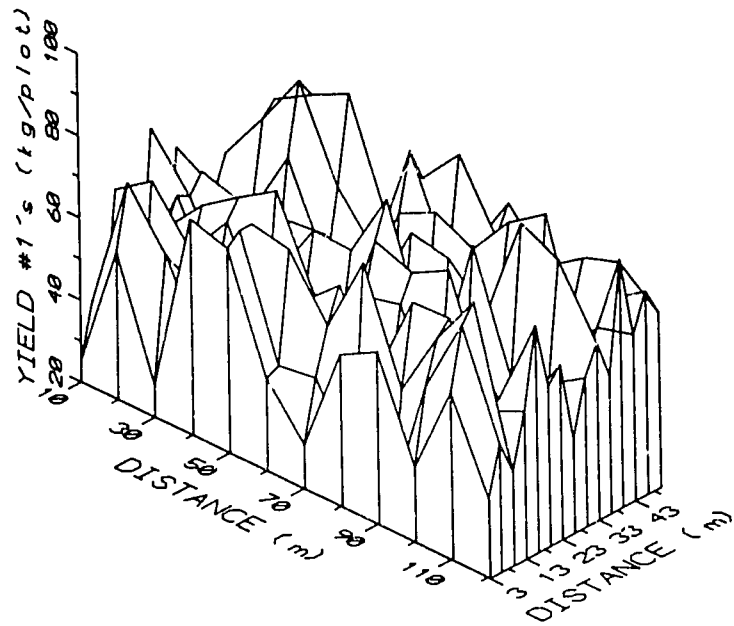


Figure 2. Three-dimensional plot of yield grade #1 potatoes (kg) for each of the 180 plots in the Russet Burbank field experiment.

Table 2. Statistical results from analysis of variance (AOV) of the yield of grade #1 Russet Burbank potatoes[a]

Source of variation	Degrees of freedom	Sum of squares	F-value
Blocks	5	1756.1	1.8
Method	4	5922.4	7.6**
Block*method (error A)	20	3877.2	
Rate	5	6202.3	14.8**
Method*rate	20	4298.2	2.6**
Block*method*rate (error B)	125	10474.6	
Total	179	32530.9	

[a] Results significant at the 1% level are denoted by **, while results significant at the 5% level are denoted by *.

Classical statistical analysis of the experiment was conducted using SAS for both AOV and AOC. Results of the AOV (Table 2) show that both the method and rate of fertilizer application are highly significant. A *t*-test comparison of means (not shown) on the AOV results using an alpha value of .05 indicated that broadcasting fertilizer resulted in significantly higher yields than any other method, and that applying fertilizer at a rate of 224 kg/ha resulted in significantly higher yields than any other rate. Thus, the AOV indicates that treatment 2 results in statistically higher yields than any other treatment.

Results from the AOC are shown in Table 3. In contrast to the results from AOV, only rate of fertilizer application is statistically significant after adjustment for the effect of soil pH. Note that the interaction between pH and method in the covariance analysis is significant (Table 3). This violated the standard assumption for simple AOC of independence between treatments and the covariate. As a result, a more complicated covariance model involving the interaction term was used.

Another assumption of both AOV and AOC is the requirement that experimental errors on adjacent plots be uncorrelated. To test this assumption, the effect on

Table 3. Statistical results from analysis of covariance (AOC) of the yield of grade #1 Russet Burbank field experiment

Source of variation	Degrees of freedom	Type III sum of squares	F-value
Blocks	5	1694.3	2.1
Method	4	904.8	1.5
Block*method (error A)	20	3041.2	
Rate	5	5994.8	15.0**
Method*rate	210	4449.8	2.8**
pH	1	7.6	0.02
pH*method	4	1881.4	2.7*
Error B	120	9604.9	

[a] Results significant at the 1% level are denoted by **, while results significant at the 5% level are denoted by *.

yield due to soil trends, ${}^1\xi_{it}$, was estimated for each plot using Eq. 2. These values were used to compute semivariance, $\gamma(h)$, as a function of separation distance, h, between plots using the standard expression (Davis, 1986):

$$\gamma(h) = (1/2N(h)) \sum_{i=1}^{N(h)} [{}^1\xi_{it} - {}^1\xi_{i+h,t}]^2 \tag{6}$$

where $N(h)$ is the number of pairs of plots separated by a distance h. Values of semivariance are useful as an indicator of spatial correlation of experimental errors. Increases in semivariance with increasing separation distance, h, indicate that experimental errors are correlated. Approximately constant values of semivariance at all separation distances indicate an absence of correlated errors.

The analysis using Eq. 6 was conducted in two different ways: first by considering only pairs of plots in the same column of the experiment, and second by considering only pairs of plots in the same row of the experiment. These two analyses, which indicate the extent of spatial correlation for errors in two different directions, are referred to as the column or row semivariances, respectively.

Figure 3 shows the computed values of column and row semivariance plotted versus separation distance between plots. Using the guidelines of the previous paragraph, it is evident from these results that estimated experimental errors are correlated between adjacent plots, especially along the rows, and to a lesser extent along the columns.

This example shows that correlated errors are not always eliminated by the use of randomization in the experimental design. Thus, a basic premise of both the AOV and AOC procedures has been violated by the presence of yield trends caused by soil variability. It is also interesting to note that in spite of the presence of correlated errors, the results from AOV indicate that no significant differences exist between blocks (Table 2). This observation is due to the fact that the correlated errors exist only for distances that are relatively short compared to the dimensions of the blocks.

Table 4 gives the unadjusted treatment means from the AOV, the treatment means adjusted for soil pH from the AOC, and the adjusted treatment means from nearest-neighbor analysis (NNA) using seven cycles of iteration. The relative rank of yield for each treatment is given in parentheses. A comparison of the rankings shows that 14 of the treatment rankings are identical for both the AOV and AOC procedures, whereas 11 are identical for the AOV and NNA procedures, and 13 are identical for the AOC and NNA procedures.

The highest yields in Table 4 are obtained from treatments 5, 3, and 2 using the AOV, AOC, or NNA rankings, respectively. If a researcher were to use the AOV rankings, the optimum recommendation would be to broadcast 560 kg of fertilizer per hectare. In contrast, if a researcher were to use the AOC or NNA rankings, the optimum recommendation would be to broadcast 336 or 224 kg of fertilizer per hectare, respectively.

Obviously, significant errors can result when recommendations are based on the highest yielding treatment unless corrections are first made for the effects of soil variability. Because of the violation of several assumptions required for both

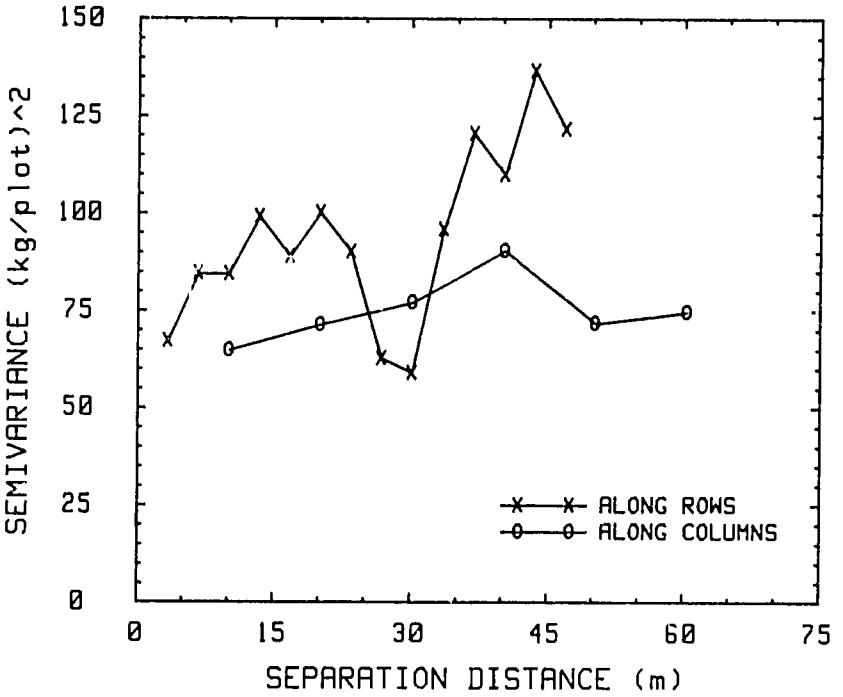


Figure 3. Plot of semivariance of experimental error from Eq. 6 along field experiment columns (square symbols) and along field experiment rows (triangular symbols).

the AOV and AOC procedures, the results of the NNA procedure are probably more accurate for this example than the results from the AOV or AOC procedures. Results from several other investigations (Bartlett, 1978; Wilkinson et al., 1983; Besag and Kempton, 1986) have consistently shown that the NNA procedure is more accurate than the classic AOV procedure when yield trends are present.

VI. Summary

Field research trials conducted on spatially variable soil must be carefully designed and interpreted to allow separation of true treatment effects from effects of yield trends. Proper selection of experimental design, use of randomization, replication, blocking, and appropriate plot dimensions can improve the interpretation of research trials conducted on heterogeneous soil. Researchers should avoid the routine use of analysis of variance or covariance for interpreting these experiments without first verifying that assumptions required for their use are satisfied. Significant improvement in interpretations can often be obtained by removing the effects of soil trends with nearest-neighbor analysis.

Table 4. Treatment means and relative ranking (in parentheses) for yield #1 Russet Burbank potatoes from analysis of variance, analysis of covariance, and nearest-neighbor analysis

	Yield #1 potato treatment means (kg)		
Treatment #	Analysis of variance	Analysis of covariance	Nearest-neighbor analysis
1	48.66 (24)	48.02 (25)	48.66 (24)
2	69.98 (4)	69.52 (4)	72.11 (1)
3	70.29 (3)	71.43 (1)	68.84 (4)
4	71.07 (2)	71.43 (2)	71.88 (2)
5	71.20 (1)	71.25 (3)	69.16 (3)
6	59.09 (10)	58.87 (12)	58.78 (11)
7	56.46 (14)	57.82 (14)	59.96 (14)
8	68.93 (5)	68.71 (5)	68.62 (5)
9	66.98 (7)	66.53 (7)	65.26 (7)
10	55.87 (16)	55.78 (16)	54.97 (17)
11	54.56 (17)	53.74 (18)	55.60 (16)
12	47.98 (25)	48.80 (24)	46.17 (26)
13	56.78 (15)	57.89 (13)	57.23 (13)
14	62.36 (8)	61.95 (8)	64.49 (8)
15	57.46 (12)	56.01 (15)	55.65 (15)
16	40.59 (28)	40.18 (29)	39.56 (29)
17	39.68 (29)	40.27 (28)	40.68 (28)
18	35.74 (30)	35.33 (30)	36.87 (30)
19	57.23 (13)	59.23 (10)	58.23 (12)
20	67.57 (6)	67.71 (6)	68.16 (6)
21	59.50 (9)	60.68 (9)	59.41 (10)
22	53.61 (18)	55.06 (17)	52.97 (18)
23	51.38 (20)	48.93 (23)	51.88 (19)
24	46.37 (27)	46.08 (27)	45.67 (27)
25	52.02 (19)	51.52 (19)	49.84 (22)
26	58.96 (11)	58.96 (11)	60.00 (9)
27	49.57 (22)	49.34 (21)	49.75 (23)
28	49.43 (23)	49.16 (22)	51.29 (20)
29	50.48 (21)	50.61 (20)	50.93 (21)
30	46.26 (26)	46.39 (26)	46.67 (25)

Acknowledgments. The authors would like to thank Dr. J. R. Alldredge for advice concerning the analysis of covariance for split-plot designs.

References

Atkinson, A.C. 1969. The use of residuals as a concomitant variable. Biometrika 56(1):33–41.

Bartlett, M.S. 1978. Nearest-neighbor models in the analysis of field experiments. J.R. Statist. Soc. B 40(2):147–174.

Besag, J., and R. Kempton. 1986. Statistical analysis of field experiments using neighboring plots. Biometrics 42:231-251.

Davis, J.C. 1986. Statistics and Data Analysis in Geology, 2nd ed. New York: John Wiley.

Freeman, G.H. 1979. Some two-dimensional designs balanced for nearest-neighbors. J.R. Statist. Soc. B 41(1):88-95.

Green, P.J. 1985. Linear models for field trials, smoothing and cross-validation. Biometrika 72(3):527-537.

Green, P.J., C. Jennison, and A. Seheult. 1985. Analysis of field experiments by least squares smoothing. J.R. Statist. Soc. B 47(2):299-315.

Myers, J.L. 1966. Fundamentals of Experimental Design. Boston: Allyn and Bacon.

Papadakis, J.S. 1937. Methode statistique pour des experiences sur champ. Bull. Inst. Amel. Plantes a Salonique No. 23.

Trangmar, B.B., R.S. Yost, M.K. Wade, G. Uehara, and M. Sudjadi. 1987. Spatial variation of soil properties and rice yield on recently cleared land. Soil Sci. Soc. Am. J. 51(3):668-674.

Schwarzbach, E. 1984. A new approach in the evaluation of field trials: The determination of the most likely genetic ranking of varieties. Votr. Pflanzenzuchtung 6:249-259, Proc. Eucarpia Cereal Section Meeting, Weihenstephan.

Steel, R.G.D., and J.H. Torrie. 1980. Principles and Procedures of Statistics. A biometrical approach, 2nd ed. New York: McGraw-Hill.

Wilkinson, G.N., S.R. Eckert, T.W. Hancock, and O. Mayo. 1983. Nearest neighbor (NN) analysis of field experiments. J.R. Statist. Soc. B 45(2):151-211.

Diseases Caused by Root-Infecting Pathogens in Dryland Agriculture

R.J. Cook

I. Introduction 215
II. Etiology 216
III. Epidemiology 218
A. Related to Depth of Pathogens in Soil 218
B. Related to Stage of Plant Growth 219
C. Related to Environment 222
IV. Host Range and the Effects of Crop Rotations 223
V. Tillage and Crop Residue Management 225
VI. Strategies and Approaches to Economic Control 229
VII. Research Needs 231
VIII. Epilog 233
References 233

I. Introduction

This chapter is concerned with the diseases of roots, rootlets, and root hairs—portions of the plant that cannot be seen except by special observation techniques or by destroying the plant. Specifically, I focus on those diseases caused mainly by fungi (*Fusarium*, *Gaeumannomyces*, *Pythium*, and *Rhizoctonia* spp.) nematodes, and to a lesser extent bacteria that infect through roots and complete part or all of their life cycle in root tissues or in soil surrounding the roots (the rhizosphere). This includes the vascular diseases (wilts) caused by fungal (*Cephalosporium*, *Fusarium*, *Verticillium* spp.) and bacterial pathogens that gain entry into the vascular system of plants through root infections, but does not include the leaf spots and other above-ground plant diseases caused by pathogens such as *Ascochyta* and *Septoria* spp. that use crop residue on the soil surface as a springboard for attack of the leaves.

1990 by Springer-Verlag New York Inc.
Advances in Soil Science, Volume 13

Previous Page Blank

Table 1. Influence of soil fumigation with methyl bromide, or application of metalaxyl [N-(2,6-dimethylphenyl)-N-(methoxyacetyl) alanine methyl ester] to the soil on growth and yield of winter wheat direct drilled into winter wheat stubble. (Data of Cook et al., 1980.)

Treatments	Plants (no./m)	Tillers with heads (no./m)	Plant height (cm)	Yield (kg/ha)
Check	11.6±3.6	167.0±44.0	77.7±7.4	3,924
Methyl bromide[a]				
Block 1	25.8±5.5	250.7±11.9	83.0±5.8	5,040
Block 2	28.2±3.5	264.2±24.8	85.2±5.5	5,587
Metalaxyl[b]	21.4±2.5	248.0±31.0	80.9±6.7	5,567

[a] Methyl bromide fumigation is broad-spectrum in its effect on the soil biota.
[b] Metalaxyl is a fungicide specific for *Pythium* spp. and other oomyceteous fungi. Since *Pythium* spp. were the only oomyceteous fungi pathogenic to wheat in this soil, the growth and yield response of wheat was due to control of *Pythium* spp.

By way of further refinement, this chapter draws mainly on information obtained through observation and experimental research on root and vascular diseases of small grain and pulse crops. The diseases of these crops adequately illustrate principles, and the crops themselves represent major components of the cropping systems used under dryland/rainfed conditions worldwide. Perhaps more important, my personal research program has been largely with these crops. For more complete treatments of diseases caused by soilborne plant pathogens, the reader is referred to a recent book of Bruehl (1987) and to the proceedings of six international symposia on soilborne plant pathogens (Baker and Snyder, 1965; Bruehl, 1975; Hornby, 1990; Parker et al., 1986; Schippers and Gams, 1979; and Toussoun et al., 1970).

II. Etiology

Root diseases can be subdivided into two broad categories (Cook, 1984): the acute and generally well-defined diseases caused by root-infecting fungi and endoparasitic nematodes; and the chronic, subclinical, and ill-defined kinds of root damage caused by deleterious rhizosphere microorganisms and ectoparasitic nematodes. The well-defined, root-infecting fungi and endoparasitic nematodes cause damage that usually can be diagnosed by characteristic symptoms or signs on the damaged roots. The subclinical damage caused by deleterious rhizosphere-inhabiting microorganisms and ectoparasitic pathogens are more difficult to diagnose but can be just as important as the acute root diseases. It is important to recognize, however, that whether acute or subclinical, root diseases are caused by specific microorganisms with specific determinants responsible for pathogenesis.

The occurrence of one or more root diseases usually is indicated by a range of symptoms in the tops that might be expected as a consequence of damage to the

Table 2. Influence of crop rotation on the yield response of wheat to soil fumigation in cultivated (tilled) fields in eastern Washington[a]

Previous crops[b]	Exp.	Check t/ha	Fumigated t/ha	Increase %
Continuous wheat				
WW/WW/WW	1	3.2	6.5	103
WW/WW/WW	2	3.6	6.2	72
L/WW/SW	3	4.1	4.8	14
WW/WW/WW	4	1.7	3.5	106
WW/WW/WW	5	3.6	5.5	53
Average				70
2-yr rotations				
P/WW/P	1	4.9	6.8	36
L/WW/L	2	6.9	8.3	20
P/WW/P	3	6.2	7.2	16
P/WW/P	4	5.5	6.2	13
L/WW/L	5	4.8	6.0	26
Average				22
3-yr rotations				
WW/SB/P	1	7.5	8.4	12
WW/SB/L	2	9.6	10.0	4
WW/SB/P	3	7.5	8.6	15
WW/SB/P	4	6.1	6.2	2
WW/SB/P	5	7.0	7.2	3
Average				7

[a] Representative trials from about 50 experiments conducted over a 15-yr period (Cook and Haglund, 1982; Cook et al., 1987; Moore and Cook, 1985; Cook, unpublished).
[b] WW = Winter wheat; SW = spring wheat; L = lentil; P = pea; SB = spring barley.

absorptive and conductive capacity of the root and vascular systems. The acute symptoms include missing plants, owing to death of the plant at an early stage; severe stunting, caused by loss of roots early in the life of the plant; and premature death (early ripening), caused by restrictions to water uptake or transfer to the tops. The more subclinical symptoms include uneven plant height; nutrient deficiency-like symptoms in the tops (e.g., pale green or yellow color), caused by loss of roots and root hairs; and delayed maturity, caused by retardation of plant growth, general starvation of the tops, and possibly the fact that the plants with damaged roots have not used up their supply of soil water. Acute forms of root disease can also delay maturity where the damage occurs early in the life of the plant.

Soil fumigation beneath a plastic tarp, using either chloropicrin injected at 300 to 400 kg/ha (80 to 100 L/ha) or methyl bromide at 400 to 450 kg/ha temporarily eliminates or greatly reduces populations of the root-infecting microorganisms and provides good evidence for whether a given crop condition is due to biotic (e.g., root diseases) or abiotic (e.g., available water) constraints to root health (Tables 1 and 2). No experimental evidence has been produced to show that the

release of nitrogen or other changes in soil fertility, sometimes associated with killed microorganisms, can account for the plant growth responses to soil fumigation (Aldrich and Martin, 1952). In contrast, a considerable body of experimental evidence supports the conclusion that the response of crops to soil fumigation is the result of healthier roots and more efficient uptake of soil nutrients (Wilhelm, 1965; Wilhelm and Paulus, 1980; Cook and Haglund, 1982).

The most valuable tools for diagnosis of the etiology of a root disease are the standard tools required to isolate the suspected pathogen in pure culture and complete Koch's postulates. Isolation from diseased tissue can be difficult because of the myriad of secondary colonists that establish quickly in rotting tissue. *Fusarium* species are especially aggressive as secondary colonists of tissue damaged by a physical factor or some other organism. Many kinds of root damage have been attributed erroneously to *Fusarium* spp. because these were the only fungi that could be isolated from the damaged tissue. As a general rule, if isolations from diseased root yields a wide array of fungi, for example, several *Fusarium* spp., none are likely to be the true cause of the damage.

As a corollary to isolation from diseased tissue, a suspected pathogen might also be isolated from soil by dilution plating onto a selective medium (Tsao, 1970). Such media are available for *Fusarium* (Nash and Snyder, 1962; Komada, 1975), *Pythium* (Mircetich, 1971), *Rhizoctonia* (Ko and Hora, 1971), and *Thelaviopsis* (Tsao and Canetta, 1964), and are becoming available for other root-infecting fungi. I once diagnosed a symptom on winter wheat (*Triticum aestivum*) in Washington state as foot rot caused by *Fusarium culmorum*. However, soil from the site where the plants were taken, when dilution plated onto a *Fusarium*-selective medium (Cook, 1968), failed to reveal the suspected pathogen, even with 100 mg of soil/agar plate. This prompted a reexamination of the plants, which turned out to have frost damage on the lower internodes that resembled Fusarium foot rot. On the other hand, detection of a suspected pathogen at soil populations sufficient to produce root disease (see Table 6.1 in Baker and Cook, 1974) is not adequate in itself to conclude that disease caused by this pathogen is a factor in performance of a crop. A crop may be remarkably healthy growing in soil with a *Pythium* population approaching 1000 propagules per gram if the soil is too dry, for example, drier than −0.05 to −1.0 MPa (Cook and Duniway, 1981), for activity of this pathogen.

III. Epidemiology

A. Related to Depth of Pathogens in Soil

About 80 to 90% of the inoculum of *Fusarium culmorum*, *Pythium* spp., and *R. solani* AG8 occurs in the top 10 to 15 cm of soil. Pathogens responsible for vascular diseases (*C. graminicum*, *Fusarium oxysporum*, and *Verticillium dahliae*) occur mainly in the top 20 to 30 cm of soil. This is the layer where crop residues are most concentrated. This is also the layer where root density tends to be

greatest; S.M. Neate (unpublished) showed for wheat fields in Australia that the total length of wheat roots in 143 cm^3 of conventionally cultivated soil was 1450 to 1560 cm in the top 10 cm, 170 to 220 cm in the layer 10 to 20 cm deep, 180 to 200 cm at 20 to 30 cm deep, and 200 to 250 cm at 30 to 40 cm deep. Cook et al. (1990) showed that the inoculum density of *Pythium* spp. in plots in northern Idaho where wheat and peas were grown in rotation was greatest in the top 5 cm in plots where only mulch tillage (chisel plow and disk) had been used for the previous 7 years and in the 15- to 20-cm layer where the residue had been buried 15 to 20 cm deep (plots moldboard plowed) each year for the same 7-year period. (The influence of tillage and crop residue management on root diseases is covered in more detail later in this review.)

A residual population of *Fusarium solani* f.sp. *pisi*, cause of Fusarium root rot of pea (*Pisum sativum* L.), was found almost exclusively in a layer 30 to 50 cm deep in plots in Pendleton, Oregon, where peas had not been grown for about 20 years (Allmaras et al., 1988). The presence of the fungus to this depth was attributed to a history of multiplication of the pathogen in the roots of pea. Its persistence at this depth, after so many years without access to roots of pea, was attributed either to long-term survival of the dormant chlamydospores or to production by the pathogen of replacement chlamydospores (nonpathogenic recycling) in the rhizosphere of wheat and other nonhost plants (weeds) in the plots during the 20 ensuing years. The failure of the pathogen to survive in the top 15 to 20 cm of soil was explained on the basis of a plow pan that occurred at 15 to 18 cm depth. The plow pan was a barrier to infiltration of water; soil above it therefore tended to become saturated (and anaerobic) during rainy periods while the soil below it was almost always drained. Flooding of the soil has been used as a means to eradicate Fusarium-wilt pathogens from the soil (Stover, 1979). The remarkable fact, in the case of the plots near Pendleton, is that a source of *F. solani* f. sp. *pisi* exists deep in the soil and is available to reestablish the fungus at economically important inoculum densities once peas are grown again on that site.

Pathogens confined very near the soil surface are vulnerable to eradication by burning of crop residues on the soil surface. The heat (or smoke?) generated by the burn can kill pathogens to different depths according to the amount of residue burned. At Pullman, 75% of the *Pythium* population was eliminated from the top 5 cm of soil where wheat straw at an artificially high 12 to 15 t/ha was burned as a layer on the soil surface (Cook et al., 1987). Adult plants were taller and yields were 25% greater where straw was burned compared to straw ash by itself applied to the soil surface or to no treatment (check). The heat-treatment by burning was as effective as heating by solarization (Katan, 1980) of the soil for about 5 weeks beneath a clear plastic tarp (Table 3).

5. Related to Stage of Plant Growth

Pythium spp. are probably the first of the many soilborne plant pathogens in soil to establish parasitic relationships with plants under dryland/rainfed agriculture.

Table 3. Influence of burning wheat straw, adding ash and solar heating the soil on the *Pythium* population and growth and yield of winter wheat. (Data of Cook et al., 1987.)

Soil treatment 1984	Pythium population (prop/g) per soil depth (cm)			Wheat response	
	0-5	5-10	10-15	Height (cm)	Yield (t/ha)
Check[a]				92.2z	5.7c
Straw burned[b]	83	190	57	97.0x	6.5ab
Ash only[c]	350	160	65	94.4yz	5.7c
Solar heated[d]	13	43	57	96.2xy	6.8a

[a] Plots were bare-fallow.
[b] Straw at 12-15 t/ha was burned as a layer on the surface of the bare-fallow soil.
[c] No straw was burned; straw ash only was added to the soil surface.
[d] Solar heating was accomplished by covering the soil surface with a clear plastic tarp for 5 weeks.

The oospores and sporangia of these fungi have been shown many times to germinate within the first 4 to 6 hours after being placed in contact with a newly planted bean or pea seed. Embryos of germinating wheat seeds are infected by *Pythium* spp. within the first 24 to 48 hours after sowing in soil at 20°C (Hering et al., 1987). This infection occurs maximally in soil at −0.01 to −0.02 MPa and is prevented in soils drier than −0.04 to −0.05 MPa (Hering et al., 1987). However, since embryo infection is fast, the wet soil condition need only exist for a short time; the need for −0.01 to −0.02 MPa or wetter should not, therefore, be misconstrued as evidence that *Pythium* spp. are not important in dryland agriculture. Maximal embryo infection generally is achieved at about 40 degree days (0°C base) (Ingram, 1987); thus, the percentage of infection achieved in 2 days at 20°C occurs in 8 days at 5°C. Large-seeded crops such as bean, chickpea maize, and pea commonly are killed by *Pythium* if they are infected during germination (Hoppe, 1949; Kerr, 1964; Kaiser and Hannan, 1983). In contrast, infection of germinating wheat seeds by *Pythium* is likely to be nonlethal unless (a) the seed is old or damaged (Schroth and Cook, 1964; Hering et al., 1987); (b) the temperature is well below or above the optimum for seedling emergence (Leach, 1947); or (c) the fungus is unusually aggressive, as when provided with a rich food base such as oatmeal or wheat chaff (Cook et al., 1990). While infection of emerging seedlings of wheat and barley may be nonlethal, the emerged seedlings are stunted nevertheless and may never produce plants equal in stature to those without *Pythium* as a parasite in the embryo region.

Pythium spp., *Phythophthora* spp., *Rhizoctonia solani*, *Fusarium* spp., and *Gaeumannomyces graminis* var. *tritici* all may infect the radicle, other main roots, and laterals as they emerge on the developing seedling. These fungal parasites colonize roots at or behind the root tip and establish in the cortex, although it is unlikely that different species of root parasites comingle to any significant extent in the exact same tissues. *Pythium* spp. are efficient colonists of root hairs and fine rootlets, destroying these tissues in a very juvenile stage. *Rhizoctonia* and *Fusarium* spp. are more commonly associated with damaged cortical tissues on

the main roots and lower stem tissues. Root rot, typified by discolored (usually brown-black) lesions and severed roots, is easily recognized and diagnosed, but subclinical damage typified by missing root hairs and fine rootlets is easily overlooked unless plants are available for comparison from a pathogen-free (fumigated or heat-treated) site.

Rhizoctonia solani, *Fusarium* spp., *Cochliobolus sativus*, and several other soilborne plant pathogens also infect the cortical tissues of stems during and after seedling emergence. Such infections usually occur in the top 10 to 15 cm of soil and may then extend above the soil surface as the lesions develop. Examples include the cankerouslike lesions on stems of beans and cotton caused by *R. solani*, the black and usually coalesced lesions on the epicotyls of pea caused by *F. solani* f.sp. *pisi*, the basal stem and crown rots of wheat caused by *F. culmorum* and *C. sativus*, and the stalk rots of sorghum, caused by *F. moniliforme*, and maize, caused by *F. graminearum*. Vascular pathogens, such as *Fusarium oxysporum*, *Verticillium* spp., and *Cephalosporium* spp., enter the xylem through wounds or by infecting the meristematic or elongating root tips and then growing into undifferentiated vascular (xylem) tissues. Such infections may occur through roots at virtually any stage of plant growth. The pathogen then progresses upward within the xylem and eventually into the midrib and veins of the leaves by a combination of hyphal growth and carriage as microconidia in the transpirational stream (Beckman, 1987). Eventually these pathogens also colonize the stem tissues, but usually not until after the plant is dead. Death is caused by lack of water to the leaves owing to plugging of the xylem and associated increased resistance to water flow (Duniway, 1973).

As a general principle, pathogens that cause damage to roots and rootlets of annual plants, beginning when the plants are young, reduce the efficiency of nutrient uptake and delay plant maturity. In contrast, pathogens that cause damage to stem tissues when plants are older, including the vascular pathogens, reduce the efficiency of water flow to leaves, curtail plant development, and cause premature death. Pythium root rot of wheat and barley delays maturity of these plants, whereas Cephalosporium stripe and Fusarium foot rot of wheat accelerate plant death. Rhizoctonia root rot of wheat and barley and take-all of wheat may cause either delayed maturity or premature death, depending, respectively, on whether the disease is mainly a root rot of young plants or destruction of the basal stem and crown tissue of adult plants. The cereal cyst nematode (*Heterodera avenae*) is endoparasitic mainly on the seminal roots of wheat, beginning early in the life of the plant and tends to delay plant maturity (Brown, 1984). *Cochliobolus sativus* spreads from the subcrown internode upward into the basal stem tissue of wheat and may then accelerate plant death, although the opposite can occur if this pathogen attacks the roots early in the life of the plant (Butler, 1961).

Pathogens that cause early loss of roots and rootlets and thereby limit the efficiency of nutrient uptake also limit the leaf area of the plants beginning with the earliest stages of plant development. This results in less capture of sunlight, less photosynthesis and transpiration per plant, and slower use of soil moisture. These effects may account for why such pathogens delay crop maturity under

dryland/rainfed agriculture. In contrast, plants with relatively healthy roots early in their life tend to produce a large leaf area and use up the soil moisture supply relatively quickly; if basal stem tissue of such plants is then damaged or water movement to the tops is restricted, these plants cannot meet the transpirational demand and death is accelerated.

C. Related to Environment

Entry of root pathogens into susceptible host tissue is generally controlled by the soil and rhizosphere environment, and disease progress after infection (pathogen now in the tissue) is controlled by the plant-tissue environment. Conditions such as soil or plant water potentials, soil or plant temperatures, gas exchange in the root zone or within the plant tissues, and nutrition of the host are all important in determining both the incidence of infection and symptom development, in that order. However, with many root, stem, and stalk diseases, the major influence of environment on disease development is expressed postinfection rather than as an aid to penetration of the host by the pathogen.

As pointed out previously, colonization of wheat seed embryos by *Pythium* spp. is a function of thermal time; more time is required for embryo infection at lower than at higher temperatures, but the final incidence of embryo infection is generally the same for all temperatures that allow growth of the pathogen (Ingram, 1987). On the other hand, Leach (1947) showed that a cool-temperature crop such as spinach showed the highest incidence of *Pythium*-incited damping-off in warm soil, and a warm-temperature crop such as watermelon (*Citrulus vulgaris*) showed the highest incidence of this disease in cool soil. Similarly, *F. graminearum* causes the highest incidence of seedling blight on wheat in warm soil and on corn in cool soil (Dickson, 1923). Temperatures relatively unfavorable to the growth of the host predispose the host to greater damage, but not necessarily to a higher incidence of colonization of the susceptible tissues by the pathogen. For more complete discussion of this important concept, you are referred to Baker and Cook (1974).

Fusarium root rot of bean caused by *F. solani* f. sp. *phaseoli* is more severe on bean hypocotyls and roots exposed temporarily to low-oxygen stress caused by temporary flooding of the soil (Miller and Burke, 1975). The predisposing effect of the low oxygen favors a more aggressive attack of the root tissues by the pathogen already established in the tissues. Good drainage may actually favor infection, but disease severity may then be limited, possibly because tissues with sufficient oxygen are maximally resistant (for many reasons) to this pathogen. Tissues exposed temporarily to anaerobic conditions may also produce ethanol, which stimulates growth of *Fusarium* in pea (Smucker and Erickson, 1987).

Fusarium foot rot of wheat caused by *F. culmorum*, stalk rot of sorghum caused by *F. moniliforme*, and root rot of several crops caused by *Macrophomina phaseoliola* all are most destructive under conditions that result in plant water stress. In the case of Fusarium foot rot of wheat, disease is favored by low plant water potentials (water stress) in the host (Papendick and Cook, 1974); again,

infection of roots occurs over a much wider range of conditions than does subsequent disease development. The most predisposing conditions result when the crop has ideal growing conditions through early-boot stage but then runs out of water. Such plants usually have more tillers and a greater leaf area than can be supported on the limited supply of water. A wheat crop subjected to water stress early – that is, in the seedling stage – is more likely to also compensate early for the lack of water (by pruning tillers) and may never develop the low plant water potentials necessary for severe disease. Thus, any conditions that favor early lush growth of wheat may also favor the subsequent development of Fusarium foot rot. It is not uncommon in eastern Washington to observe an increase in incidence of Fusarium foot rot when Pythium root rot is controlled.

A general principle is that pathogens most damaging to roots in wet soils also require high water potentials for growth, whereas those most damaging in dry soils are tolerant of and often grow best at low water potentials (Cook and Papendick, 1972; Cook and Duniway, 1981). However, the vascular pathogens are an exception in that incidence and severity of wilts are generally the greatest in wet soils, yet these pathogens can grow maximally at −1.5 to −2.0 MPa and cease growth only at substrate water potentials in the range of −10 to −12 MPa. This has been explained (Cook and Duniway, 1981) on the basis that, since systemic spread within the host depends on transpiration, conditions that limit transpiration (e.g., lack of available soil water) limit the potential for systemic spread and hence wilt. However, upon death of the plant owing to thorough colonization of the xylem, the pathogen must colonize the surrounding parenchymous stem tissues, often under conditions of high temperatures and low relative humidities. It is during this saprophytic mode in the dead plant standing in the field that the pathogen must be able to grow at such low substrate water potentials.

Take-all of wheat is favored by nutritional deficiencies in the host (see Cook and Baker, 1983, for complete review). Phosphorus, potassium, magnesium, copper, manganese, iron, and zinc are especially critical to expression of maximum resistance in the host. A deficiency in any one of these nutrients makes already susceptible tissue even more susceptible, and disease development is intensified accordingly (Reis et al., 1982 and 1983; Rovira et al., 1985).

IV. Host Range and the Effects of Crop Rotations

In general, root pathogens multiply in response to monoculture of their host. Thus, pathogens specialized for or adapted nutritionally to roots of wheat are enriched during culture of wheat, and those specialized for or adapted nutritionally to roots of pea are enriched during culture of pea and are likely to decline in numbers or inoculum potential (Garrett, 1956) during culture of wheat. A summary of experiments with soil fumigation for winter wheat carried out over 15 years in eastern Washington and northern Idaho (see Table 2) revealed an average yield response of 7% in fields cropped no more than every third year to wheat (3-year rotation), 22% in fields cropped every other year to wheat (2-year

rotations), and 70% in fields cropped every year to wheat (Cook et al., 1987; R.J. Cook, unpublished).

Soilborne pathogens responsible for root rots and wilts survive in soil either as dormant resting structures or as vegetatively active mycelia in plant residues and roots. The pathogens of the former type are usually long-lived and therefore generally not controlled by normal crop rotations. An example is *Fusarium culmorum*, which survives in soil as thick-walled dormant chlamydospores. The time required for 50% of a fresh supply of chlamydospores of this fungus to die in dryland soils of eastern Washington state was estimated at 200 to 250 days (Inglis and Cook, 1986). Assuming an initial inoculum density of 1000 chlamydospores per gram of soil (Cook, 1968), 2 to 3 years without access to host roots would be required before the population of this fungus would drop below 100 propagules per gram, thought to be a safe threshold (Cook, 1968).

Cephalosporium gramineum, which causes a vascular disease of winter wheat (Cephalosporium stripe), forms no known resistant structures but survives instead as active mycelium in host residue. However, this pathogen generally cannot be controlled with less than a 2-year break from winter wheat or winter barley, because it produces a broad-spectrum antibiotic (Bruehl et al., 1969) inhibitory to its would-be competitors in the straw; the longevity of this pathogen in straw between host crops is thereby prolonged. In contrast, *G. graminis* var. *tritici*, cause of take-all of wheat, can be controlled in many if not most wheat-growing areas of the world by only a 1-year break to clean fallow or virtually any crop other than wheat, barley, or susceptible grasses; this pathogen survives as vegetatively active mycelium in wheat roots and tiller bases and is very short-lived when denied access to host roots.

The significance of host range in the control of a pathogen can be illustrated by the contrast between *G. graminis* var. *tritici* and *Rhizoctonia solani* AG8 (Neate and Warcup, 1985; Rovira et al., 1986), responsible for root rot (bare patch) of wheat and barley (*Hordeum vulgare*). Both pathogens depend on parasitism of roots of host plants to maintain their inoculum potential. However, whereas *G. graminis* var. *tritici* is limited in its host range mainly to wheat, barley, *Bromus* spp., *Agropyron* spp., and certain other grasses (Sprague, 1950), *Rhizoctonia solani* AG8 parasitizes the roots of clovers, pulses, lupin, and many other crop and weed plants in addition to wheat, barley, and a wide range of grasses (Rovira and Venn, 1985). While take-all can be controlled by a 1-year rotation to any crop other than certain members of the gramineae, *R. solani* AG8 can be controlled mainly or only by several months (or even a full year) of clean bare fallow (no plants) achieved with either herbicides (chem-fallow) or tillage (conventional fallow).

Pythium spp., exemplified by *P. ultimum* and *P. irregulare*, combine the features of both a wide host range and ability to produce dormant resting structures (oospores) suited to long-term survival. This combination accounts for the success of this fungus genus as a colonist of agricultural soils worldwide. In the dryland wheat-growing areas of eastern Washington, no field has been found thus far with less than 100 propagules per gram, and most fields average 300 to 400 propagules (total of all *Pythium* species) per gram (Cook et al., 1987). Since infections occur

in the embryo region and at root tips, germinating seeds and young seedlings are most vulnerable, and damage at this young stage can seriously limit the yield potential of the crop. This total population of *Pythium* spp. is maintained collectively by the combinations and sequences of wheat, barley, and pea grown in various rotations in this dryland region. On the other hand, there may be some host preferences, with *P. ultimum* being the most pathogenic on (and presumably selectively enriched in numbers by) pea, *P. irregulare* on barley, and both *Pythium* species on wheat. Different crop sequences (rotations) theoretically could select for different mixtures of *Pythium* spp., with some mixtures being more and others less damaging to the next crop in the sequence. However, a certain amount of crop damage is to be expected from embryo and root tip infections in virtually any system of annual cropping. Like *R. solani*, the cropping system for control of *Pythium* spp. involves a clean bare fallow, but even this practice may provide unsatisfactory control, depending on longevity of the oospores.

V. Tillage and Crop Residue Management

Tillage can serve as a kind of substitute for crop rotations. This results, in part, from the ameliorating effects on root disease that result from disturbance and fragmentation of the plant residue used by the root pathogens as a food base (energy source) for attack of the next crop. There is also evidence that soil disturbance by itself can be unfavorable to root pathogens. Much of the success of U.S. farmers in maintaining high yields of major dryland crops [e.g., wheat, corn (*Zea mays*), soybeans (*Glycine max*)] while shortening or eliminating crop rotations since World War II can be attributed not only to more intensive fertilization but also to the use of intensive tillage. Root diseases occur in conventionally tilled systems but became severe mostly as growers attempted to eliminate both tillage *and* crop rotation.

Even a single year of clean chem-fallow can permit the time necessary for the antibiotic, predatory, and competitive microflora and fauna to "sanitize" the soil. For example, a 0.5-ha experimental plot near Pullman was direct drilled to winter wheat for three consecutive years (1984, 1985, and 1986), but the 1986 crop was abandoned because of at least three root diseases (take-all, Pythium root rot, and Rhizoctonia root rot) present as a mixture. However, following a full year (1987) of clean chemical fallow (no tillage) the yield of 1988 direct drilled, rainfed, dryland winter wheat crop (fifth consecutive year with no tillage) averaged 8.7 t/ha; the full year "without plants" would have reduced the inoculum potential of *R. solani* and the take-all fungus below an economic threshold. *Pythium* spp. survived (based on estimations of populations in the soil), but because the topsoil containing this pathogen was −0.05 to −0.1 MPa or slightly drier at seeding in October 1987, virtually no infections occurred during seed germination and stand establishment when wheat is most vulnerable to *Pythium* (R.J. Cook, unpublished).

Crop residues left on or mixed with the top few centimeters of soil (mulch tillage) can provide excellent control of soil erosion by wind and water. Direct

drilling has the added advantage of reducing the energy inputs needed for crop production (Phillips et al., 1980). It was estimated that in 1983, 21% of all U.S. cropland was farmed by some method of "conservation tillage," defined as at least 30% of the soil surface protected by crop residues up to the time of sowing. Some projections suggest that by the year 2000, 60 to 65% of the seven major annual crops grown in the United States [corn, soybeans, wheat, barley, oats (*Avena sativa*), sorghum (*Sorghum bicolor*) and rye (*Secale cereale*)] will be direct drilled, and by 2010, 75 to 80% of these crops will be direct drilled (Phillips et al., 1980).

Stubble-mulch tillage began in the United States in the late 1930s following the so-called dust bowl days. However, virtually from the beginning, those attempting to perfect this system of farming noted that yields of wheat were commonly lower in mulch-tilled plots than in adjacent clean-tilled (bare) plots (Zingg and Whitfield, 1957; McCalla and Army, 1961; Cook and Waldher, 1977) in spite of the better physical condition of the mulched soil (Tanchandrophongs and Davidson, 1970). Descriptions of the syndrome include spindly or distorted seedlings, yellow plants, poor tillering, small heads, reduction in size of the root system, and stunted plants (Davidson and Santleman, 1973; Kimber, 1973a,b; Lynch et al., 1981; McCalla and Duley, 1949; Papendick and Miller, 1977; Tarchandrophongs and Davidson, 1970; Whitfield and Smika, 1971; Zingg and Whitfield, 1957). Studies of available nitrogen, phosphorus, and sulfur have all but ruled out nutrient deficiencies as an explanation for the effect (Davidson and Santleman, 1973; Ferguson and Gorby, 1964; Kimber, 1973b; Smika et al., 1969). Decomposing wheat straw may be a temporary sink for nitrogen, phosphorus, or sulfur, such as during early stages of decomposition, but this effect is overcome by modern methods of injecting plant nutrients below or below and to one side of the seed at the time of sowing. Moreover, in the course of a full season, and especially where a full year of fallow occurs between wheat crops, straw is more important as a source than as a sink for nitrogen and phosphorus (Power and Legg, 1978), yet the yield depressions still occur (Cook and Waldher, 1977).

In 1949, McCalla and Duley (1949) reported that soil with decomposing wheat straw is toxic to germination of corn. Only 38 to 50% of the corn seeds germinated when sown in straw-amended soil kept "excessively wet," whereas 89 to 94% of the corn seeds germinated in the same soil kept wet but not amended with wheat straw. Wheat straw had no adverse effect on corn seed germination in soils with "optimum" water contents. The soil used by McCalla and Duley (1949) came from the top 15 cm of a site where corn, oats, and wheat had been grown in rotation. As such, the soil almost certainly contained *Pythium* spp. capable of causing corn seed decay and seedling blight. Hoppe (1949) showed in that same year that seed decay and seedling blight of corn caused by *Pythium* spp. is highly favored by cold wet soils (ideal for both pre- and postpenetration steps of pathogenesis). Moreover, it has long been known that plant materials can result in significantly greater *Pythium* damage to seedlings because of the saprophytic increase and greater inoculum potential of the pathogen (Garrett, 1956; Yarwood, 1966; Hancock, 1977). It now seems likely that the poor germination of

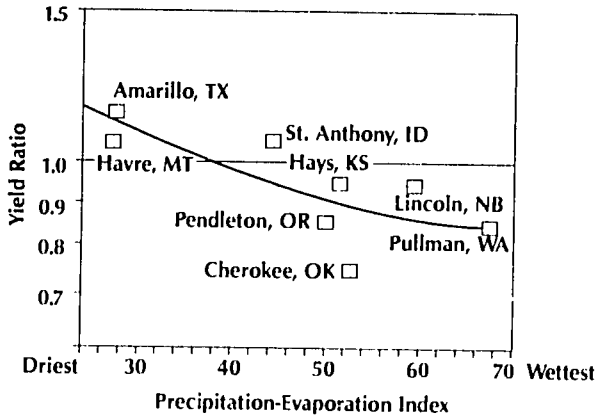


Figure 1. Relationship between the yield ratio for wheat (yield in mulch-tilled soil divided by yield in clean-tilled soil) and the precipitation-evaporation index (portion of annual evaporation potential satisfied by annual precipitation). Values are averages based on 101 separate crop-year determinations. [Data of Zingg and Whitfield, 1957.]

corn seeds noted by McCalla and Duley (1949) in straw-amended soil was the result of *Pythium*.

In eastern Washington, where the problem can be severe (Fig. 1, Zingg and Whitfield, 1957) the stunting and poor tillering of wheat plants in natural soils amended with wheat straw does not occur if metalaxyl, a fungicide specific for *Pythium* spp. and closely related fungi, is added to the soil (Cook et al., 1980, 1990; Table 1).

A vast literature on the phytotoxicity to wheat of straw and other plant materials has accumulated since the report of McCalla and Duley (1949) 40 years ago. The kinds of experiments reported fall basically into two groups: (1) wheat is shown to not emerge or grow poorly in natural soils (invariably soils from the surface of a field or plot with a history of wheat) amended with plant residue (Behmer and McCalla, 1963; Kimber, 1973a,b; Lynch et al., 1981; Norstadt and McCalla, 1967); and (2) extracts of residues in various stages of decomposition are shown to inhibit wheat seed germination, root elongation, and/or shoot growth under axenic conditions (Guenzi and McCalla, 1962; Kimber, 1967 and 1973a,b). Toxic substances have been extracted from plant materials at various stages of decomposition in the field (Cochran et al., 1977), and acetic acid was shown to accumulate in anaerobic soils at concentrations sufficient to inhibit growth of barley roots (Lynch, 1977 and 1978). However, in spite of these extensive studies, there is no direct evidence that the poor growth of wheat in soil mulched with wheat straw is caused by phytotoxins from the rotting straw.

The evidence is now clear, at least for eastern Washington and northern Idaho, that the growth- and yield-depressions of wheat grown with mulch tillage or direct drilling are due to root pathogens favored epidemiologically by the wetter

and cooler soil conditions and also by the straw serving as a food base for the pathogens. Three root pathogens of wheat have been shown experimentally to be more damaging with direct drilling (residues left on the soil surface) than where clean tillage is used. These are take-all, caused by *Gaeumannomyces graminis* var. *tritici* (Moore and Cook, 1984; R. J. Cook, W. A. Haglund, and E. Bassett, unpublished); Rhizoctonia root rot, caused by *R. solani* AG8 (Rovira and Venn, 1985; Weller et al., 1986); and Pythium root rot, caused by several *Pythium* spp. (Cook et al., 1980). In fact, these three root pathogens are the only three soil microorganisms shown experimentally to cause more damage to wheat where soils are undisturbed and covered with residue than where they are clean-tilled. Root-colonizing pseudomonads inhibitory to growth of wheat roots (possible members of the subclinical category of root pathogens described at the beginning of this chapter) also occur more frequently where wheat straw was either on the soil surface or incorporated than where it was burnt (Elliott and Lynch, 1984), and they may therefore play some additional role in the syndrome.

All three root diseases shown to be favored by surface residues are also favored by wet soil, and the causal pathogens use crop residue as a food base (energy source) for attack of the next crop. Moreover, all three root diseases result in stunting, reduced tillering, and nutrient-deficiency symptoms in the leaves typical of the symptoms attributed to phytotoxins. As evidence for the indirect effect of straw, C.L. Douglas, R.J. Cook, and L.F. Elliott (unpublished) found at Pullman in 1987 that take-all and Pythium root rot were both less severe where straw was removed by burning than where it was left undisturbed, but they were as severe or more severe when the burnt soil surface was recovered with straw at a rate similar to the undisturbed check. These experiments were done with winter wheat direct-drilled into a site where winter wheat had been grown the previous year. These observations indicate that the surface straw provides the wetter soil environment favorable to these diseases. It seems likely, therefore, that the growth and yield depression of wheat associated with surface residues and the root diseases favored by reduced tillage are one and the same.

More recent results from two 1989 field trials carried out in eastern Washington has provided further evidence for the importance of root diseases of wheat and proof that the straw is not toxic. In these experiments, soil and straw were fumigated separately and then recombined to provide natural straw on natural soil, fumigated straw on natural soil, natural straw on fumigated soil, fumigated straw on fumigated soil, and natural and fumigated soil without straw (checks). Both experiments revealed that the microorganisms responsible for the poor growth and low yield of wheat (and eliminated by soil fumigation) are in the soil and not in the straw as previously thought. The yields average 25 to 30% less in nonfumigated soil compared with fumigated soil regardless of whether these respective soil treatments were covered with natural or fumigated straw. Take-all, Rhizoctonia root rot, and Pythium root rot occurred as a mixture in both experiments and were responsible for the yield depressions in the nonfumigated soil. Covering the soil with straw helped keep the top 15 to 20 cm wet and, hence, more favorable to the diseases.

Accepting root diseases as the cause of the sick wheat syndrome in conservation tillage systems, then the primary cultural practice responsible for the problem may be more the lack of crop rotation than the use of direct drilling or mulch tillage. Similarly, the greater severity of damage within than outside the "chaff-row" (the region of most concentrated chaff left by the mechanical harvester) may be more the result of the dense volunteer wheat and grassy weeds that tend to grow in this row than of the concentrated chaff and straw contributing to the inoculum potential of these pathogens. Crop residues may serve these pathogens as a secondary source of carbon and energy, but their primary food source is likely the living roots of wheat, barley, and weeds. Clearly, practices and treatments aimed at control of specific root diseases are needed to improve the health and productivity of wheat in conservation tillage systems.

VI. Strategies and Approaches to Economic Control

The many possible approaches to control of diseases caused by soilborne plant pathogens are basically no different conceptionally from the many approaches to control of any other pest or pest complex:

1. One should seek first to lower the inoculum potential of the pathogen in soil below some economic threshold. This may be accomplished by (1) crop rotation, for pathogens that depend for survival on active mycelium in crop debris and have limited host ranges; (2) tillage and possibly burial of crop residue, for pathogens that use crop residue as a food base; (3) soil fumigation, soil solarization, or burning crop residue (applies to experimental plots; not economical or acceptable on a field scale) to destroy pathogen inoculum; and (4) clean (pathogen-free) seed, for pathogens that are seedborne.

2. The next strategy would be to prevent infection from carryover inoculum, that is, to keep the pathogen from entering the germinating seed of the plant or the root. This may be accomplished with certain fungicides and can now also be accomplished experimentally with root-colonizing microorganisms introduced on the seeds (see subsequent sections).

3. The third and only other major strategy is to maximize the plant's own systems of self-defense, that is, host-resistance mechanisms.

Management of take-all with continuous wheat (or barley), that is, without rotation to nonhost crops, illustrates how each of the three major strategies to pest control can be applied to the same disease (Cook and Weller, 1987):

1. *The inoculum potential of the pathogen can be lowered* either by tillage or by delayed seeding; tillage accelerates the biological processes that lead to destruction or displacement of the take-all pathogen in crop residues, and delayed seeding allows more time for demise of the pathogen, and for its displacement in crop residue by strict saprophytes between the harvesting of one crop and sowing of the next. Early and thorough control of the volunteer wheat or barley and grass weeds between harvest of one crop and sowing of the next is very important in limiting the amount of pathogen inoculum in the soil (Rovira and Venn, 1985).

Starving the pathogen of nitrogen during saprophytic survival can also lower its inoculum potential (Garrett, 1940).

2. *The amount of infection can be limited* by acidifying the rhizosphere by use of ammonium rather than nitrate forms of nitrogen, thereby favoring certain rhizosphere bacteria inhibitory to *G. graminis* var. *tritici* (Smiley and Cook, 1973; Smiley, 1978a,b; Christensen and Brett, 1985). These bacteria, including strains of fluorescent *Pseudomonas* species, tend to maintain higher populations or to be more inhibitory to *G. graminis* var. *tritici* around roots if the rhizosphere pH is slightly below 7.0 (Howie, 1985). Root-colonizing bacteria inhibitory to *G. graminis* var. *tritici* are also favored by growing wheat repeatedly in the same soil and are thought to play a role in take-all decline with wheat monoculture (Cook and Rovira, 1976; Cook and Weller, 1987; Weller et al., 1988). Tests are now in progress with these bacteria introduced as a living seed treatment to protect roots against take-all (Weller and Cook, 1983). In trials carried out in 1987 in a commercial field of rainfed wheat in western Washington, the best bacterial treatment resulted in about 900 kg/ha (25%) greater yield than the check (Cook et al., 1987).

3. As the third line of plant defense, the *resistance of wheat and barley plants to take-all can be maximized* with good plant nutrition (Reis et al., 1982; Cook and Weller, 1987). However, there is no known genetic sources of resistance to this pathogen (Scott, 1980).

All three strategies in the Pacific Northwest used together can maintain yields of wheat at 80 to 95% of the attainable without crop rotation (Cook and Weller, 1987). However, if any one component of this system if omitted – that is, the field is not tilled, soil pH is above 7.0, or fertility is neglected – the disease is likely to be severe. Our immediate goal with rhizobacteria introduced as a seed treatment is to elevate yields closer to the attainable while using the best cultural practices; our long-range goal is to control take-all with less tillage and less or no crop rotation in soils with the higher pH values, or perhaps with suboptimal soil fertility.

It is helpful, when deciding among the three major strategies, to know the potential (attainable) yield as limited by available water, accumulated growing degree days (heat units), soil conditions, and other physical/chemical factors associated with the year and site. This yield can be determined experimentally by use of either soil fumigation or solarization, to sanitize the soil, followed by full-season protection of the foliage against aerial pathogens and insect pests. The fact that such treatments are not commercially economical is irrelevant, since the purpose is to determine experimentally the attainable yield for the site and year. Actual yields can then be expressed as a percentage of the attainable (Cook, 1985). By knowing that the actual yield is significantly less than the attainable, one can take steps to diagnose the problem(s). The goal should then be to achieve a yield approaching 100% of the attainable, or deliberately to target some fraction of the attainable, by using practices that are more economical or acceptable and available crop varieties that are resistant to the important pathogens.

For crops grown under dryland/rainfed conditions, the limiting factor to yield is commonly water but can also be thermal time (available growing degree days) or real time (number of days from sowing to harvest). If fumigation of the soil

results in a greater yield then obviously the physical environment is not the limiting factor to yield at that site and year. Irrigation and fertilization might increase the actual yield, but such inputs can override the effects of some root diseases or help the crop produce a respectable yield in spite of root diseases. In general, the higher the attainable yield—for example, as set by available water, heat units, and time—the greater the difference between actual and attainable and the more critical the need for disease control.

In contrast to examples of actual yields below the attainable, owing to undiagnosed diseases, it is common in dryland/rainfed agriculture to manage for a yield higher than can be attained with the limited water supply. This kind of practice can lead to plant water stress and the development of diseases such as Fusarium root, foot, and stalk rots. Fusarium foot rot of wheat caused by *F. culmorum* became a problem in eastern Washington where growers were fertilizing for 5 to 6 t/ha but with available soil water adequate to produce only 4 to 5 t/ha (Papendick and Cook, 1974; Cook, 1980; Cook, 1986). The disease ceased to be important, except in unusually dry years, once growers reduced their rates of fertilization sufficient to produce only the attainable yield. It was not necessary to reduce the inoculum density of *F. culmorum*, or even to prevent the pathogen from entering the plant, since the host's own defense system can control this pathogen after infection, provided the plant water potentials do not drop below −3.3 to −3.5 MPa for long.

Fusarium stalk rot of sorghum caused by *F. moniliforme* is similarly favored by plant water stress, and has been managed in western Nebraska (Doupnik and Boosalis, 1980) by a combination of a 3-year rotation (winter wheat–sorghum–fallow) and reduced tillage (sorghum is planted into winter wheat stubble), a system known as ecofallow (Wicks, 1976). Up to 12 to 15 cm more water is available to sorghum seeded after wheat with reduced (mulch) tillage than with clean tillage.

VII. Research Needs

There is a major need to find new or improved methods for diagnosis and quantification of root and vascular diseases caused by soilborne plant pathogens and to distinguish between the effects of biotic and abiotic diseases. Physiological stresses such as winter injury, nutritional deficiencies, and drought can predispose plants to greater damage from soilborne plant pathogens; but conversely, soilborne pathogens can predispose plants to these physiological stresses. The methods should include perfection of selective soil treatments to eliminate specific pathogens while leaving the remainder of the microbiota largely intact; better and more selective media for isolation and enumeration of pathogens in soils and plant tissues; and more accurate tools for diagnosis, including use of DNA probes and serology at a molecular level.

There is also a need for more research on the interactions among predisposing stresses on crop plants and damage caused by soilborne plant pathogens.

Identification of low plant water potentials as the predisposing factor in development of Fusarium foot rot caused by *F. culmorum* (Papendick and Cook, 1974) opened the way in the Pacific Northwest for a highly successful control aimed at managing host-plant water potentials (Cook, 1980). Low or high temperature stresses, soil compaction, poor gas exchange in the root zone, and nutritional deficiencies in the plants are all potential predisposing factors to greater damage caused by these pathogens. Conversely, elimination of the pathogen can greatly alleviate the risk of these adverse environmental factors to crop growth.

Another major need is for more fundamental and applied research on the interactions of soilborne pathogens with other microorganisms in soil and especially in the rhizosphere. Some soils are highly conducive to the growth and survival of soilborne plant pathogens in the rhizosphere, because of the lack of adequate antagonism needed to shorten the life of their propagules in soil or prevent their growth in the rhizosphere. Other soils or rhizospheres are highly suppressive to soilborne pathogens, because of greater competitive, antibiotic and predatory effects of organisms on pathogens in soil and the rhizosphere. A pathogen may fail to establish, it may establish but cause little disease, or it may establish and cause disease initially but then fail as the soil (or rhizosphere) converts from conducive to suppressive (Baker and Cook, 1974). Take-all decline, mentioned earlier, is an example of the latter case; the soil is conducive at first but becomes suppressive following one or two severe outbreaks of the disease and continued monoculture of wheat. Soil amended with barley straw becomes suppressive to *F. solani* f. sp. *phaseoli* and exemplifies the situation wherein the pathogen still exits in the soil but does not cause disease (Snyder et al., 1959). Soils in France and California are naturally suppressive to vascular diseases caused by *Fusarium oxysporum*; more inoculum is required to produce a given incidence of wilt, and the pathogen tends to die out more quickly in these soils than in conducive soils (Alabouvette et al., 1985).

Studies of pathogen-suppressive soil can be valuable in at least three ways:

1. An investigation into the mechanisms involved can reveal important new information on the ecology of the pathogen. Thus, Scher and Baker (1980, 1982) found that soils may be suppressive to Fusarium-wilt pathogens because of siderophore-producing bacteria active in the rhizosphere. Siderophores are natural iron-chelating compounds. Siderophore-producing bacteria in the soil low in iron are thought to sequester the iron needed by the pathogen for germination and growth and thereby limit prepenetration growth of the pathogen in the rhizosphere. Studies of soil suppressive to Pythium root rot of cucurbits in Hawaii revealed an interaction between soil microorganisms and calcium (Kao and Ko, 1986a,b); when calcium was provided, disease was microbiologically suppressed.

2. Recognition of a suppressive soil and identification of the relevant environmental factors can lead to cultural practices designed to enhance or at least not upset the suppression. A soil that becomes suppressive to take-all with long-term wheat monoculture becomes conducive again if rotated for 3 years to alfalfa (*Medicago sativa*), oats, potatoes (*Solanum tuberosum*), or soybeans (Cook, 1981). It is therefore better to rotate regularly to keep the inoculum potential of

the pathogen low, or to grow wheat continuously to maintain a suppressive soil. Alternating between monoculture and rotation—that is, wheat for 3 to 5 years, other crops for 1 to 2 years, and then wheat for another 3 to 5 years—can result in severe take-all with less prospect for effective and lasting take-all decline.

3. Suppressive soils are also a source of potential biological control agents (Cook and Baker, 1983). Studies of the suppression responsible for take-all decline revealed an association with fluorescent *Pseudomonas* species highly inhibitory to the pathogen (Cook and Rovira, 1976; Cook and Baker, 1983; Weller et al., 1988). Further studies revealed that the most suppressive strains produced a phenazine-type antibiotic highly inhibitory to *G. graminis* var. *tritici* (Brisbane and Rovira, 1988; Gurusiddaiah et al., 1986). Inactivation of a gene for phenazine production by a Tn*5* insertion all but eliminated the ability of the strain to protect wheat against take-all, and restoration of phenazine-producing ability by complementation fully resorted the mutated strain's ability to protect wheat against take-all (Thomashow and Weller, 1988). These results on mechanisms and those on efficacy of the strains in field trials (Cook et al., 1988; Weller and Cook, 1983, 1986) reveal the potential of this approach to root disease control along with more traditional approaches. This work also reveals the power of combining the tools of gene manipulation with field testing as a means of understanding and developing systems for root disease control.

VIII. Epilog

Root diseases are major deterrents to crop productivity as well as to the adoption of practices needed to make dryland/rainfed agriculture more efficient and sustainable. Agronomic practices designed to improve crop performance within the constraints of available water and the need to conserve soil and energy also affect the activity of soilborne pathogens. From the scientific perspective, more work is needed to distinguish between the direct agronomic effects of different practices on crop growth and the effects of these practices on root diseases, which then affects performance of the crop. Better information on root diseases will open the way to more informed approaches to crop management and to research aimed more precisely at the primary rather than the secondary factors responsible for variable crop performance in dryland/rainfed agriculture.

References

Alabouvette, C., Y. Couteaudier, and J. Louvet. 1985. Soils suppressive to Fusarium wilt: Mechanisms and management of suppressiveness. *In* C.A. Parker, A.D. Rovira, K.J. Moore, and P.T.W. Wong, eds. Ecology and Management of Soilborne Plant Pathogens. Amer. Phytopathol. Soc., St. Paul, MN, pp. 101-106.

Aldrich, D.G., and J.P. Martin. 1952. Effect of fumigation on some chemical properties of soils. Soil Science 73:149-159.

Allmaras, R.R., J.M. Kraft, and D.E. Miller. 1988. Effects of soil compaction and incorporated crop residue on root health. Ann. Rev. Phytopathol. 26:219–243.

Baker, K.F., and R.J. Cook. 1974 (original ed.). Biological Control of Plant Pathogens. San Francisco: W.H. Freeman. Reprinted ed., 1982. St. Paul, Minn.: Amer. Phytopathol. Soc.

Baker, K.F., and W.C. Snyder. 1965. Ecology of Soil-Borne Plant Pathogens. Prelude to Biological Control. Berkeley: Univ. Calif. Press.

Beckman, C.H. 1987. The Nature of Wilt Diseases of Plants. St. Paul, Minn.: APS Press.

Behmer, D.E., and T.M. McCalla. 1963. The inhibition of seedling growth by crop residues in soil inoculated with *Penicillium uritacae* Bainer. Plant Soil 18:199–206.

Brisbane, P.G., and A.D. Rovira. 1988. Mechanisms of inhibition of *Gaeumannomyces graminis* var. *tritici* by fluorescent pseudomonads. Plant pathology 37:104–111.

Brown, R.H. 1984. Ecology and control of cereal cyst nematode (*Heterodera avenae*) in southern Australia. J. Nematol. 16:216–222.

Bruehl, G.W., ed. 1975. Biology and Control of Soil-borne Plant Pathogens. St. Paul, Minn.: Amer. Phytopathol. Soc.

Bruehl, G.W. 1987. Soilborne Plant Pathogens. New York: Macmillan Publishing Co.

Bruehl, G.W., R.L. Millar, and B. Cunfer. 1969. Significance of antibiotic production by *Cephalosporium gramineum* to its saprophytic survival. Can. J. Plant Sci. 49:235–246.

Butler, F.C. 1961. Root and foot rot diseases of wheat. New South Wales Dept. Agr. Sci. Bull. 77.

Christensen, N.W., and M. Brett. 1985. Chloride and liming effects on soil nitrogen form and take-all of wheat. Agron. J. 77:157–163.

Cochran, V.L., L.F. Elliott, and R.I. Papendick. 1977. The production of phytotoxins from surface crop residues. Soil Sci. Soc. Am. J. 41:903–908.

Cook, R. James. 1968. Fusarium root and foot rot of cereals in the Pacific Northwest. Phytopathology 58:127–131.

Cook, R.J. 1980. Fusarium foot rot of wheat and its control in the Pacific Northwest. Plant Disease 64:1061–1066.

Cook, R.J. 1981. The influence of rotation crops on take-all decline phenomenon. Phytopathology 71:189–192.

Cook, R.J. 1984. Root health: Importance and relations to farming systems. *In* D.F. Bezdicek and J.F. Power, eds. Organic Farming: Current Technology and Its Role in a Sustainable Agriculture. Amer. Soc. Agron. Special Publications.

Cook, R.J. 1985. Use of the term "crop loss." Plant Disease 69:95.

Cook, R.J. 1986. Wheat management systems in the Pacific Northwest. Plant Disease 70:894–898.

Cook, R.J., and K.F. Baker. 1983. The Nature and Practice of Biological Control of Plant Pathogens. St. Paul, Minn.: American Phytopathological Society.

Cook, R.J., and D.M. Duniway. 1981. Water relations in the life-cycles of soilborne plant pathogens. *In* J.F. Parr, ed. Water Potential Relations in Soil Microbiology. pp. 119–139. Madison, Wisc.: Am. Soc. Agron. Special Publication.

Cook, R.J., and R.I. Papendick. 1972. Influence of water potential of soils and plants on root disease. Ann. Rev. Phytopathol. 10:349–372.

Cook, R.J., and W.A. Haglund. 1982. Pythium root rot: A barrier to yield of Pacific Northwest wheat. Wash. State College of Agric. Res. Bull. No. XB0913.

Cook, R.J., and A.D. Rovira. 1976. The role of bacteria in the biological control of *Gaeumannomyces graminis* by suppressive soils. Soil Biol. Biochem. 8:269–273.

Cook, R.J., and J.T. Waldher. 1977. Influence of stubble-mulch residue management on *Cercosporella* foot rot and yields of winter wheat. Plant Dis. Rept. 61:96–100.

Cook, R.J., and D.M. Weller. 1987. Management of take-all in consecutive crops of wheat or barley. *In* I. Chet, ed. Innovative Approaches to Disease Control. New York: John Wiley & Sons.

Cook, R.J., J.W. Sitton, and J.T. Waldher. 1980. Evidence for *Pythium* as a pathogen of direct-drilled wheat in the Pacific Northwest. Plant Disease 64:1061–1066.

Cook, R.J., J.W. Sitton, and W.A. Haglund. 1987. Increased growth and yield responses of wheat to reduction in the *Pythium* populations by soil treatments. Phytopathology 77:1192–1198.

Cook, R.J., D.M. Weller, and E.N. Bassett. 1988. Effect of bacterial seed treatments on growth and yield of recropped wheat in western Washington, 1987. Biological and Cultural Tests 3:53.

Cook, R.J., C. Chamswarng, and W-h. Tang. 1990. Influence of wheat chaff and tillage on *Pythium* populations and *Pythium* damage to wheat. Soil Biol. Biochem. 22: (In Press).

Davidson, J.M., and P.W. Santleman. 1973. An evaluation of various tillage systems for wheat. Oklahoma Agric. Exp. Stn. Bull. B-711.

Dickson, J.G. 1923. Influence of soil temperature and moisture on the development of the seedling-blight of wheat and corn caused by *Gibberella saubinetti*. J. Agric. Res. 23: 837–870.

Doupnik, B., and M.G. Boosalis. 1980. Ecofallow—A reduced tillage system—and plant diseases. Plant Disease 64:31–35.

Duniway, J.M. 1973. Pathogen-induced changes in host water relations. Phytopathology 63:458–472.

Elliott, L.F., and J.M. Lynch. 1984. Pseudomonads as a factor in the growth of winter wheat (*Triticum aestivum* L.) Soil Biol. Biochem. 16:69–71.

Ferguson, W.S., and B.J. Gorby. 1964. Effect of straw on availability of nitrogen to cereal crops. Can. J. Soil Sci. 44:286–291.

Garrett, S.D. 1940. Soil conditions and the take-all disease of wheat. V. Further experiments on the survival of *Ophiobolus graminis* in infected wheat stubble buried in soil. Ann. Appl. Biol. 27:199–204.

Garrett, S.D. 1956. Biology of Root-infecting Fungi. London: Cambridge Univ. Press.

Guenzi, W.D., and T.M. McCalla. 1962. Inhibition of germination and seedling development by crop residues. Soil Sci. Soc. Am. Proc. 26:456–458.

Gurusiddaiah, S., D.M. Weller, A. Sarkar, and R.J. Cook. 1986. Characterization of an antibiotic produced by a strain of *Pseudomonas fluorescens* inhibitory to *Gaeumannomyces graminis* var. *tritici* and *Pythium* spp. Antimicrobial Agents and Chemotherapy 29:488–495.

Hancock, J.G. 1977. Factors affecting populations of *Pythium ultimum* in the San Joaquin Valley of California. Hilgardia 45:107–122.

Hering, T.F., R.J. Cook, and W.-h. Tang. 1987. Infection of wheat embryos by *Pythium* species during seed germination and the influence of seed age and soil matric potential. Phytopathology 77:1104–1108.

Hoppe, P.E. 1949. Differences in *Pythium* injury to corn seedlings at high and low temperatures. Phytopathology 39:77–84.

Hornby, D. 1990. Biological Control of Soil-borne Plant Pathogens. C.A.B. International, Wallingford, Oxon, U.K. (In Press).

Howie, W.J. 1985. Factors affecting colonization of wheat roots and suppression of take-all by pseudomonads antagonistic to *Gaeumannomyces graminis* var. *tritici*. PhD. Thesis, Washington State University, Pullman.

Inglis, D.A., and R.J. Cook. 1986. The persistence of chlamydospores of *Fusarium culmorum* in wheat-field soils of eastern Washington. Phytopathology 76:1205-1208.

Ingram, D.M. 1987. Pathogenicity of *Pythium* species on major crops in the Palouse. Ph.D. thesis. Washington State University, Pullman.

Kaiser, W.J., and R.M. Hannan. 1983. Etiology and control of seed decay and preemergence damping-off of chickpea by *Pythium ultimum*. Plant Disease 67:77-81.

Kao, C.W., and W.H. Ko. 1986a. Suppression of *Pythium splendens* in a Hawaiian soil by calcium and microorganisms. Phytopathology 76:215-220.

Kao, C.W., and W.H. Ko. 1986b. The role of calcium and microorganisms in suppression of cucumber damping-off caused by *Pythium splendens* in a Hawaiian soil. Phytopathology 76:221-225.

Katan, J. 1980. Solar pasteurization of soils for disease control: Status and prospects. Plant Disease 64:450-454.

Kerr, A. 1964. The influence of soil moisture on infection of peas by *Pythium ultimum*. Aust. J. Biol. Sci. 17:676-685.

Kimber, R.W.L. 1967. Phytotoxicity from plant residues. I. The influence of rotted wheat straw on seedling growth. Aust. J. Agric. Res. 18:361-374.

Kimber, R.W.L. 1973a. Phytotoxicity from plant residues. II. The effect of time of rotting of straw from some grasses and legumes on the growth of wheat seedlings. Plant Soil 38:347-361.

Kimber, R.W.L. 1973b. Phytotoxicity from plant residues. III. The relative effect of toxins and nitrogen immobilization on the germination and growth of wheat. Plant Soil 38: 543-555.

Ko, W.H., and F.K. Hora. 1971. A selective medium for the quantitative determination of *Rhizoctonia solani* in soil. Phytopathology 61:707-710.

Komada, H. 1975. Development of a selective medium for quantitative isolation of *Fusarium oxysporum* from natural soil. Rev. Plant Prot. Res. 8:114-125.

Leach, L.D. 1947. Growth rates of host and pathogen as factors determining the severity of preemergence damping-off. J. Agr. Res. 75:161-179.

Lynch, J.M. 1977. Phytotoxicity of acetic acid produced in the anaerobic decomposition of wheat straw. J. Applied Bact. 42:81-87.

Lynch, J.M. 1978. Production and phytotoxicity and acetic acid in anaerobic soils containing plant residues. Soil Biol. Biochem. 10:131-135.

Lynch, J.M., F.B. Ellis, S.H.T. Harper, and D.G. Christian. 1981. The effect of straw on the establishment and growth of winter cereals. Agriculture and Environment 5:321-328.

McCalla, T.M., and T.J. Army. 1961. Stubble-mulch farming. Adv. Agron. 13:125-196.

McCalla, T.M., and F.C. Duley. 1949. Stubble-mulch studies. III. Influence of soil microorganisms and crop residues on the germination, growth, and direction of root growth of corn seedlings. Soil Sci. Soc. Am. Proc. 14:196-199.

Miller, D.E., and D.W. Burke. 1975. Effect of soil aeration on Fusarium root rot of beans. Phytopathology 65:519-523.

Mircetich, S.M. 1971. The role of *Pythium* in feeder roots of diseased and symptomless peach trees and in orchard soils in peach tree decline. Phytopathology 61:357-360.

Moore, K.J., and R.J. Cook. 1984. Increased take-all of wheat with direct-drilling in the Pacific Northwest. Phytopathology 74:1044–1049.

Nash, S.M., and W.C. Snyder. 1962. Quantitative estimations by plate counts of propagules of the bean root rot *Fusarium* in field soils. Phytopathology 52:567–572.

Neate, S.M. and J.N. Warcup. 1985. Anastomosis grouping of some isolates of *Thanatephorus cucumeris* from agricultural soils in South Australia. Trans. Brit. Mycol. Soc.

Norstadt, F.A., and T.M. McCalla. 1967. Microbially induced phytotoxicity in stubble-mulched soil. Paper No. 2085. Journal Series, Nebraska Agr. Exp. Sta.

Papendick, R.I., and R.J. Cook. 1974. Plant water stress and development of Fusarium foot rot in wheat subjected to different cultural practices. Phytopathology 64:358–363.

Papendick, R.I., and D.E. Miller. 1977. Conservation tillage in the Pacific Northwest. J. Soil Water Conserv. pp. 49–56.

Parker, C.A., A.D. Rovira, K.J. Moore, P.T.W. Wong, and J.F. Kollmorgen. 1986. Ecology and Management of Soilborne Plant Pathogens. St. Paul, Minn.: APS Press.

Phillips, R.E., R.L. Bevins, G.W. Thomas, W.W. Freye, and S.H. Phillips. 1980. No-tillage agriculture. Science 208:1108–1113.

Power, J.F., and J.O. Legg. 1978. Effect of crop residues on the soil chemical environment and nutrient availability. *In* W.R. Oschwald, ed. Crop Residue Management Systems. pp. 85–100. Am. Soc. Agron. Spec. Publ. 31.

Reis, E.M., R.J. Cook, and B.L. McNeal. 1982. Effect of mineral nutrition on take-all of wheat. Phytopathology 72:224–229.

Reis, E.M., R.J. Cook, and B.L. McNeal. 1983. Elevated pH and associated reduced trace-nutrient availability as factors contributing to increased take-all of wheat upon soil liming. Phytopathology 73:411–413.

Rovira, A.D., and N.R. Venn. 1985. Effect of rotation and tillage on take-all and Rhizoctonia root rot in wheat. *In* C.A. Parker, A.D. Rovira, K.J. Moore, P.T.W. Wong, and J.F. Kollmorgen, eds. Ecology and Management of Soilborne Plant Pathogens. pp. 225–258. St. Paul, Minn.: APS Press.

Rovira, A.D., R.D Graham, and J.S. Ascher. 1985. Reduction in infection of wheat roots by *Gaeumannomyces graminis* var. *tritici* with application of manganese to soil. *In* C.A. Parker, A.D. Rovira, K.J. Moore, P.T.W. Wong, and J.F. Kollmorgen, eds. Ecology and Management of Soilborne Plant Pathogens. pp. 212–214. St. Paul, Minn.: APS Press.

Rovira, A.D., A. Ogoshi, and H.J. McDonald. 1986. Characterization of isolates of *Rhizoctonia solani* from cereal roots in South Australia and New South Wales. Phytopathology 76:1245–1248.

Schroth, M.N., and R.J. Cook. 1964. Seed exudation and its influence on pre-emergence damping-off of bean. Phytopathology 54:670–673.

Scher, F.M., and R. Baker. 1980. Mechanism of biological control in a *Fusarium*-suppressive soil. Phytopathology 70:412–417.

Scher, F.M., and R. Baker. 1982. Effect of *Pseudomonas putida* and a synthetic iron chelator on induction of soil suppressive to Fusarium wilt pathogens. Phytopathology 72:1567–1573.

Schippers, B., and W. Gams, eds. 1979. Soil-borne Plant Pathogens. New York: Academic Press.

Scott, P.R. 1980. Variation in host susceptibility. *In* M.J.C. Asher and P.J. Shipton, eds. Biology and Control of Take-all. pp. 219–236. London: Academic Press.

Smika, D.E., A.C. Black, and B.W. Breb. 1969. Soil nitrate, soil water, and grain yields in a wheat-fallow rotation in the Great Plains as influenced by straw mulch. Agron. J. 61:785–787.

Smiley, R.W. 1978a. Antagonists of *Gaeumannomyces graminis* from the rhizoplane of wheat in soils fertilized with ammonium- or nitrate-nitrogen. Soil Biol. Biochem. 10: 169–174.

Smiley, R.W. 1978b. Colonization of wheat roots by *Gaeumannomyces graminis* inhibited by specific soils, microorganisms and ammonium-nitrogen. Soil Biol. Biochem. 10: 175–179.

Smiley, R.W., and R.J. Cook. 1973. Relationship between take-all of wheat and rhizosphere pH in soils fertilized with ammonium vs. nitrate-nitrogen. Phytopathology 63: 882–890.

Smucker, A.J.M., and A.C. Erickson. 1987. Anaerobic stimulation of root exudates and disease of peas. Plant Soil 99:423–433.

Snyder, W.C., M.N. Schroth, and T. Christou. 1959. Effect of plant residue on root rot of bean. Phytopathology 49:755–756.

Sprague, R. 1950. Diseases of Cereals and Grasses in North America. New York: Ronald Press.

Stover, R.H. 1979. Flooding of soil for disease control. *In* D.Mulder, ed. Soil Disinfestation. pp. 19–28. Amsterdam: Elsevier Sci. Publ.

Tarchandrphongs, S., and J.M. Davidson. 1970. Bulk density, aggregate stability, and organic matter content as influenced by two wheatland soil management practices. Soil Sci. Soc. Am. Proc. 34:302–305.

Thomashow, L.S., and D.M. Weller. 1988. Role of a phenazine antibiotic from *Pseudomonas fluorescens* in biological control of *Gaeumannomyces graminis* var. *tritici*. J. Bacteriol. 170:3499–3508.

Toussoun, T.A., R.V. Bega, and P.E. Nelson, eds. 1970. Root Diseases and Soil-borne Pathogens. Berkeley: Univ. Calif. Press.

Tsao, P.H. 1970. Selective media for isolation of pathogenic fungi. Ann. Rev. Phytopathol. 8:157–186.

Tsao, P.H., and A.C. Canetta. 1964. Comparative study of quantitative methods used for estimating the population of *Thielaviopsis basicola* in soil. Phytopathology 54:633–635.

Weller, D.M. 1983. Colonization of wheat roots by a fluorescent pseudomonad suppressive to take-all. Phytopathology 73:1548–1553.

Weller, D.M., and R.J. Cook. 1983. Suppression of take-all of wheat by seed treatments with fluorescent pseudomonads. Phytopathology 73.463–469.

Weller, D.M., and R.J. Cook. 1986. Increased growth of wheat by seed treatments with fluorescent pseudomonads, and implications of *Pythium* control. Can. J. Plant Pathol. 8:328–334.

Weller, D.M., R.J. Cook, G. McNish, E.N. Bassett, R.L. Powelson, and R.R. Petersen. 1986. Rhizoctonia bare patch of small grain, favored by reduced tillage in the Pacific Northwest. Plant Disease 70:70–73.

Weller, D.M., W.J. Howie, and R.J. Cook. 1988. Relationship between in vitro inhibition of *Gaeumannomyces graminis* var. *tritici* and suppression of take-all of wheat by fluorescent pseudomonads. Phytopathology 78:1094–1100.

Whitfield, C.J., and D.E. Smika. 1971. Soil temperature and residue effects on growth components and nutrient uptake of four wheat varieties. Agron. J. 63:297–300.

Wicks, G. 1976. Ecofallow: A reduced tillage system for the Great Plains. Weeds Today 7:20–23.

Wilhelm, S. 1965. *Pythium ultimum* and the soil fumigation growth response. Phytopathology 55:1016–1020.

Wilhelm, S., and A.O. Paulus. 1980. How soil fumigation benefits the California strawberry industry. Plant Disease 64:264–270.

Yarwood, C.E. 1966. Detection of *Pythium* in soil. Plant Dis. Rept. 50:791–792.

Zingg, A.W., and C.J. Whitfield. 1957. Stubble-mulch farming in the western states. U.S. Dept. Agric. Tech. Bull. 1166, 1–56.

The Role of Soil Biodiversity in Sustainable Dryland Farming Systems

C.S. Potter and R.E. Meyer

I. Introduction 241
II. Diversity/Erodibility Relationships 242
III. Early Bioindicators of Soil Degradation 243
IV. Measurements to Characterize Biodiversity 246
V. Implications for Conservation of Marginal Lands 246
VI. Future Research Needs 247
References 248

I. Introduction

Environmental degradation has been recognized as one consequence of modern agricultural development. Clearing of vegetation and erosion of topsoil are occurring on a global scale, often in the absence of extensive knowledge of the long-term consequences on sustainable production. In addition, global biodiversity (commonly referred to as the variety of and variability among living organisms and the ecological systems in which they occur), is being lost at an alarming rate. Some experts estimate that up to 25% of all species will become extinct over the next 30 years; almost half of these occur in the developing countries (Wilson, 1988). The implications of species extinction for the stability of natural and agricultural ecosystems are not well understood.

Soil biota play a critical role in carbon (C) cycling, and are principal agents for the breakdown of organic matter and the natural maintenance of soil fertility in agricultural systems (Elliott et al., 1984). On a global scale, the balance of soil respiration and CO_2 fixation may be linked to greenhouse gas dynamics and atmospheric warming trends (Hobbie and Melillo, 1984). Consequently, monitoring of environmental degradation might be improved by the extensive

© 1990 by Springer-Verlag New York Inc.
Advances in Soil Science, Volume 13

Prashant Pure Plant

study of soil population dynamics and biodiversity patterns, which may provide early-warning signs of serious ecological disturbance. Better understanding of soil ecology may eventually lead to *bioindicators* of land degradation.

Microbial diversity indices have been developed to assess the effect of disturbances on ecosystems (Atlas, 1984), and they represent a promising tool to evaluate pattern and process in agricultural systems. A research question of central importance is "Can a decline in species diversity in soil agroecosystems serve as an early bioindicator of soil degradation?" Specifically, we will review the relationship of biodiversity dynamics to changes in soil physical parameters (erodibility and aggregate stability), and potential productivity of agricultural lands.

II. Diversity/Erodibility Relationships

Land use planning requires, among other components, reliable diagnostic parameters for predicting potential productivity and erodibility of various soil types. For example, in deciding whether to bring marginal, highly erodible lands into agricultural production, assessment of the capacity of the soil to sustain long-term yields should be made according to objective agronomic and ecological criteria. Few such reliable yardsticks have been developed with which to continually monitor changes in the potential productivity of fragile lands. Topographic features and soil physical characteristics are frequently considered in appraisals of the potential erodibility of uplands, but where slopes are moderate and/or land has been returned to fallow for several years, soil ecological characteristics, correlated with taxonomic information, may serve as useful indicators of areas that remain vulnerable to erosion and degradation if cultivation or other intensive use is undertaken.

The relationship between soil organic matter (SOM) content and stability of soil macro- and microaggregates is well established (Martin, 1945; Chaney and Swift, 1984; Burns and Davies, 1986). Evidence suggests, however, that simple incorporation of organic matter into soil does not lead to increased aggregation and stability; rather it is the subsequent microbial transformation of SOM that leads to structural improvement of soils (Tisdall et al., 1978). Additionally, more water-stable aggregates are present in the rhizosphere than in extrarhizosphere soil, because of the activity of root-associated microflora (Harris et al., 1964). Rapid increases in soil microbial activity contribute to the formation of soil aggregates, through bacterial polysaccharide secretion and fungal hyphae growth (Hepper, 1975; Burns and Davies, 1986). For instance, organisms such as *Azotobacter* sp. and *Beijerinckia indica* are prominent polysaccharide-producing microbes (Dommergues et al., 1979). The relative abundance and distribution of such microbes in soil communities may provide indicators of potential erodibility, and could supplement theoretical estimations of actual erosion rates for marginal croplands.

From a soil management perspective, evidence suggests that conventional tillage reduces the size of soil aggregates, which can promote pore clogging and

decreased infiltration (Grohman, 1960; Moura and Buol, 1972). Such soil physical modification may affect soil ecological patterns. For example, Doran (1980) showed that microbial populations were more abundant in no-till systems to a depth of 7.5 cm, compared to conventional tillage management. Examining SOM dynamics and microbial activity under differing levels of disturbance can show decreased rates of plant residue decomposition in cultivated soil compared to fallow soils, a pattern that may be attributed to lower microbial activity resulting from either restricted aeration or less available soil moisture in cropped soils, although evidence on this issue is conflicting (Martin, 1987). Total C and N, water-stable soil aggregates, and polysaccharides in abandoned farmlands frequently increase with time since disturbance, whereas chelating resin-extractable C, humic acid/fulvic acid ratios, caloric content of the rootmass, and dehydrogenase activity decrease (Dormaar and Smoliak, 1985). The preceding evidence suggests that changes in the soil biotic community are closely linked to management-induced alterations in soil physical parameters. Soil structure degrades easily if biological activity falls below a minimal threshold level, which may be related to declines in the functional diversity of the microbial community (Lal, 1988). Biodiversity dynamics as prime indicators of erodibility potential is a research topic that warrants much detailed investigation.

III. Early Bioindicators of Soil Degradation

Previous studies have shown that monitoring soil enzyme activity may indicate plant growth potential and contribute to understanding of microbial processes necessary for soil formation (Rice and Pancholy, 1972). In addition, changes in mineralization:biomass and microbial C:N ratios between rangeland and cropland soils indicate differences in substrate and soil microbial population composition under the different land uses (Schimel et al., 1985). At the composite level of investigation, increases in total soil microbial biomass have proved to be reliable indicators of the positive effects of organic matter management in cereal cultivation. For example, Insam et al. (1989) demonstrated that the microbial biomass C to soil organic C ratios were higher under crop rotation systems than in monocultures, and higher in organically manured plots than in mineral-fertilized plots. Similarly, soil from organic farms typically has higher levels of urease, phosphatase, and dehydrogenase (compared to farms that received inorganic fertilizer inputs), indicating a larger and more active microflora composition (Bolton et al., 1985; Fraser et al., 1988).

As early-warning signals of soil degradation, microbial populations, particularly within bacterial communities, can provide advance evidence of subtle changes in SOM content long before they could be accurately measured against background organic matter levels already present in the soil (Powlson et al., 1987). Because actively metabolizing bacteria depend on external nutrient sources for survival, they respond promptly to soil amendment and decline rapidly once SOM nutrients are depleted (Alexander, 1977).

The relative diversity and abundance of the various microbial taxa in soils regularly vary with different agronomic management practices. For instance, the numbers and types of bacteria are highly dependent on cultivation methods. In general, bacterial and fungal populations immediately proliferate upon organic amendments (Fraser et al., 1988). Bacterial abundance on root surfaces increases with SOM levels in the rhizosphere, whereas root surface fungal abundance has been found to be positively affected by the presence of nongrass cover vegetation (Newman et al., 1981). *Azotobacter* populations and anaerobes growing on N-free medium frequently increase with straw incorporation rates (Mukherjee and Gaur, 1980). Actinomycete populations are greater in grassland and pasture soils than in cultivated fields, and changes in the fungal genera *Penicillium*, *Aspergillus*, *Fusarium*, and *Mucor* are particularly conspicuous following organic amendments (Alexander, 1977), indicating their association with enhanced soil fertility.

Evidence from restoration ecology provides trends in microbial community changes during reclamation of degraded lands. Spent oil shale soils are commonly characterized by low numbers of microorganisms, depressed values of bacterial diversity and low rates of cellulose decomposition, compared to regional control soils (Segal and Mancinelli, 1987). Soil reclamation through top-soiling and revegetation can restore populations of heterotrophic aerobic bacteria, *Streptomyces*, ammonium oxidizers, *Azotobacter*, and fungal propagules to levels found in undisturbed soils. Subsequent microbial population declines in reclaimed soils can be attributed to exhaustion of SOM and declines in plant productivity following termination of irrigation (Fresquez et al., 1986). Changes in mycorrhizal associations during restoration offer an additional case in point: reclamation of degraded lands often begins with nonmycorrhizal plants in place; facultative mycorrhizal plants follow, which are finally replaced by obligately mycorrhizal species (Cundell, 1977; Waaland and Allen, 1987). Finally, soil algae may play an important role in reclaiming barren or badly eroded lands, adding organic matter de novo during colonization (Alexander, 1977).

Studies in the drylands offer specific trends in soil microbial biodiversity associated with land management in moisture-stressed areas. In general, bacteria and actinomycetes dominate the arid soil environment (Jung, 1970; Sasson, 1972). More specifically, nitrifying bacteria (*Nitrosomonas* sp.) may be rare in sandy soils, compared to clay soils (Abdel-Salam et al., 1971). Venkateswarlu and Rao (1981) found that stabilization of dunes in the Indian desert leads to approximately a 200-fold increase in microbial populations of fungi, bacteria, and actinomycetes; *Azotobacter* and nitrifying bacteria populations in stabilized dunes are higher than in unstabilized dunes. Addition of farmyard manure to desert soils can also increase soil microbial biomass, particularly in fungal communities (Rao and Venkateswarlu, 1983). With reference to protozoans, flagellate microfauna tend to dominate the soil environment in arid zones (Alexander, 1977).

The investigation of soil biodiversity, however, need not be limited to microbial studies. Management effects on soil arthropods have been linked directly to modification of the physical habitat and to changes in SOM (Usher, 1985). For

example, microarthropod distribution and diversity apparently depends on a number of soil parameters such as temperature, moisture, depth, soil nutrient status, microhabitat availability, and vegetative cover in different vegetative regimes (grass litter, leaf litter, alfalfa, fescue grass; Berg and Pawluk, 1984). Although total soil faunal biomass expressed as a proportion of primary production tends to be inversely related to accumulated organic matter (O'Neill and DeAngelis, 1981), additions of living mulches often increase populations of predator arthropods in cropping systems (Altieri et al., 1985).

In addition to microbial species sensitivity to soil management, certain soil faunal species appear to be reliable indicators of disturbance. As a prime illustration, earthworms appear to be dependable indicators of species-level changes in soil communities resulting from alternative management practices, such as manure treatments (Eijsackers, 1983). In other examples of management-related changes in soil fauna, chemical fertilizers and herbicides may reduce numbers of predacious phytoseiids and *Pergamasus* species in relation to declines in their diet-forming Collembola species (Conti, 1984). Organic manure application and liming reduces soil compaction and can result in greater diversity and abundance of arthropod decomposers such as mites, springtails, isopods, and diplopods (Luizao, 1985). Mixed farming systems have led to increases in the number and biomass of soil fauna compared to continuous cereal cropping with straw removal (Steen, 1983). Diversity, abundance, and biomass of most major soil macroarthropods (especially carabids) are significantly higher in no-tillage than in conventional-tillage agroecosystems (House and Stinner, 1983). Arthropod species composition has been shown to change during barley straw decomposition as collembola and astigmatid mites progressively become the most abundant populations (Lagerlof and Andren, 1985). Plant root exudates appear to promote population increases in nematodes, which are found in association with high levels of SOM and percent total N (Pradhan and Dash, 1984). Finally, termite abundance is thought to be associated with improved soil porosity following organic matter amendments in arid West Africa (Lal, 1988).

Management-induced changes in soil fauna may, in turn, affect microbial processes and soil fertility. For example, litter-feeding animals can have significant qualitative and quantitative effects on N mineralization (ammonification and nitrification) of SOM, through either element transfers in food webs or indirect effects involving feedbacks on microbial activity (Anderson et al., 1985). Additionally, reductions in the density of litter and mor-living soil invertebrates can result in significantly lower C and N mineralization and lower leaching of dissolved organic C (Bengtsson et al., 1988).

In summary, evidence from the literature suggests that increased soil biodiversity, viewed in terms of development of higher trophic levels of secondary consumer populations, is a major factor determining the efficient cycling of nutrients in agroecosystems (Heal and Ineson, 1984). Soil fertility as mediated by rhizosphere ecology in drylands is thought to involve a complex series of plant–microbe interactions, only a small portion of which is well understood (Clarholm, 1985).

IV. Measurements to Characterize Biodiversity

Microbial diversity indices, coupled with rarefication analysis, have been developed to evaluate the effect of disturbances on soil ecosystems (Mills and Wassel, 1980; Atlas, 1984; Klein et al., 1986). An important limiting factor to greater use of these indices is the absence of detailed information on the microbial species composition of below-ground ecosystems. Regular soil sampling for enumeration of microbial characteristics by selective media can be used to distinguish bacteria, actinomycetes, and fungi (Wollum, 1982). These results provide the raw data for developing diversity indices, such as the commonly cited Shannon index (Shannon and Weaver, 1949). This index of microbial diversity has been shown to change in response to environmental pollution stresses (Atlas, 1984); sensitive species are eliminated, competition is reduced, and more stress-tolerant species flourish.

As more information becomes available on biodiversity patterns under various disturbance regimes, the next step is to correlate community composition changes with system stability characteristics. Ecological succession is generally related to an increase in the number of species and the density of most soil fauna groups (Usher, 1985). Traditionally, there has been much debate in the ecological literature on the relationship between species diversity and ecosystem stability. A consensus view is that the functional complexity of ecosystems is associated with stability, although causal relationships based on equilibrium assumptions are different to establish (Van Voris et al., 1980). Agroecosystems are dynamic, and nonequilibrium models apply best in their study. The missing link in the diversity/stability connection may well be better understanding of the dynamic role of microbial populations in ecosystem processes (Wiebe, 1984), and increased knowledge concerning the importance of functional diversity responses to environmental stresses (Klein et al., 1986). Nevertheless, evidence to date indicates that changes in the biological diversity of a given ecosystem are often associated with the magnitude of human exploitation and degenerative use of its natural resources (Atlas, 1984).

V. Implications for Conservation of Marginal Lands

In 1985, the U.S. Congress passed the Food Security Act, which contained provisions for implementing soil and water conservation practices on highly erodible cropland. The Conservation Reserve Program (CRP) encourages farmers to take erodible land out of annual cultivation for a 10-year contract period. Approximately 12 million ha of land has been placed into the CRP. Environmental groups are concerned, however, that farmers will return CRP land to previous cultivation methods at the end of the 10-year fallow period, and soils will again become degraded. A number of important questions arise for the future use of these lands. Should crop production systems be restricted to using minimum-till to reduce expected soil losses? Can SOM and productivity in marginal lands be maintained

over extended periods of time? What measures of soil structural stability improvement and enhanced fertility should be used to evaluate the long-term success of the CRP and subsequent land use?

Answers may lie in further study of soil ecology and biodiversity. The purpose of fallowing in fragile lands is to allow SOM levels to build up and promote microbial activity for improvement of soil structure and productivity. Where marginal soils are not maintained with soil conservation measures, or at least periodically taken out of production, they tend to develop poorer tilth, low organic matter contents, and diminished nutrient concentrations (Kishk, 1985). Intense surface runoff and erosion can transport large portions of applied fertilizers (Jung, 1970). Ultimately, yields may decline in a deteriorating cycle of continuous nutrient extraction from the soil at crop harvest.

With continuous decline in organic matter, the soil microbial community may be altered so that fungi are replaced by a secondary microflora of bacteria and actinomycetes, which display population crashes with further substrate depletion. The soil degradation process can lead to a more stressed soil microclimate (lower soil moisture and wider temperature extremes), which in turn would lower overall soil microbial activity, species diversity, and population abundance (Kaul, 1970; Rao and Venkateswarlu, 1983) and lead to a breakdown of nutrient cycles and loss of soil structure. Since microbial populations can provide early-warning signs of subtle changes in SOM against high background levels, careful monitoring of soil biodiversity dynamics may provide a sensitive index of a shift from land rehabilitation to degradation and allow for timely modification of management techniques. Information feedback from bioindicators concerning the status of marginal lands in turn would assist in developing a farm program to sustain long-term productivity.

VI. Future Research Needs

More research is necessary to predict the influence of soil type, climatic conditions, and management on below-ground microbial ecology in drylands. The relative abundance of soil microbes appears to be highly variable from site to site in arid zones. For instance, 90% of total soil microbial populations found during drought conditions in desert soils of Kenya were actinomycetes (Meiklejohn, 1957), whereas actinomycetes and fungi were in lower abundance than gram-positive, spore-forming bacterial populations in an Indian desert soil (Rao and Venkateswarlu, 1983). Furthermore, high spatial variability may exist within a site; populations of actinomycetes have been shown to decrease with soil depth after 30 cm, whereas bacteria and fungi generally increased with depth from the soil surface (Venkateswarlu and Rao, 1981).

The hypothesis that the diversity of higher soil taxa (phyla) can serve as a reliable bioindicator of agroecosystem productivity and potential soil fertility is fairly well supported by the current literature. Disturbance-related changes in soil biodiversity at the species level, although not well documented at present

for a variety of ecosystems, holds much promise for establishing objective, site-specific ecological criteria for projecting degradation potentials and system recovery from disturbance. Further understanding of soil ecological dynamics may be gained by elucidating the life-styles and strategies of microbial populations. Certain species appear to be well-adapted to stress tolerance, whereas others thrive under disturbance regimes (Swift, 1984). With intensive study and detailed measurement, microbial community composition should reveal a great deal more practical information on the productive status of managed agricultural s-

There is a pressing need for further experimentation with different dryland tillage/residue management systems for regulating microorganisms to enhance soil structural stability and sustained plant production. Since a certain minimal level of disturbance may be optimal for regulating soil microbial dynamics in favor of maximum structural stability, more information is needed on the community structure and physiology of the soil microbial ecosystem to develop sound recommendations for soil conservation in the drylands. There is much room for innovative research in microbial ecology related to limiting factors in the environment. Conceptual models must be generated for tests in field experiments of changes in soil community components. Correlations between biodiversity patterns and soil physical properties, SOM dynamics, and nutrient-use efficiency would contribute greatly to an empirical understanding of agricultural sustainability. Diversity indices must be further developed for a range of disturbed and undisturbed lands. Such predictive measures of soil productivity and deterioration potential would be of considerable value to land-use planners in both developed and developing countries.

Acknowledgments. The authors wish to thank J. Doran, T. Grove, R. Papendick and J. Parr for comments on an earlier version of the manuscript.

References

Abdel-Salam, M.A., M. Monib, Y. Abdel-Malek, and M.A. Shadt. 1971. Some factors governing the soil nitrifying capacity under the conditions of Kharga oasis soils. A.R.E. Journal of Desert Research Institute. 21:49-59.

Alexander, M. 1977. Introduction to Soil Microbiology. New York: John Wiley & Sons.

Altieri, M.A., R.C. Wilson, and L.L. Schmidt. 1985. The effects of living mulches and weed cover on the dynamics of foliage and soil arthropod communities in three crop systems. Crop Protection. 4(2):201-213.

Anderson, J.M., S.A. Huish, P. Ineson, M.A. Leonard, and P.R. Splatt. 1985. Interactions of invertebrates, micro-organisms, and tree roots in nitrogen and mineral element fluxes in deciduous woodland soils. *In* A.H. Fitter, D. Atkinson, D.J. Read, and M.B.J. Usher, eds. Ecological Interactions in Soil: Plants, Microbes and Animals, pp. 377-392. Oxford: Blackwell Scientific Publications.

Atlas, R.M. 1984. Use of microbial diversity measurements to assess environmental stress. *In* M.J. Klug and C.A. Reddy, eds. Current Perspectives in Microbial Ecology pp. 540-545. Washington, D.C.: American Society for Microbiology.

Bengtsson, G., M. Berden, and S. Rundgren. 1988. Influence of soil animals and metals

on decomposition processes: A microcosm experiment. J. Environ. Qual. 17(1): 113-119.

Berg, N.W., and S. Pawluk. Soil mesofaunal studies under different vegetative regimes in north central Alberta. Can. J. Soil Sci. 64(2):209-223.

Bolton, H., L.F. Elliott, R.I. Papendick, and D.F. Bezdicek. 1985. Soil microbial biomass and selected soil enzyme activities: Effects of fertilization and cropping practices. Soil Biol. Biochem. 17:297-302.

Burns, R.G., and J.A. Davies. 1986. The microbiology of soil structure. In J.M. Lopez-Real and R.D. Hodges, eds. The Role of Microorganisms in a Sustainable Agriculture. pp. 1-8. Kent: A B Academic Publishers.

Chaney, K., and R.S. Swift. 1984. The influence of organic matter on aggregate stability in some British soils. J. Soil Sci. 35:223-230.

Clarholm, M. 1985. Possible role for roots, bacteria, protozoa, and fungi in supplying nitrogen to plants. In A.H. Fitter, D. Atkinson, D.J. Read, and M.B.J. Usher, eds. Ecological Interactions in Soil: Plants, Microbes and Animals. pp. 355-365. Oxford: Blackwell Scientific Publications.

Conti, B. 1984. The first results of comparative research on the relationship between Acari and Collembola in two plots of land with different types of cultural treatments. Frustula Entolmologica. 7-8:575-588.

Cundell, A.M. 1977. The role of microorganisms in the revegetation of strip-mined land in the western United States. J. Range Management. 30(4):299-305.

Dommergues, Y.H., H.D. Diem, and F. Ganry. 1979. The effect of soil microorganisms on plant productivity. In: H.O. Mongi and P.A. Huxley, eds. Soils Research in Agroforestry. International Council for Research in Agroforestry, Nairobi, Kenya, pp. 205-241.

Doran, J.W. 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Amer. J. 44:765-771.

Dormaar, J.F., and S. Smoliak. 1985. Recovery of vegetative cover and soil organic matter during revegetation of abandoned farmland in a semi-arid climate. J. Range Management. 38(6):487-491.

Elliott, E.T., D.C. Coleman, R.E. Ingham, and J.A. Trofymow. 1984. Carbon and energy flow through microflora and microfauna in the soil subsystem of terrestrial ecosystems. *In* M.J. Klug and C.A. Reddy, eds. Current Perspectives in Microbial Ecology. pp. 424-433. Washington, D.C.: American Society for Microbiology.

Eijsackers, H. 1983. Soil fauna and soil microflora as possible indicators of soil pollution. Environ. Monitoring and Assessment. 3(3/4):307-316.

Fraser, D.G., J.W. Doran, W.W. Sahs, and G.W. Lesoing. 1988. Soil microbial populations and activities under conventional and organic management. J. Environ. Qual. 17: 585-590.

Fresquez, P.R., E.F. Aldon, and W.C. Lindemann. 1986. Microbial diversity of fungal genera in reclaimed coal mine spoils and soils. Reclamation and Revegetation Research. 4(3):245-258.

Grohman, F. 1960. Distribucao de tamanho de poros en tres de solos do Estado de San Paulo. Bragantia. 19:319-328.

Harris, R.F., G. Chesters, O.N. Allen, and O.J. Attoe. 1964. Mechanisms involved in soil aggregate stabilization by fungi and bacteria. Soil Sci. Soc. Amer. Proc. 28:529-532.

Heal, O.W., and P. Ineson. 1984. Carbon and energy flow in terrestrial ecosystems: Relevance to microflora. *In* M.J. Klug and C.A. Reddy, eds. Current Perspectives in Microbial Ecology, pp. 394-404. Washington, D.C.: American Society for Microbiology.

Hepper, C.M. 1975. Extracellular polysaccharides of soil bacteria. *In* N. Walker, ed. Soil Microbiology. pp. 93-110. London: Butterworths.

Hobbie, J.E., and J.M. Melillo. 1984. Role of microbes in global carbon cycling. *In* M.J. Klug and C.A. Reddy, eds. Current Perspectives in Microbial Ecology. pp. 389-393. Washington, D.C.: American Society for Microbiology.

House, G.J., and B.R. Stinner. 1983. Arthropods in no-tillage soybean agro-ecosystems: Community composition and ecosystem interactions. Environmental Management. 7(1):23-28.

Insam, H., D. Parkinson, and K.H. Domsch. 1989. Influence of macroclimate on soil microbial biomass. Soil Biol. Biochem. 21:211-221.

Jung, G. 1970. Variations saisonnières des caractéristiques microbiologiques d'un sol ferrugineux tropical peu lessivé (Dior), soumis ou non a l'influence d'*Acacia albida* (Del.). Oecologia Plantarum. 5(2):113-136.

Kaul, R.N. 1970. Afforestation in Arid Zones. The Hague: W. Junk.

Kishk, M.A. 1985. Desert encroachment in Egypt's Nile Valley. Soil Conservation Society of America Report, p. 15.

Klein, D.A., W.C. Metzger, B.A. Frederick, and E.F. Redente. 1986. Environmental stress—functional diversity relationships in semi-arid terrestrial microbial communities. *In* V. Jensen, A. Kjoeller, and L.H. Soerensen, eds. Microbial Communities in Soil. pp. 105-114. Essex: Elsevier Publishers.

Lal, R. 1988. Soil degradation and the future of agriculture in sub-Saharan Africa. J. Soil Water Conserv. 43:444-451.

Langerlof, J., and O. Andren. 1985. Succession and activity of microarthropods and enchytraeids during barley straw decomposition. Pedobiologia. 28(5):343-357.

Luizao, F.J. 1985. Influence of liming and organic fertilization on the mesofauna and some physical characteristics of a clayey yellow latosol. Revista Brasilera de Ciencia do Solo. 9(1):81-84.

Martin, J.P. 1945. Microorganisms and soil aggregation. I. Origin and nature of some aggregating substances. Soil Science. 59:163-174.

Martin, J.P. 1987. Effect of plants on the decomposition of 14 C-labelled soil organic matter. Soil Biol. Biochem. 19(4):473-474.

Meiklejohn, J. 1957. Numbers of bacteria and actinomycetes in a Kenya soil. J. Soil Sci. 8:240-247.

Mills, A.L., and R.A. Wassel. 1980. Aspects of diversity measurement for microbial communities. Appl. Environ. Microbiol. 41.578-586.

Moura, F.W., and S.W. Buol. 1972. Studies of a Latosol Roxo in Brazil. Experimentiae. 13:201-234.

Mukherjee, D. and A.C. Gaur. 1980. A study of the influence of straw incorporation on soil organic matter maintenance, nutrient release and asymbiotic nitrogen fixation. Zentralbl. Bakteriol. Parasitenkd. Infekttionshr. Hyg., II. 135(8):663-668.

Newman, E.I., A.L. Heap, and R.A. Lawley. 1981. Abundance of mycorrhizas and root-surface micro-organisms of *Plantago lanceolata* in relation to soil and vegetation: A multivariate approach. New Phytologist. 89:95-108.

O'Neill, R.V., and D.L. DeAngelis. 1981. Comparative productivity and biomass relations of forest ecosystems. *In* D.E. Reicle, ed. Dynamic Properties of Forest Ecosystems. pp. 411-449. IBP 23. Cambridge: Cambridge University Press.

Powlson, D.S., P.C. Brookes, and B.T. Christensen. 1987. Measurement of soil microbial biomass provides an early indication of changes in total soil organic matter due to straw incorporation. Soil Biol. Biochem. 19(2):159-164.

Pradhan, G.B., and M.C. Dash. 1984. Rhizosphere effect of *Andropogon pumilus* on soil nematodes, soil organic matter and nitrogen. Proceed. Indian Acad. Animal Sci. 93(2):77-82.

Rao, A.V., and B. Venkateswarlu. 1983. Microbial ecology of the soils of the Indian desert. Agri. Ecosystems and Environ. 10:361-369.

Rice, E.L., and S.K. Pancholy. 1972. Inhibition of nitrification by climax vegetation. Amer. J. Botany. 59:752-755.

Sasson, A. 1972. Microbial life in arid environments – prospects and achievements. Ann. Arid Zone. 11:67-86.

Schimel, D.S., D.C. Coleman, and K.A. Horton. 1985. Soil organic matter dynamics in paired rangeland and cropland toposequences in North Dakota. Geoderma. 36:201-214.

Segal, W., and R.L. Mancinelli. 1987. Extent of regeneration of the microbial community in reclaimed spent oil shale land. J. Environ. Qual. 16(1):44-47.

Shannon, C.E., and W. Weaver. 1949. The mathematical theory of Communication. Urbana: University of Illinois Press.

Steen, E. 1983. Soil animals in relation to agricultural practices and soil productivity. Swedish J. Agric. Res. 13:157-165.

Swift, M.J. 1984. Microbial diversity and decomposer niches. *In* M.J. Klug and C.A. Reddy, eds. Current Perspectives in Microbial Ecology. pp. 8-16. Washington, D.C.: American Society for Microbiology.

Tisdall, J.M., B. Cocheroft, and N.C. Uren. 1978. The stability of soil aggregates as affected by organic materials, microbial activity and physical disruption. Austr. J. Soil Res. 16:9-17.

Usher, M.B. 1985. Population and community dynamics in the soil ecosystem. *In* A.H. Fitter, D. Atkinson, D.J. Read, and M.B.J. Usher, eds. Ecological Interactions in Soil: Plants, Microbes and Animals. pp. 243-265. Oxford: Blackwell Scientific Publications.

Van Voris, P., R.V. O'Neill, W.R. Emanuel, and H.H. Shugart, Jr. 1980. Functional complexity and ecosystem stability. Ecology. 61(6):1352-1360.

Venkateswarlu, B., and A.V. Rao. 1981. Distribution of microorganisms in stabilized and unstabilized sand dunes of the Indian desert. J. Arid Environ. 4:203-207.

Waaland, M.E., and E.B. Allen. 1987. Relationship between VA mycorrhizal fungi and plant cover following surface mining in Wyoming. J. Range Management. 40:272-276.

Wicbe, W.J. 1984. Some potential uses of microorganisms in ecological theory. *In* M.J. Klug and C.A. Reddy, eds. Current Perspectives in Microbial Ecology. pp. 17-21. Washington, D.C.: American Society for Microbiology.

Wilson, E.O., ed. 1988. Biodiversity. National Forum on Biodiversity, Washington, D.C., September 21-25, 1986. Washington, D.C.: National Academy Press.

Wollum, II, A.G. 1982. Cultural methods for soil microorganisms. *In* A.L. Page, R.H. Miller, and D.R. Keeney, eds. Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties. pp. 781-802. Madison, Wisc: American Society of Agronomy.

Managing Crop Residues to Optimize Crop/Livestock Production Systems for Dryland Agriculture

R.I. Papendick, J.F. Parr, and R.E. Meyer

I. Introduction 253
II. Available Water and Crop Yields 254
III. Value of Crop Residues for Water Conservation 255
A. Runoff Control 256
B. Evaporation Control 258
C. Snow Control 261
IV. Effect of Surface Residue Management on Crop Yields 263
V. Value of Crop Residues for Erosion Control 265
VI. Progress with Residue Management Systems 266
A. No-Till Fallow 266
B. Seeding and Fertilizer Placement Technology 266
C. Crop Residue Management in Crop/Livestock Systems 268
VII. Conservation Management and Water Quality 269
References 270

I. Introduction

An important conclusion of the recent International Conference on Dryland Farming was that dryland agriculture must play an increasingly important role in meeting future world needs for food and fiber (International Conference on Dryland Farming, Executive Summary, 1989). Improvements in crop and livestock production in the dryland regions is constrained not only by the limited supply of available water but also by the low and declining soil productivity. As a result of improper soil management and overgrazing, the soils in many areas

1990 by Springer-Verlag New York Inc.
Advances in Soil Science, Volume 13

have been severely degraded by wind and water erosion and loss of soil organic matter. Water conservation must be regarded as the essential first step in improving the production capability of these lands whether the soils have been degraded or not. Little can be gained from various technological inputs such as fertilizers, improved crop varieties, pesticides, and better sowing methods unless the available water supply is maximized for crop production.

Crop residues represent an important potential resource for returning organic matter and conserving soil and water. Small to moderate amounts of surface residues can be highly effective for controlling wind and water erosion over a wide range of climatic, slope, and soil conditions. During the rainy season a surface mulch slows evaporation and breaks raindrop impact, which in turn reduces runoff and surface crusting, especially on structurally weak soils. The water saved can result in production of additional plant biomass and crop residues which are essential for improving the physical and nutritional properties of the soil. The return of organic matter also enhances the activity of microbes, earthworms, termites, and other soil animals, which improves water infiltration and facilitates early root development.

II. Available Water and Crop Yields

Water conservation pays because there is a sensitive relationship between crop water use and yield. Tanner and Sinclair (1983) express this relationship as

$$Y_t = \frac{kT_c}{\Delta e} \tag{1}$$

where Y_t is the total dry matter produced by the crop (kg/ha), T_c is the crop transpiration (kg/ha), k is a constant combining plant production characteristics (mbar), and Δe is the average vapor pressure deficit of the air during daylight hours (mbar). Equation 1 can be extended to partition Y_t into shoot, root, and grain dry matter components of the crop (Papendick and Campbell, 1990). Their equation gives a good field prediction of an empirical relationship between grain yield and available water developed for wheat (*Triticum* aestivum) production in the Pacific Northwest (Leggett, 1959, and Fig. 1). Figure 1 shows that approximately 100 mm of available water is required by wheat to grow the crop to where grain production starts. Thereafter an average of 15 kg/ha of grain are produced for each millimeter of available water. With current wheat varieties the slope of the line in Figure 1 is about 18 kg/ha/mm if the same conventional clean-tillage practices are used that were used to establish the original slope.

With the relationship in Figure 1, the potential wheat yield was graphed as a function of fallow efficiency for two precipitation areas representative of eastern Oregon wheatlands (Fig. 2). Fallow efficiency is defined as the percentage of precipitation that is stored in the soil at the end of the fallow season (in this case 19 months, from August 1 to March 1 of the second year). The precipitation

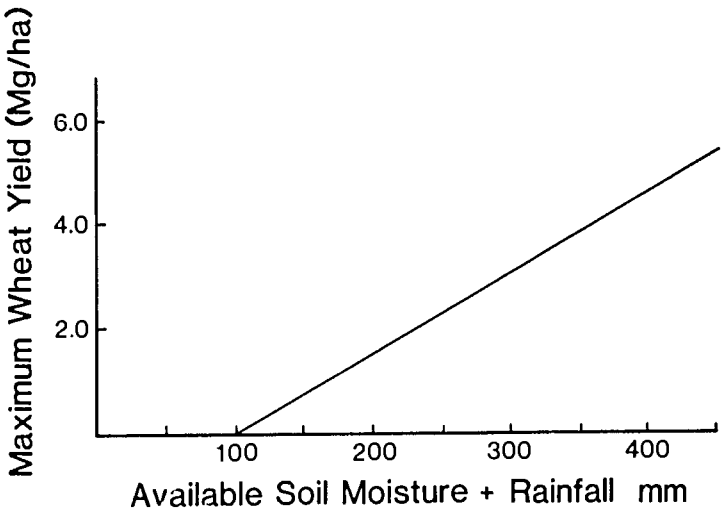


Figure 1. Relationship between available moisture and wheat yields for the Pacific Northwest of the United States (Leggett, 1959). The slope is approximately 15 kg/ha/mm. With current wheat varieties, it is 18 kg/ha/mm.

amounts used were an average of five seasons reported by Ramig (1990) in fallow-water conservation experiments conducted during the years 1978 through 1984. These were 587 mm for the 300-mm precipitation site and 720 mm for the 400-mm precipitation site. Long-term mean rainfall from March through June given by Ramig (1990) was added to the stored water to give the total available water for the yield calculations. Figure 2 clearly demonstrates the importance of water conservation to potential wheat grain yield. For each percentage increase in fallow efficiency the average yield is increased by 106 kg/ha at the 300-mm precipitation site and by 130 kg/ha at the 400-mm site.

III. Value of Crop Residues for Water Conservation

The value of surface residues for water conservation has long been recognized, and today crop residue management forms the basis for conservation tillage systems that are gaining acceptance in the United States and other dryland farming areas. Early work in the United States showed that a surface cover of plant materials conserved water by reducing both runoff and evaporation (Russel, 1939). In the northern latitudes surface cover is also important for trapping snow (Staple et al., 1960; Black and Power, 1965). Relatively low amounts of residues can be effective in enhancing infiltration, but more is necessary to reduce evaporation losses. Surface residues are most effective in suppressing

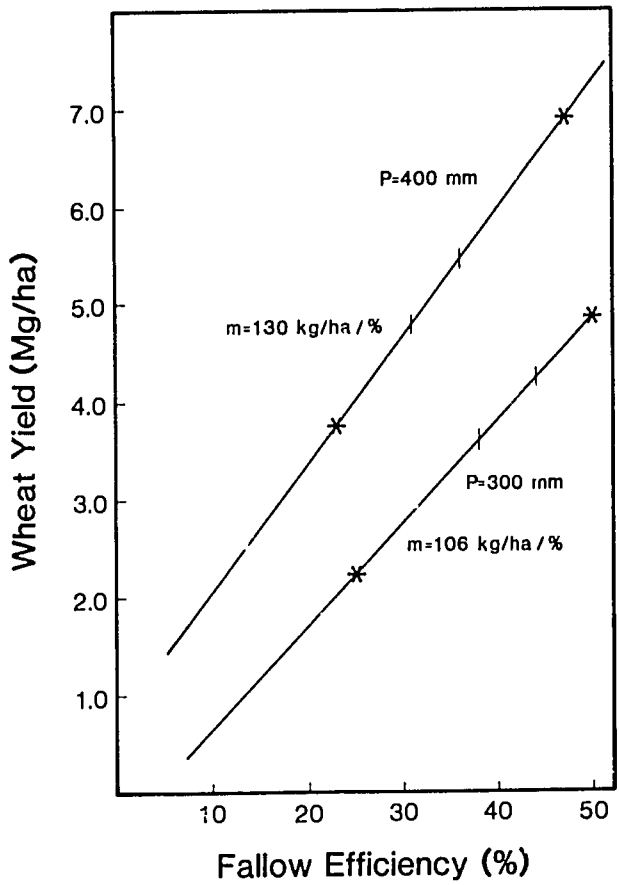


Figure 2. Relationship between fallow efficiency and wheat yield for two precipitation zones (P = 300 mm and 400 mm) in the Pacific Northwest of the United States. The slope of the lines m is the grain yield for each increase in precipitation efficiency (percentage of the precipitation that is stored and becomes available to the crop). The vertical ticks on the graphs represent the range of efficiencies achieved by Ramig (1990) in fallow treatments in eastern Oregon, which are an average of 5 years; the asterisks represent the range for individual years during the 5-year experimental period.

evaporation during the rainy season and may be of little or no benefit for this purpose during the dry season.

A. Runoff Control

There are conditions under which runoff losses can be substantial. For example, in West Africa, runoff from the first rains after the long dry season may exceed 70% of the rainfall amount (Roose and Piot, 1984). A rainfall simulator study

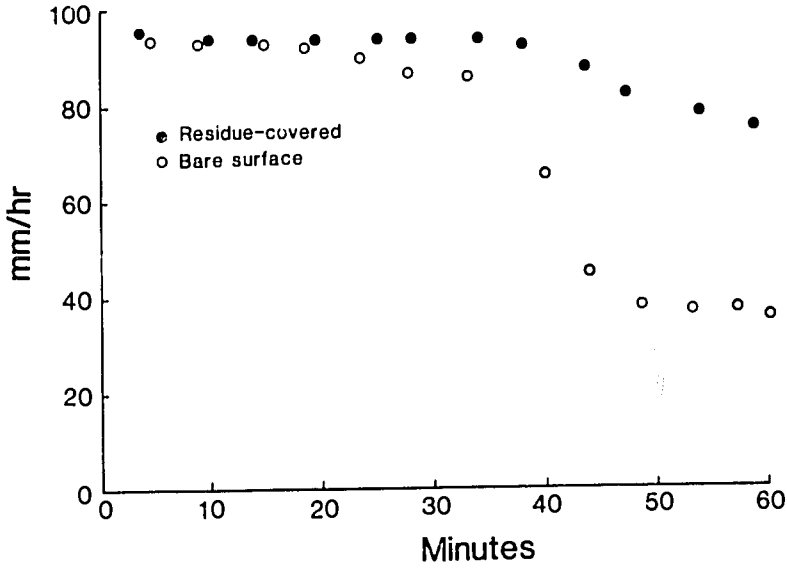


Figure 3. Infiltration rate as affected by residue cover at the Cinzana Experiment Station, Mali, West Africa (Kouyate et al., 1988).

conducted on a sandy soil at the Cinzana Experiment Station in Mali showed that a complete cover of stiff-strawed residue over tilled soil essentially eliminated runoff from rainfall applied at 93 mm/hour for 40 minutes (Kouyate et al., 1988, and Fig. 3). This rate was maintained for much less time for the bare, tilled soil, and the final infiltration rate after 60 minutes of rainfall was below 40 mm/hour for the bare soil and double this for the residue-covered soil. The sharp decrease in infiltration rate on the bare soil was attributed to surface sealing from raindrop impact.

Experiments in the U.S. Pacific Northwest, where soil freezing causes runoff, show the beneficial effects of surface residues on overwinter water storage. Soil water gains were highest with a combination of paraplow tillage and surface residues and lowest with bare surface (Fig. 4; Elliott, L.F., Saxton, K.E., and Papendick, R.I., USDA, ARS, Pullman, Washington, unpublished data). The benefits from the residues was associated with reduced runoff from rain and snowmelt while the soils were partially frozen.

Researchers and farmers in West Africa and India are aware of the benefits of small quantities of surface residues in reducing runoff losses. The reason is that residues stimulate termite activity. These soil insects bore stable channels to the surface to access the residues for food, which lets water readily percolate into the subsoil layers. Evidence of soil disturbance by termites in the presence of a small amount of millet (*Panicum* miliaceum) residues on runoff plots at the International Center for Research in the Semiarid Tropics (ICRISAT), Hyberbad, India, is shown in Figure 5.

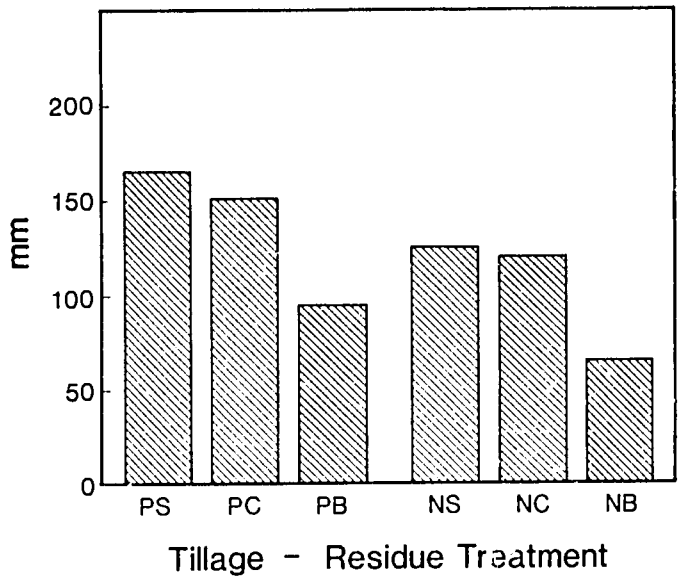


Figure 4. Effect of fall paraplow and surface residues on overwinter water storage in eastern Washington dryland. PS = paraplow plus standing wheat stubble; PC = paraplow plus chopped wheat stubble; PB = paraplow with stubble burned. The N is for no paraplow.

B. Evaporation Control

Most of the water lost from soil is by evaporation, which is the loss source most difficult to control. The greatest benefit from surface residues in reducing evaporative loss occurs when the soil surface is wet and in the first stage of drying. In this case the surface cover reduces energy input for evaporation, and vapor exchange with the atmosphere. After a dry layer forms, the soil liquid conductivity to the surface limits water loss and the benefits of the residue decrease. In fact, during extended drying the total water loss by evaporation from a residue-covered surface can actually exceed that from a bare surface. This is because the covered surface maintains first-stage drying much longer than the bare surface, which forms a dry layer much sooner.

The effect of residues on evaporation is demonstrated clearly in a simulation study using a physically based heat-water flow model capable of describing the dynamics of mass and energy transfer in a soil–residue–atmosphere system (Bristow et al., 1986). Recorded precipitation and simulated evaporation values by month for a bare and residue-covered silt loam soil are presented in Figure 6 for the period September 1, 1981, to August 31, 1982, using meteorological inputs measured at Pullman, Washington (latitude 47°46'N, longitude 117°12'W). From late fall until early spring, when most of the precipitation

Figure 5. Soil working by termites due to the presence of small quantities of millet residues on runoff plots at ICRISAT, Hyberbad, India.

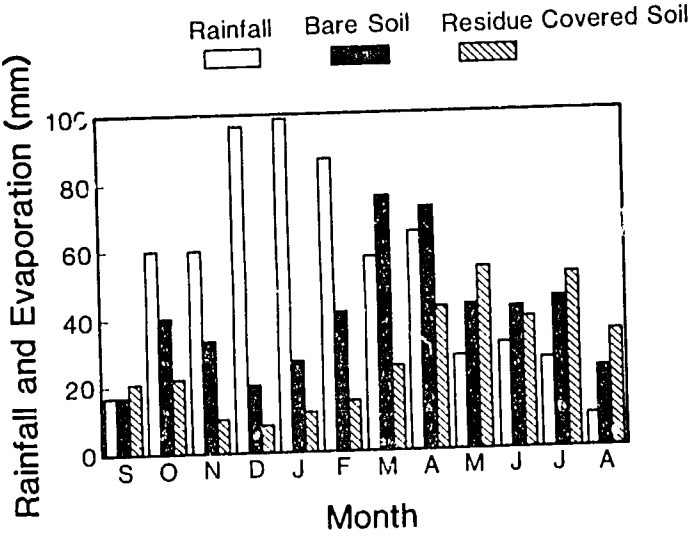


Figure 6. Monthly precipitation and simulated evaporation for a bare and residue-covered soil at Pullman, Washington (Bristow et al., 1986).

occurs and temperatures are low, the soil surface is wet almost continuously. During this time evaporation from the bare soil is considerably greater than from the residue-covered soil. After rains decrease in May and onward through the summer with decreasing rainfall, simulated evaporation from the residue-covered soil exceeds that from the bare soil. The reason for this is that the soil surface remains wet longer and the transition to second-stage drying is slower for the residue-covered soil than for the bare surface. In spite of this negating effect during the summer, the simulated evaporation for the year was 36% less from the residue-covered soil than from the bare soil (Bristow et al., 1986).

More recent simulations have been made of tillage-residue and soil type-residue interactions on evaporative water loss using the SHAW (Simultaneous Heat and Water) model developed by Flerchinger and Saxton (1989). These runs were made starting with a moisture profile at field capacity in early May and inputing actual weather data for the summer of 1986 at Pullman, Washington. Recorded rainfall was used in one analysis but taken as zero in a second run to simulate a more extreme extended drying. Simulations were made for about 10 weeks. In Figure 7 the soil thermal and hydraulic properties are representative of a loam soil. Figure 7, with precipitation (top graph), shows that evaporation loss is highest from the bare, untilled soil. Tillage has little effect on evaporative loss for residue-covered soil. Although initial evaporation from the tilled, bare soil is higher for the residue-covered soil, cumulative evaporation at the end of the run is similar.

Figure 7 for the same soil and treatments but with no precipitation (bottom graph) shows that the initial evaporation rate and cumulative loss is highest on the bare, untilled soil. The no-till, residue-covered soil remains in first-stage evaporation during the entire period and at the end of 10 weeks the cumulative loss approaches that from the bare, untilled soil. Evaporative loss at the end of the simulation for the tilled soils is half or less than for the untilled soil. Note that for the tilled, residue-covered soil, the cumulative loss early in the simulation period and at the end exceeded that for the bare, tilled soil. This occurred because the residue extended the duration of the first-stage drying and delayed the transition to the second stage.

Figure 8 compares residue effects on evaporation for a sand versus a clay soil. The top precipitation graph shows a reduction in evaporation loss with residues (131% reduction with residue for the clay soil) and considerably lower losses with the sand than the clay soil for the same residue treatment. The clay soil, because of its much higher unsaturated conductivity, tends to remain in first-stage drying longer than the sand which forms a surface dry layer more rapidly.

The bottom graph in Figure 8, without precipitation, shows that the bare clay soil has the highest evaporation rate and goes into second-stage drying about 10 days after the run begins, whereas the clay with residues stays in the first stage throughout the simulation period. Note that the evaporation loss for the clay with residues is the same with or without precipitation (compare top and bottom graphs). The sand with residue remains in first-stage drying for several days after

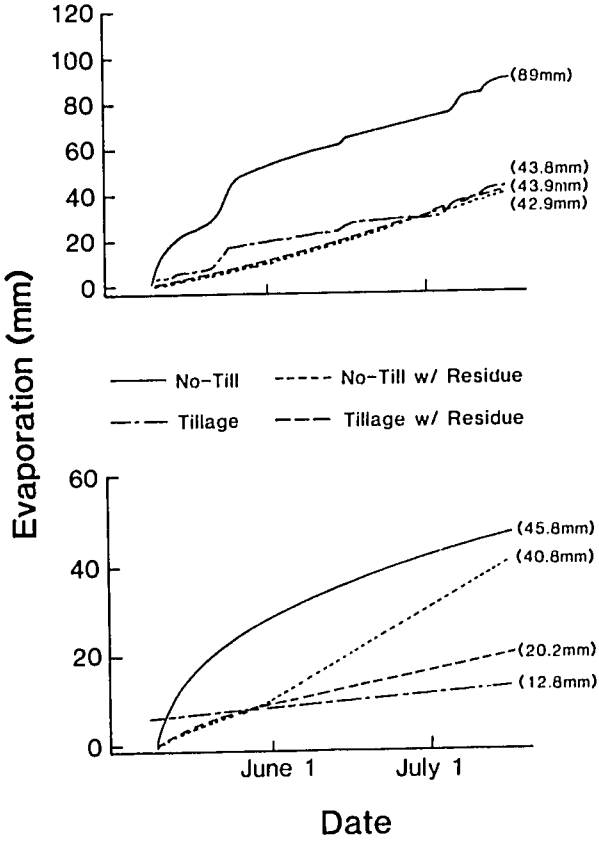


Figure 7. *Top*: Simulated evaporation as affected by tillage and residue for an initially moist loam soil using weather inputs for 1986, Pullman, Washington. The number after each curve is the total evaporation at the end of the simulation. *Bottom*: Same as top graph, except without precipitation during the simulation.

the run is initiated and loses slightly less water at the end of the run than the sand without residues. In this case, cumulative losses from the clay soil far exceed those from the sand which is as expected based on marked differences in hydraulic properties of the two soils and the extended duration of drying without rain.

C. Snow Control

Snow is an important source of water in the northern latitudes and if held on the fields can be more efficiently stored than rain. For example, in the northern Great Plains of the United States, where a substantial part of the winter precipitation is snow, storage efficiencies during the overwinter period ranged from 60 to

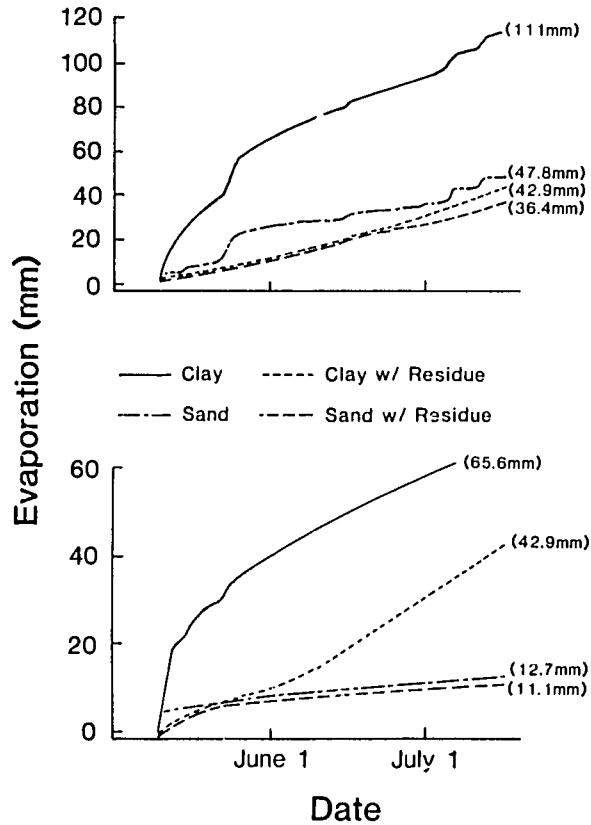


Figure 8. *Top*: Simulated evaporation for an initially moist clay and sand soil, bare, and with residue using the same weather inputs as for top graph in Figure 7. The number after each curve is the total evaporation at the end of the simulation. *Bottom*: Same as top graph, except without precipitation during the simulation.

84% whereas maximum storage during the summer was 25% (Black and Bauer, 1985). In the central Great Plains, north of latitude 39°, snowfall in standing stubble during the first winter of fallow plus snowfall on wheat in the second winter accounts for 35 to 45% of the area's wheat production (Greb, 1983). Disking in the fall to control weeds results in a net loss of stored water because of snow blowoff caused by loss of stubble with tillage. In North Dakota overwinter water storage ranged from 32 to 90 mm with no fall tillage and from 5 to 54 mm after fall plowing (Bauer and Kucera, 1978). The snow cover with standing stubble also protects winter wheat from freeze damage. This has made it possible in the northern United States and Canada to move winter wheat production with higher yield capability further into the traditional spring wheat producing areas.

Table 1. Effect of changes in fallow tillage on water storage and wheat yields, Akron, Colorado (Unger et al., 1988)

Years	Tillage system	Fallow water storage mm	Fallow water storage % Efficiency	Wheat yield (Mg/ha)
1916–1930	Maximum tillage; plow harrow	102	19	1.07
1931–1945	Conventional tillage; shallow disk, rodweeder	118	24	1.16
1946–1960	Improved conventional tillage; began stubble mulch 1957	137	27	1.73
1961–1975	Stubble mulch and minimum tillage	157	33	2.16
1975–1990	Projected estimate; minimum and no-tillage	183	40	2.69

IV. Effect of Surface Residue Management on Crop Yields

There is a wealth of field documentation on the benefits of surface residues for water conservation and crop yields on dryland farms (Unger et al., 1988). The pattern is generally the same; use of tillage practices that increase the retention of surface residues (with good weed control) leads to higher crop yields because of the increase in amount of available water. Less tillage and use of subsurface tillage which have been made possible with effective herbicides has led to significant yield increases of wheat, and sorghum (*Sorghum* vulgare) in the Great Plains of the United States (Smika and Wicks, 1968; Unger, 1984; Unger, 1978; Unger and Wiese, 1979). Table 1 presents a classical illustration of the effect of changes in tillage and residue management practices on long-term wheat yield in the central Great Plains. The average wheat yields have well more than doubled over the 70-year period concomitant with changes in tillage practices which conserved greater amounts of crop residues on the surface. Approximately 45% of the yield increase was credited to water conservation due to improved residue management and weed control.

Another regional example showing the effect of improved tillage and residue management on water conservation and wheat yields is demonstrated by changes in fallow practices in western Nebraska drylands. Wheat yields doubled (increased from 0.7 to 1.5 t/ha) during the late 1930s when stubble grazing was eliminated, and mulch tillage and improved weed control were introduced in the wheat–fallow cropping system (Fenster, 1990). Fertilizer usage was an important but secondary factor contributing to this yield increase. The change in farming practice amounted to a "snowball" effect, that is, without grazing there was more surface cover, and this coupled with good weed control substantially increased the available water, which in turn produced more crop residues for additional water conservation benefits and higher yield. The increase in yield was sufficient

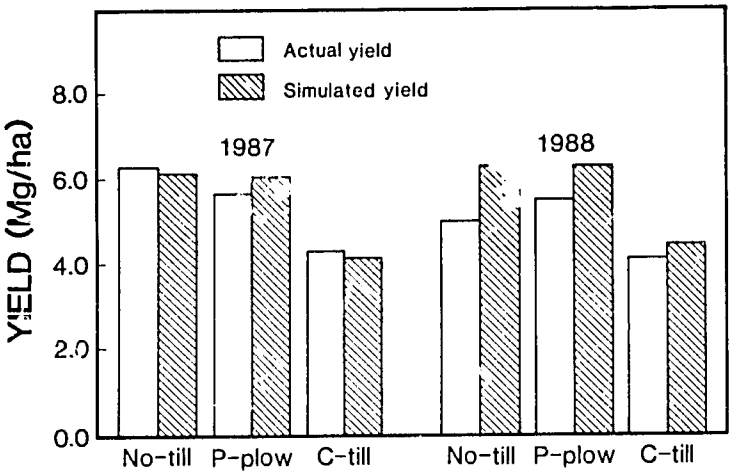


Figure 9. Simulated and measured barley grain yields for three tillage systems at Pullman, Washington. P-plow is fall paraplow tillage and C-till is conventional moldboard plow-based tillage.

to justify separating the production of livestock and grain on the same land in many dryland areas of the United States. This, to a large extent, is the practice today. Moreover, retention of surface stubble reduces wind and water erosion, which helps sustain the long-term productivity of the soil.

A recently developed crop production/erosion prediction model was applied to predict barley (*Hordeum* vulgare) yields under different tillage-residue management combinations for crop years 1987 and 1988 at Pullman, Washington (Fig. 9; Yan, 1989). The model accounts for transpiration and evaporation by water budget. In Figure 9 the conventional tillage treatment leaves a bare soil surface while the paraplow loosens the tillage layer, but as with no-till, it leaves the surface residues intact. The model predicts grain yields based on actual water available for transpiration but does not account for losses due to biotic factors such as weeds, diseases, or insects. The actual grain yield and information on planting and harvesting dates, tillage operations, and initial residue amounts was provided from a long-term rotation experiment conducted by author R.I. Papendick.

The yields under paraplow and no-till with good residue cover are higher than those under conventional tillage for both simulated and actual yields. This difference can be accounted for by the higher winter and springtime evaporation and lower end-of-the growing season transpiration with the conventional treatment compared with the paraplow and no-till treatments (data not shown). With the paraplow and no-till treatments the soil water was increased by the residue mulch so that it could be transpired by the plant and thus increase growth and production.

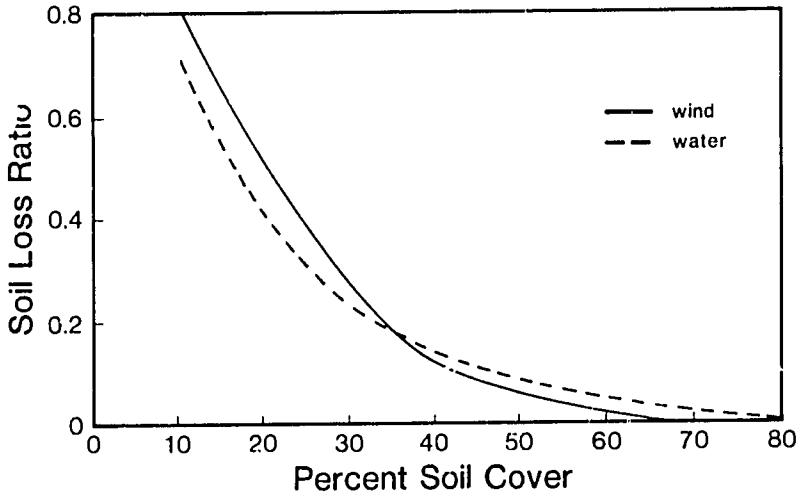


Figure 10. Relationship between soil loss ratio (SLR = soil loss with cover divided by soil loss from bare soil) and percentage surface cover. [Adapted from Laflen et al. (1981) for water erosion and Fryrear (1985) for wind erosion.]

V. Value of Crop Residues for Erosion Control

In the United States the early interest in surface crop residue management was to reduce runoff so that water erosion could be controlled. Benefits for controlling wind erosion were recognized at about the same time. Numerous studies in various dryland areas around the world document that control of water erosion in areas of high potential runoff depends mainly on the amount of vegetative cover and roughness of the soil surface rather than on type of soil and the cultivation practices per se. The importance of soil cover for wind erosion control also appears to extend across all soil types. In general, crop residue management practices employed for water conservation are also highly effective for control of both wind and water erosion. However, the latter may require lesser amounts to achieve desired goals.

Residue position or configuration may influence its effectiveness for erosion control. For example, flattened residues are more effective in dissipating raindrop impact and slowing runoff than vertical cover, and hence more effective for water erosion control. Nevertheless, soil loss caused by either wind or water is still most directly related to the percentage of surface cover. The relationships between the soil loss ratio (i.e., the ratio of soil loss from residue-covered soil to bare soil) for wind and water erosion is presented in Figure 10. The graph shows that the relationships are quite similar and that small quantities of residues are highly effective for control of either type of erosion. For example, approximately

1 t/ha of wheat straw uniformly distributed on the surface would provide about 50% surface cover. According to Figure 10 this amount would reduce both wind and water erosion to about 20% of that of bare soil. The graph shows that the lower quantities of surface cover (<30%) are more effective for water erosion control than wind erosion control. The reverse is true when the residue cover exceeds 40%.

VI. Progress with Residue Management Systems

A. No-Till Fallow

There has been considerable research in the dryland areas on technology development for no-till fallow to maximize retention of surface residues. The potential benefits of no-till fallow are minimal soil erosion, higher water storage and crop yields, and lower energy costs per unit of production. The main approach to no-till fallow has been to substitute herbicides for tillage to control weeds. A major limitation has been lack of cost-effective, broad-spectrum chemicals that give season-long weed control and do not damage the subsequent crop from residual carryover.

Most success with chemical fallow has been achieved in the summer rainfall areas such as the Great Plains of the United States. There has been less progress in the winter precipitation zones such as the U.S. Pacific Northwest, because there is substantial loss of seedzone moisture during the dry summer without tillage (Lindstrom et al., 1974). This reduces the chances of early fall establishment of wheat and the farmer must then rely on late planting with lower yield potential. Under these conditions the greatest potential for no-till is on sandy soils (Hammel et al., 1981). These soils self mulch upon drying, making the effect of tillage in reducing evaporative loss less important than for finer textured soils.

B. Seeding and Fertilizer Placement Technology

Considerable progress has been made on the development of no-till drills that can simultaneously apply seed and fertilizer, and in some cases herbicides, all in a single pass. Commercial machines are now available that can operate in heavy residues and hard soil, and deep band all or part of the fertilizer requirement between or below the seed rows. These machines are equipped with either hoe-type or heavy-duty double disc openers, the latter sometimes being offset to facilitate cutting through crop residues or penetrating hard, dry soil.

1. Fertilizer Placement

There has been considerable research to develop fertilizer placement technology for surface residue management systems. Although crop response to fertilizer placement depends on a number of factors, early access to nutrients by roots of seedlings has been shown to be important. In general, banding fertilizer in

Table 2. Effect of fertilizer band placement on wheat yield in a no-till winter wheat-spring wheat rotation with 41-cm row spacing

Fertilizer placement	Wheat yield (Mg/ha)	
	Winter wheat	Spring wheat
5 cm below seed row	3.8	2.9
5 cm below and 20.5 cm to side of seed row	2.9	2.2

Source: Veseth, 1987.

proximity to the seedzone produces a greater yield for most grain crops than broadcasting the fertilizer. Banding the fertilizer some distance away from the seed row can reduce the fertilizer response compared with banding closer to the row (Veseth, 1987, and Table 2). As a result, a method of seed-fertilizer placement emerged in commercial practice in the United States with small grains and is referred to as paired row planting. Seedings are made in pairs of rows 10 to 18 cm apart with a wider space of 33 to 40 cm between the pairs. This configuration allows a single band of fertilizer to supply nutrients efficiently to two closely spaced rows of the small grain crop. With paired row planting the fertilizer is placed 6 to 9 cm below and only 5 to 9 cm to the side of the seed row. In this particular arrangement the crop roots tend to envelope the fertilizer band, thereby providing opportunity for early uptake and possibly increased crop competition against weeds. Recent research indicates that the paired row fertilizer placement does not give a greater fertilizer response to wheat than banding directly below each wheat row. The main advantage with paired row seed-fertilizer placement is that one fertilizer band can be used to supply two rows of the crop. It also allows for improved trash clearance with no-till seeding.

2. Cross-Slot Seed-Fertilizer Placement Technology

A newly developed combination seed-fertilizer drill opener termed "cross-slot" appears to have some advantages over hoe or disc openers for operating in surface residues. The opener, first developed in New Zealand and followed by adaptive research in the United States, features a single 56-cm-diameter sharp disc to penetrate residues and soil (Baker and Saxton, 1988). Two winged side blades situated on opposite sides of the disc create a cavity at the seeding depth for simultaneous placement of the seed and fertilizer with a separation of about 2 to 3 cm. Two packer wheels running at a slight angle flank the rear of the disc and both close the disc slot and firm the soil over the seed. The wheels also maintain the seed opener depth. Performance of this opener with regard to seed placement is significantly different from that of conventional double-disc or hoe-type openers. Unique advantages of the opener include minimal disturbance of surface residues and soil, minimum plugging problems, superior stand establishment under marginal moisture conditions compared with disc or hoe openers, and lower horsepower requirements than most other no-till drills that place seed and

fertilizer. Field tests with the cross-slot opener show that the full complement of fertilizer can be placed at seeding time without adversely affecting stand establishment of cereal crops. Yields of wheat, peas (*Pisum* sativum), and barley from plantings with this opener are equal or greater than with the standard double-disc or hoe-type openers that are commonly used (K.E. Saxton and R.I. Papendick, USDA-ARS, Pullman, Washington, unpublished data).

C. Crop Residue Management in Crop/Livestock Systems

Much of the world's dryland agriculture is committed to the production of crops and livestock on the same land. In many areas crop residues are an important source of animal feed. When farmers sow food crops they expect to get feed for their livestock from the straw and stover. Weeds may also be allowed to grow during fallow to supply additional forage.

Pressure to increase ruminant livestock production has led to overgrazing and severe soil erosion in many dryland areas. The complete removal of stubble and weedy fallow is also costly in terms of water loss through increased runoff and evapotranspiration. With less available water the yield of the following crop is reduced at the expense of animal production.

Where animals are an integral part of the farming system, use of residues for nutrient cycling, maintenance of tilth, and soil and water conservation must be balanced with competitive use for animal feed. Little is known about crop residue management to optimize production of both crops and livestock while at the same time achieving effective water conservation and sustaining the soil resource. The influence of soil type and climate also needs to be evaluated.

1. A Research Plan

A comprehensive study plan has been developed for research in the Near East region on crop residue management to optimize crop/livestock production and resource conservation (U.S. Department of Agriculture and U.S. Agency for International Development, 1988). The proposed research was designed as a "ribbon" project on soil and water management to be conducted by countries in the Near East.

The research objective is to determine the relative value and optimum use of crop residues for soil and water conservation, maintenance of soil fertility and productivity, and feed for small ruminant animals. Since the use of residues as a mulch to sustain or increase crop productivity would be in direct competition for use as animal feed, it is necessary to know what compromises and trade-offs are possible for the benefit of both. It is especially important to understand the influence of soil type/climate interaction on soil and water conservation.

Proposed treatments include grazing levels, tillage, weed control, and crop rotations. Grazing will either be accomplished with animals or simulated by mechanical removal of surface residues. In the case of mechanical removal, estimates of digestible energy are based on chemical analysis or inferred from known

data. Outputs from the various treatments are crop biomass, grain, and animal product. These data are subject to economic analysis for short- and long-term profitability. Treatments will also be analyzed as to social benefits of erosion control and long-term changes in soil productivity. The field research will be closely allied with modeling studies on the water-conserving and erosion control benefits of various methods of crop residue management.

Although the proposed ribbon project has been designed primarily around conditions and problems representative of the Near East region, the basic approach could be applied to other semiarid regions. The experimental plan would need to be tailored to meet conditions prevailing in the specific area, including types of crops and animals, climate, and available technologies and resources.

VII. Conservation Management and Water Quality

Contamination of surface and groundwater by runoff or leaching of agrichemicals is a growing concern, including in many dryland areas. Some conservation practices are being questioned because of increased use of pesticides and greater potential for leaching. Baker and Johnson (1983) report that conservation tillage, on the average, reduces the volume of runoff by 25% which means that this practice involves greater potential for increased infiltration and hence movement of water and soluble chemicals through the profile. Fox and Bandel (1986) concluded that there is a greater potential for nitrate leaching in no-till than in tilled soils. The greater loss in no-till was explained on the basis of increased drainage losses in the undisturbed soil. However, other studies indicate lower nitrate concentrations in soil with no-till as a result of greater denitrification and immobilization than in tilled soil (Doran, 1980; Fox and Bandel, 1986, Rice and Smith, 1984). This compensating effect offsets the greater leaching potential with no-till.

The effect of conservation tillage on pesticide leaching is complex, with many confounding factors. On the one hand, the increased infiltration along with increased use of pesticides with conservation tillage could increase the risk of pesticide leaching. On the other hand, the moister soil environment associated with conservation tillage could increase the microbial degradation rate of pesticides in soil compared with conventional clean tillage.

Opportunities to reduce nitrate leaching lie mainly with improved management of fertilizer nitrogen and using practices that reduce the need for nitrogen fertilizer. These can be achieved by matching the nitrogen supply with crop needs, improved timing of fertilizer application, and selecting and applying nitrogen sources to minimize nitrate accumulation in the soil at times when the leaching potential is high (Papendick et al., 1987). Use of crop rotations, green manure crops, and animal manures, crop residues, and other organic materials can reduce the need for nitrogen fertilizers.

With herbicides, banded application can substantially reduce the amount of herbicide applied for some situations. This reduces herbicide costs and the potential for surface and groundwater contamination. For example, farm demonstrations in

Iowa have shown that banding herbicide over the crop row and not in the interrow area can reduce the need for herbicide by one-half (Stoltenburg, 1989).

Currently interest is growing in alternative methods of weed control that reduce the need for chemicals in conservation management systems. Possible approaches include greater use of crop rotations, planting methods that increase crop competition against weeds, and the use of rhizosphere bacteria that selectively inhibit growth of weeds in the presence of the growing crop (Elliott and Kennedy, 1987).

References

Baker, C. and K.E. Saxton. 1988. The cross-slot conservation grain drill opener. American Society of Agricultural Engineers. Paper No. 88-1568. Winter Meeting, St. Joseph, Mich.

Baker, J.L., and H.P. Johnson. 1983. Evaluating the effectiveness of BMP's from field studies. *In* R.W. Schaller and G.W. Bailey, eds. Agricultural Management and Water Quality. Ames: Iowa State University Press.

Bauer, A., and H.L. Kucera. 1978. Effect of tillage on some physiochemical properties and on annually cropped spring wheat yields. Bul 506. North Dakota State Univ. Agric. Exp. Station, Fargo.

Black, A.L., and A. Bauer. 1985. Soil water conservation strategies for Northern Great Plains. *In* Planning and Management of Water Conservation Systems in the Great Plains. pp. 76-86. Proc. Workshop, Lincoln, NE. 21-25 October. USDA-SCS, Lincoln.

Black, A.L., and J.F. Power. 1965. Effect of chemical and mechanical fallow methods on moisture storage, wheat, and soil erodibility. Soil Sci. Soc. Am. Proc. 29:465-468.

Bristow, K.L., G.S. Campbell, R.I. Papendick, and L.F. Elliott. 1986. Simulation of heat and moisture transfer through a surface residue-soil system. Agriculture and Forest Meteorology 36:193-214.

Doran, J.W. 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Amer. J. 44:465-771.

Elliott, L.F., and A.C. Kennedy. 1987. Effect of deleterious rhizobacteria on the growth of downy brome (*Bromus tectorum* L.). Agron. Abstracts. American Society of Agronomy, Madison, Wisc., p. 181.

Fenster, C.R. 1990. Fifty years of tillage practices for winter wheat. *In* P.W. Unger, W.R. Jordan, and T.V. Sneed, eds. Proceedings of the International Conference on Dryland Farming. Texas Agric. Exp. Sta. College Station, Texas. (In press).

Flerchinger, G.N., and K.E. Saxton. 1989. Simultaneous heat and water model of a freezing snow-residue-soil system: I. Theory and development. Trans. Amer. Soc. Agric. Engr. 32(2):565-571.

Fox, R.H., and V.A. Bandel. 1986. Nitrogen utilization with no-tillage. *In* M.A. Sprague and G.B. Triplett, eds. No-Tillage and Surface Tillage Agriculture—The Tillage Revolution. pp. 117-148. New York: John Wiley & Sons.

Fryrear, D.W. 1985. Wind erosion on arid croplands. Sci. Reviews, Aridzone Research, Scientific Publishers, Jodpur, India, pp. 31-48.

Greb, B.W. 1983. Water Conservation: Central Great Plains. *In* H.E. Dregne and W.O. Willis, eds. Dryland Agriculture. pp. 57-72. Agronomy Monograph No. 23. Madison, Wisc.: American Society of Agronomy.

Hammel, J.E., R.I. Papendick, and G.S. Campbell. 1981. Fallow tillage effects on evaporation and seedzone water content in a dry summer climate. Soil Sci. Soc. Am. J. 45: 1016-1022.

International Conference on Dryland Farming. 1989. Executive Summary. Texas Agri. Exp. Sta., College Station, Texas.

Kouyate, Z., C.W. Wendt, and D.K. McCool. 1988. Report on Exploratory Rainfall Simulator Study at Cinzana Experiment Station, Mali, West Africa. Washington, D.C.: U.S. Agency for International Development.

Laflen, J.M., W.C. Moldenhauer, and T.S. Calvin. 1981. Conservation tillage and soil erosion on continuously rowcropped land. *In* Crop Production with Conservation in the 80's. ASAE Pub. 7-81, pp. 121-133.

Leggett, G.E. 1959. Relationships between wheat yield, available moisture and available nitrogen in eastern Washington dry land areas. Bulletin 609. Institute of Agricultural Sciences, Washington Agri. Exp. Sta., Washington State University, Pullman, Wash.

Lindstrom, M.J., E.E. Koehler, and R.I. Papendick. 1974. Tillage effects on fallow water storage in the eastern Washington dryland region. Agron. J. 66:312-316.

Papendick, R.I., and G.S. Campbell. 1990. Concepts and management strategies for water conservation in dryland farming. *In* P.W. Unger, W.R. Jordan, and T.V. Sneed, eds. Proceedings of the International Conference on Dryland Farming. Texas Agric. Exp. Sta., College Station, Texas. (In press).

Papendick, R.I., L.F. Elliott, and J.F. Power. 1987. Alternative production systems to reduce nitrates in ground water. Am. J. Alternative Agri. II:19-24.

Ramig, R.E. 1990. Tillage and stubble management for fallow in a winter rainfall area. Soil Sci. Soc. Amer. J. (Accepted for publication).

Rice, C.W., and M.S. Smith. 1984. Short-term immobilization of fertilizer N at the surface of no-till soils. Soil Sci. Soc. Amer. J. 44:765-771.

Roose, E., and J. Piot. 1984. Runoff, erosion and soil fertility restoration on the Mossi Plateau (Central Upper Volta). Challenges in African Hydrology and Water Resources (Proceedings of the Harare Symposium, July 1984). IAHS Pub. no. 144, pp. 485-498.

Russel, J.C. 1939. The effect of surface cover on soil moisture losses by evaporation. Soil Sci. Soc. Am. Proc. 4:65-70.

Smika, D.W., and G.A. Wicks. 1968. Soil water storage during fallow in the central Great Plains as influenced by tillage and herbicide treatments. Soil Sci. Soc. Am. Proc. 32: 591-595.

Staple, W.J., J.J. Lehane, and A. Wenhardt. 1960. Conservation of moisture from fall and winter precipitation. Can. J. Soil Sci. 40:80-88.

Stoltenburg, D.E. 1989. Reducing herbicide inputs. Water Watch. Issue No. 19. Iowa State University Extension. Mimeo.

Tanner, C.B., and T.R. Sinclair. 1983. Efficient water use in crop production: Research or re-search? Limitations to Efficient Water Use in Crop Production, pp. 1-27. Madison, Wisc.: American Society of Agronomy.

Unger, P.W. 1978. Straw mulch rate effect in soil water storage and sorghum yield. Soil Sci. Soc. Am. J. 42:486-491.

Unger, P.W. 1984. Tillage and residue effects on wheat, sorghum, and sunflower grown in rotation. Soil Sci. Soc. Am. J. 48:885-891.

Unger, P.W., G.W. Langdale, and R.I. Papendick. 1988. Role of Crop Residues—Improving water conservation and use. *In* W.L. Hargrove, ed. Cropping Strategies for Efficient Use of Water and Nitrogen. Special Publication No. 51. Madison, Wisc.: American Society of Agronomy.

Unger, P.W., and A.F. Wiese. 1979. Managing irrigated winter wheat residues for water storage and subsequent dryland grain sorghum production. Soil Sci. Soc. Am. J. 43: 582–588.

U.S. Department of Agriculture and U.S. Agency for International Development. 1988. *In* R.I. Papendick and J.F. Parr, eds. Proceedings of a workshop on crop residue management to optimize crop/livestock production and resource conservation in the Near East Region. Amman, Jordan. 31 January–2 February.

Veseth, Rodger. 1987. Paired row versus single row spacing. STEEP Extension Conservation Farming Update. Winter, 1987. STEEP Extension Program. University of Idaho, Moscow; Oregon State University, Corvallis; and Washington State University, Pullman.

Yan, Ying. 1989. A model for predicting soil loss ratio and crop production in eastern Washington. M.S. thesis. Washington State University, Pullman, Wash.

Agroclimatic Approaches for Improving Agricultural Productivity in Semiarid Tropics*

E.T. Kanemasu, J.I. Stewart, S.J. van Donk, and S.M. Virmani

I. Introduction 273
II. Agroecological Features of the Semiarid Tropics 275
A. Rainfall and PE in the SAT 278
B. Rainfall during Crop Growing Season 278
III. The Indian SAT 280
IV. The Sahelian SAT 285
A. Climatology of the Sahel 285
B. Onset of the Rainy Season as Rainfall Predictor 287
V. Botswana SAT 302
A. Crop Production Potential of Different Regions of Botswana 304
B. The Relationship Between Onset of Rains Versus Season Duration and Rainfall Amount 305
VI. Summary and Conclusions 306
A. Role of Agroclimatic Studies 306
B. Sub-Saharan Agriculture 307
C. Botswana 307
D. Outlook for Future 308
References 308

I. Introduction

The semiarid tropics (SAT) is a region of limited, erratic rainfall and nutrient-poor soils. It is populated by more than 700 million people, most of whom live at subsistence levels and depend for their food on the limited production of small

*Contribution No. 88-210-B from the Kansas Agricultural Experiment Station.

© 1990 by Springer-Verlag New York Inc.
Advances in Soil Science, Volume 13

farms. Current yields are low and production is unstable because of aberrant weather. Semiarid tropics with 13% of the world's land and 15% of its people produce only 11% of its food.

As a result of rising populations, food deficits in the SAT are increasing. The situation is alarming in some regions. As an example, it is projected that countries of sub-Saharan Africa will need food imports in excess of 20 million tons per annum by the 1990s. India, where more than 100 million ha of land are dryland farmed, also has a very large area of land under irrigated agriculture (some 40 to 50 million ha). Although India has accumulated food reserves of over 20 million tons in recent years, these reserves are drastically reduced during drought years. Thus, there is an urgent need to harness soil and climatic resources in an agroecologically balanced sense for sustained and increased agricultural production in the SAT.

The SAT are relatively dry areas of the tropics. These regions are characterized by a uniformly high temperature throughout the year and have seasonally wet climates. The rainy season is generally short. The dry season lasts for several continuous months during the year. Therefore in semiarid agriculture, water is one of the most limiting resources. In most situations, dryland farming is the primary management system; therefore, rainfall amount, intensity, frequency, and variability are important factors in developing a cropping system. Thus, the climate, soil, nutrients, and biological resources are linked with social and economic constraints to collectively circumscribe the alternative strategies for dryland agriculture.

In semiarid agriculture, an agroclimatologist is primarily concerned with rainfall variability and less with average rainfall amount. If the cropping season always had uniform rainfall, the farmer would choose a single management plan. He would plant certain crops on specific soil/topography areas of his farm. His planting date, seeding rate, fertility, herbicide, and insecticide would be planned for the optimal yield for that anticipated single rainfall pattern. Obviously, life is not that simple, and the high variability of rainfall creates major problems for the farmer. He must begin the season with a perception of what the rainfall pattern will be. As the season progresses, he makes alternative management decisions based on what the rainfall pattern has been. Thus, it is important that the farmer knows with a significant degree of confidence the expected rainfall pattern in order to make decisions within or even before the growing season.

In this chapter we present the following:

1. The agroecological features of the semiarid tropics.
2. Agroclimatic analyses of some selected areas for identifying agroclimatic constraints for increased agricultural production.
3. An overview of the impacts of climatic variability and changes that have occurred in the recent years in the Sahelian SAT, in relation to dependable harvests in this marginal agroecological zone; and finally.
4. Summary and conclusions of this study.

II. Agroecological Features of the Semiarid Tropics

The climate of the SAT has a pervasive influence on agricultural production. It is also clearly a primary constraint to agricultural development. We therefore commence this paper with a general description of the climatic characteristics of the SAT. For classifying SAT climate, a number of geographic techniques have been proposed. The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has accepted the climatic classification proposed by Troll (1965) as the working definition for defining its world mandate region. According to Troll the tropical areas can be classified as follows:

Climate class	Length of rainy season	Associated vegetation
1.	Tropical rainy climates with 9.5 to 12 humid months	Tropical rainforest
2.	Tropical rainy climates with 7 to 9.5 humid months	Humid savanna
3.	Wet-dry tropical climates with 4.5 to 7 humid months	Dry savanna
4a.	Tropical dry climates with 2 to 4.5 humid months	Thorn savanna
5.	Tropical semidesert climates with less than 2 humid months	Semidesert

A humid month is defined as a month in which mean monthly rainfall exceeds potential evapotranspiration. The classes of interest in terms of semiarid climates are the wet-dry tropical climates and the tropical dry climates. The ICRISAT climatologists consider that Troll's climate classes 3 and 4a generally represent what is usually termed as semiarid tropics or SAT. This agroecological zone is typified by dry and thorn savannas. In terms of the length of the rainy season the wet-dry tropical climates (also termed wet SAT) have a longer humid period than the tropical dry climatic region (also termed dry SAT). The wet SAT represents a climatic zone where the growing season may extend from 150 to 210 days; in the dry SAT the growing season ranges between 60 and 150 days or longer. World regions that have climate in accord with this classification scheme are depicted in Figure 1.

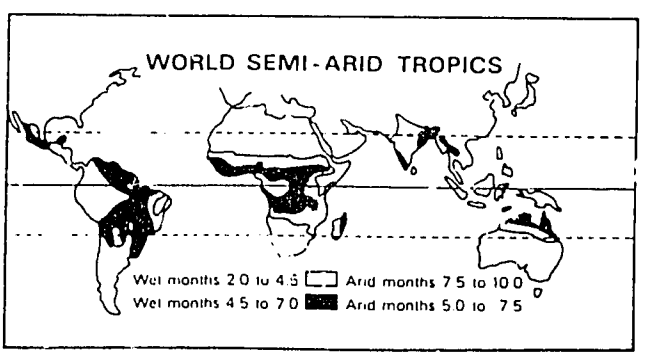


Figure 1. Distribution of semiarid tropics of the world, according to classification proposed by Troll (1965).

Table 1. Mean monthly rainfall (mm) and potential evapotranspiration (PE) at some selected locations in the semiarid tropics

Location		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Hyderabad	Rainfall	2	11	13	24	30	107	105	147	163	71	25	6	704
(India)	PE	110	130	182	198	220	196	140	136	119	124	104	99	1758
17°27′N; 78°28′E														
Bangalore	Rainfall	3	10	6	46	117	80	117	147	143	185	54	16	924
(India)	PE	117	130	166	158	157	127	116	114	109	105	98	103	1500
12°58′N; 77°35′E														
Dakar	Rainfall	0	1	0	0	0	10	87	220	164	58	2	3	546
(Senegal)	PE	142	134	160	173	165	165	159	141	143	149	149	151	1831
14°44′N; 17°30′W														
Niamey	Rainfall	0	0	0	0	26	77	159	201	101	15	0	0	580
(Niger)	PE	163	165	207	202	215	204	157	131	135	172	154	141	2046
13°29′N; 02°10′W														
Debre-Zeit	Rainfall	11	25	41	58	45	88	231	229	110	18	6	4	866
(Ethiopia)	PE	101	107	129	129	131	109	97	97	99	114	106	100	1319
08°44′N; 39°02′E														

Nairobi	Rainfall	63	34	81	107	130	24	7	11	21	62	188	116	844
(Kenya)	PE	135	143	151	116	102	93	90	95	106	124	113	117	1385
01°19'S; 36°55'E														
Morogoro	Rainfall	94	104	167	208	96	27	15	10	17	27	54	73	892
(Tanzania)	PE	137	124	132	103	92	85	92	106	123	149	143	143	1429
06°50'S; 37°39'E														
Motopos	Rainfall	123	99	68	26	7	3	0	1	4	26	85	130	572
(Zimbabwe)	PE	126	108	114	97	76	49	57	102	142	178	139	131	1322
20°23'S; 28°30'E														
Katherine	Rainfall	234	246	195	44	6	3	3	1	7	31	90	152	1012
(Australia)	PE	155	125	138	149	144	135	146	170	188	234	218	194	1997
14°28'S; 132°20'E														

Source: India Meteorological Department, Climatological Tables of Observatories in India, 1931–1960. Food and Agriculture Organization of the United Nations, Agroclimatological Data for Africa. FAO Plant Production and Protection Series No. 22, 1984. World Meteorological Organization, Climatological Normals for Climate and Climatsbip Stations for the Period 1931–1960. WMO No. 117. T.P.52, 1971.

A. Rainfall and PE in the SAT

The spatial and temporal variations in rainfall in the semiarid tropics are due to seasonal migration of the equatorial trough or the intertropical convergence zone (ITCZ), which occurs in response to the seasonal variation in the latitude of maximum insolation. Thus, the annual rainfall over the semiarid tropics can be thought of as the integrated effect of the annual visit of the ITCZ to the region. The annual distribution of rainfall and potential evapotranspiration for some typical dry SAT locations are set out in Table 1. The annual rainfall in the dry SAT varies from about 500 to 1200 mm. The PE values range between 1200 and 2000 mm. The rainfall is unimodal with a peak corresponding to the time at which the ITCZ is over the region. In these latitudes the month receiving maximum amount of rainfall is August or September. In the southern latitudes peak rainfall is observed in any of the months during the period December to May. For example, at Motopos, Zimbabwe, peak rainfall is recorded in the month of December, while the month of April registers maximum rainfall at Moragoro, Tanzania. In the equatorial zone, the rainfall is bimodal. Nairobi, Kenya, lying just 1° south of the equator shows the first rainfall peak during the "short rains" in the month of May, and a second peak is observed in the month of November during the "long rains." Debre-Zeit, Ethiopia, located 8°N of the equator, shows the first peak of rainfall in the month of April and the second peak in July.

The atmospheric demand for water in the semiarid tropics is high. It is particularly high before the rainy season or at the beginning of the rainy season. For example, in the month of May, we have noted the average open-pan evaporation to range around 10 mm/day, while on some days it could be as high as 15 mm both at Hyderabad, India, and Niamey, Niger. Mean monthly and annual PE averaged over 169 locations in India are shown in Table 2. These data show that the variability of PE during the prerainy and rainy seasons extending from April to October is somewhat lower than in other months of the year and that the atmospheric demand for water in the SAT is consistently high.

High rates of evaporation coupled with low and variable rainfall in the semiarid tropics often lead to periods of water deficit and have serious implications for stability of crop production in this ecological zone. It is only during the rainy period of the year when the rainfall exceeds PE that the soil moisture reserves are recharged. This period extends from 2 to 4.5 months in the dry SAT.

B. Rainfall during Crop Growing Season

In an agricultural sense, then, the length of the crop growing season in the SAT is primarily limited by the duration and other characteristics of the rainy period. The reliability of the rainfall at the beginning of the season is generally low. Consequently the SAT exhibits a high degree of risk to the establishment of crops, because the soil moisture reserves at this time are practically nonexistent. The soil temperatures are also fairly high, generally the surface 5 cm of soil has a

Table 2. Potential evapotranspiration (PE) statistics for 169 locations in rainfed areas of India

Month	Mean PE (mm)	Standard deviation (mm)	Coefficient of variation (%)
January	85	27	32
February	103	24	23
March	151	23	15
	Prerainy hot season		
April	177	21	14
May	207	33	16
	Rainy season		
June	174	34	19
July	132	27	20
August	122	21	18
September	122	18	15
	Postrainy cool season		
October	119	15	12
November	90	19	21
December	78	25	32
Annual	1556	196	13

maximum temperature of 40 to 50°C. The variability of rainfall at the end of the season is also high, affecting crop yield and their quality.

In agronomic sense, the year in the SAT climates can be divided into four phases:

1. The prerainy season, which may extend from 1 to 2 months, and is also sometimes called as the period of "short rains."
2. The rainy season, which is the period during which the monsoons or the ITCZ is active. It is also called the period of "long rains."
3. The postrainy season, which is generally a cool and dry season. The crops during this time thrive on the moisture stored in the soil profile.
4. A hot dry season, which may extend from a month to several months. It generally precedes the rainy season. During this period the temperatures are quite high.

In the following sections agroclimate characteristics and recent advances in agroclimatological research to aid in increasing and stabilizing agricultural production for some selected areas of SAT are discussed. These areas are the Indian subcontinent, the sub-Saharan Sahelian zone, and Botswana.

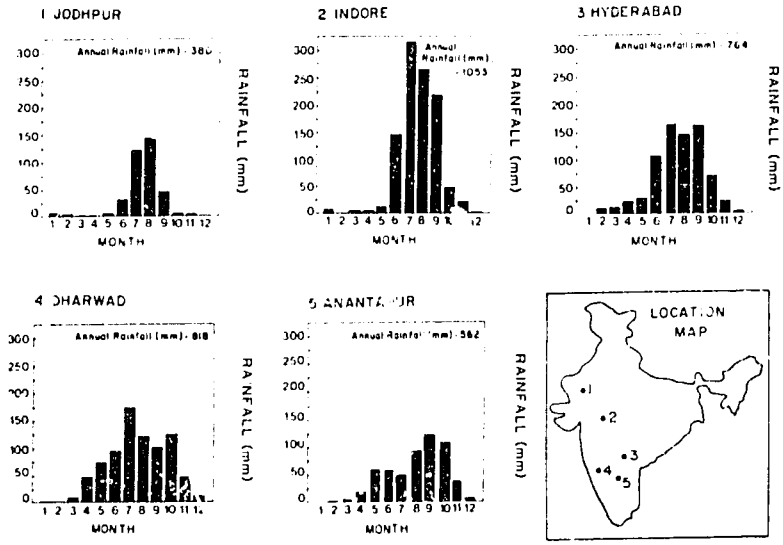


Figure 2. Mean monthly rainfall at five representative SAT stations in India.

III. The Indian SAT

Semiarid area covers almost 80% of the total land surface of India of which a major proportion lies in the dry SAT (Fig. 1). The Indian dry SAT is characterized by a short and intense rainy season followed by a relatively long dry season. The amount of rainfall received annually ranges between 400 and 1400 mm; the rainy season may have one peak (unimodal) or two peak periods (bimodal) of rainfall. Figure 2 shows the rainfall distribution of some SAT locations of India.

The Indian SAT areas lying between 5 and 12°N latitude are distinctly bimodal, whereas the rainfall is generally unimodal in areas located above 20°N latitude. In the Indian SAT some 85% of the total annual rainfall is received during the rainy months. As was described in the previous section, the dry SAT areas show considerable variability of rainfall from year to year. The annual rainfall variability for the five locations is shown in Figure 3. The mean annual rainfall based on data from 1941 to 1970 ranged between 382 mm (Jodhpur) and 1001 mm (Indore), and the coefficient of variation ranged between 20 (Hyderabad) and 42% (Jodhpur). In the Indian SAT droughts occur frequently. The Indian Planning Commission defines a year as a drought year when the annual rainfall is 75% or less of the long-term average of the location. Accordingly, the number of years which received rainfall below 75% of the corresponding average for the location was 8 in Jodhpur, 6 in Anantpur, 2 in Hyderabad, 4 in Dharwad, and 6 in Indore (out of 30 years).

Therefore, for planning any agricultural development strategy, the relative distribution of drought years when the crops are likely to fail or yield poorly should

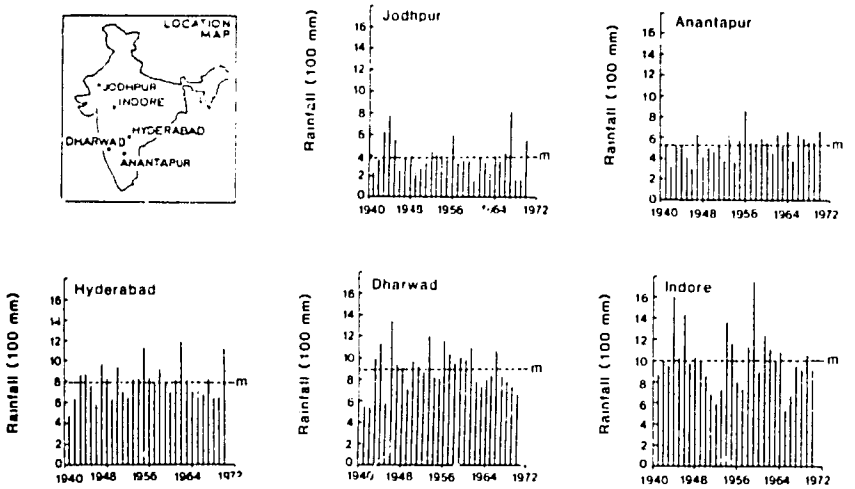


Figure 3. Annual rainfall for five locations during 1941 to 1970. m = mean annual rainfall.

be taken into consideration. This is one of the major considerations for the farmers in the adoption of improved technologies, because these require investments in new seeds, fertilizers, and crop protection against diseases and pests. The small farmers of the SAT can ill afford to lose a cropping season.

The distribution of rainfall during the year in the SAT is quite erratic. Distribution of rainfall during 5 years at the ICRISAT Center is shown in Figure 4 as an example. The figure depicts that the rainfall is quite unevenly distributed and that there are periods of marked high rainfall followed by relatively dry or rainless periods. Therefore in developing alternate crop production strategies, it is important to consider rainfall distribution pattern as well as its reliability. At ICRISAT, it has been found that the rainfall can be characterized, in agronomic terms, most usefully by estimating the probabilities of soil moisture in a stochastic process. Markov chain procedures can be used effectively to define the dependability of rainfall during the rainy season (Robertson, 1976; Virmani et al., 1982; Huda and Virmani, 1987). The risks that sowing rains received by crops will not be enough to ensure survival, and the dependability of rainfall later at critical stages of crop development, can then be assessed through such analyses.

We examined the mean weekly rainfall distribution and the probability of receiving at least 10 mm and 20 mm of rainfall in each week for these five locations (Figure 5). The average number of weeks receiving at least 20 mm was 11 in Jodhpur, 10 in Anantpur, 16 in Hyderabad, 22 in Dharwad, and 16 in Indore. The continuity of rainfall is important for determining the length of growing season. The consecutive weeks receiving at least 20 mm of rainfall were 11 in Jodhpur, 5 in Anantpur, 15 in Hyderabad, 15 in Dharwad, and 16 in Indore.

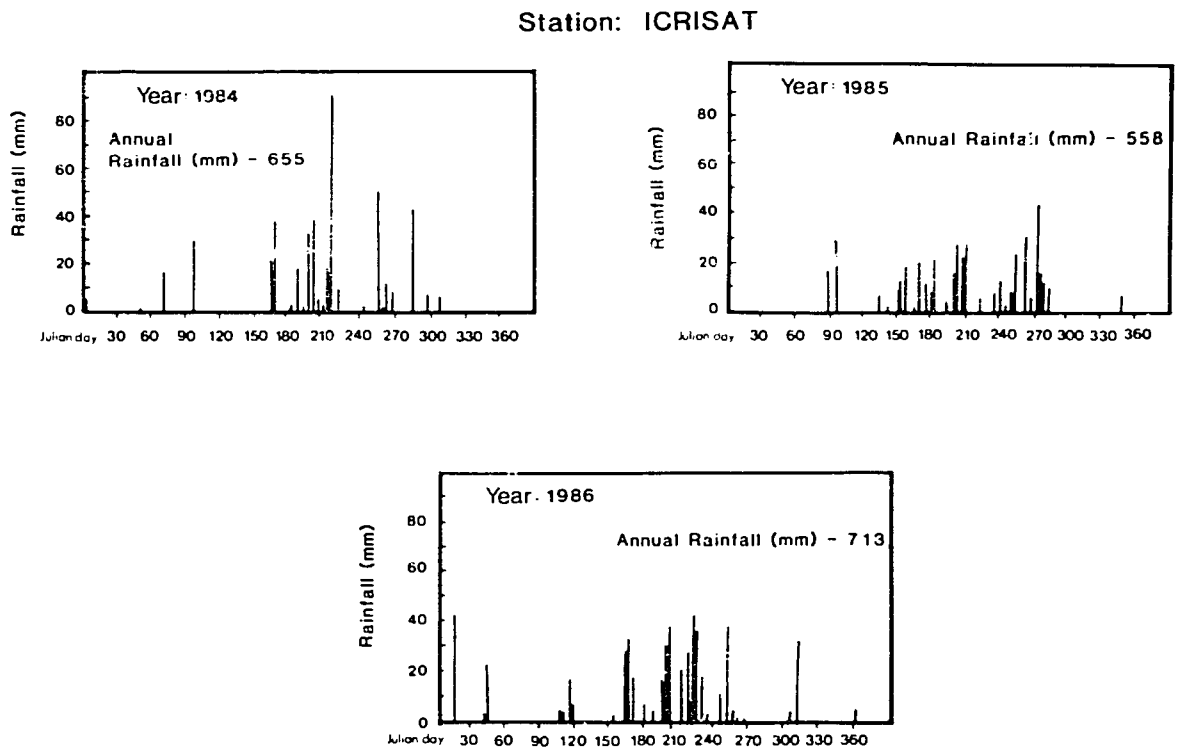


Figure 4. Daily rainfall recorded in the years 1984, 1985, and 1986 at the ICRISAT Center, Patancheru, located near Hyderabad (India). Note that during the core rainy season there are periods of relatively low rainfall such as August 1984/85 and September 1986.

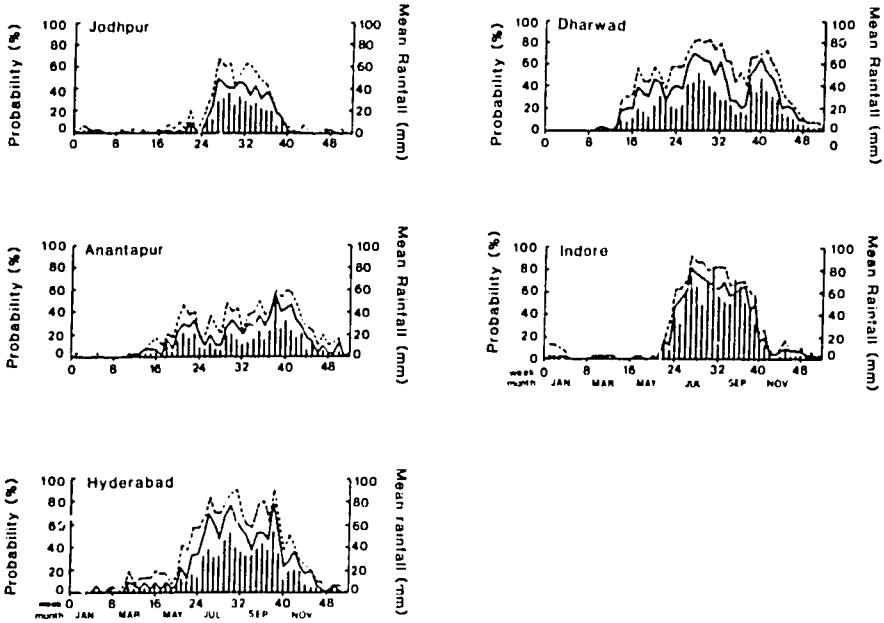


Figure 5. Mean weekly rainfall distribution (vertical lines) and the probabilities of receiving at least 10 mm (dashed lines) and 20 mm (solid lines) of rainfall in a week for five locations. (Data base 1941-1970.)

Figure 5 also depicts the results of the Markov chain procedure to determine the probability of receiving different amounts of rainfall in each week. The number of weeks with at least 70% probability of receiving more than 20 mm was five in Indore, two in Hyderabad, one in Dharwad, and zero each in Jodhpur and Anantapur. These results indicate the relative risks of growing rainy season crops across the range of agroclimates represented by these locations.

Considering the discussion on the distribution and dependability of rainfall presented so far for the Indian subcontinent, the following could be considered as main agroclimatic constraints/attributes of the five selected locations to increased crop production:

1. Jodhpur [26° 18′ N; 73° 01′ E; elevation 224 m. Soils Orthids and Psamments]. In this western Indian location water is the most limiting factor, and improved agriculture production should aim at stabilizing crop production. The average length of the growing season is 88 days. Risks to dependable crop production are high because of the recurrence of droughts. One short duration crop of pearl millet yielding in excess of 1500 kg/ha can be harvested 4 years in 10; in other years the grain yield is likely to be low. The agroenvironment in Jodhpur represents a large tract of western India where the rainy season is restricted to about 2 months, the PE rates during the rainy cropping season are high and the soils are light

textured. Agropastural rather than crop production systems would be more productive and ecologically sound for areas with an agroclimate like Jodhpur.

2. Anantpur [14° 41′ N; 77° 37′ E; elevation 348 m. Soils Ustalfs]. In this southern Indian bimodal rainfall location, the average rainfall is 563 mm, which meets 30% of the annual ET demand. Although the rainy season commences in May and the rains continue up to October, the average monthly rainfall is always less than ET. The soils of Anantpur region are shallow sandy Alfisols, therefore the growing season is restricted to 120 days, out of which the stress-free period extends to only 45 days in the months of August and September. In this location, as in Jodhpur, successful crop production is generally limited to 4 out of 10 years. Foxtail millet and groundnut crops are commonly growing. Agroecologically the area seems more suitable for agroforestry systems.

3. Dharwad [15° 27′ N; 75° 00′ E; elevation 740 m. Soils Usterts]. This location represents an area of less dependable rainfall in central and southern peninsular India. The rainy season here commences in May and ends in October. The rainfall is bimodal. The first peak of rainfall is seen in June and the second in October. September is a transition period. It is dry in most years. The Dharwad area is suited for growing a long duration crop with an indeterminate growth habit (e.g., cotton). Two short duration crops can be grown. Yields are intermediate.

4. Hyderabad [17° 27′ N; 78° 28′ E; elevation 545 m. Soils Usterts and Ustalfs]. This southern Indian location represents a substantial area of dependable rainfall of the semiarid tropics in peninsular India. Two types of soils contrasting in their water holding capacity are represented here. The Alfisols are sandy loams with 50 cm to 100 cm depth and can hold about 100 mm available soil moisture in the root zone. The Vertisols are clay loam soils generally more than 100 cm deep and can hold about 200 mm of available soil water in the root zone. Therefore, in Alfisols the growing season is about 150 days whereas in the Vertisols it extends to 210 days. In the Alfisols of the Hyderabad region intercropping of a short-duration crop such as sorghum or millet with a long-duration crop of groundnut or castor has proven successful. In the Vertisols maize–pigeonpea intercropping or maize followed by a sequential crop of chickpea has generally performed well. In extremely shallow soils, the agroforestry systems have been found to stabilize agricultural production. The Hyderabad climatic zone represents a medium to high potential for dryland crop production. Good harvest of crops is feasible for about 8 out of 10 years in the Vertisols, and 6 or 7 years in every 10 years in the Alfisols.

5. Indore [22° 43′ N; 75° 48′ E; elevation 567 m. Soils Usterts, Orthents]. This central Indian location represents a high potential crop production zone of Vertisols in the peninsular India. Dryland agriculture is commonly practiced in this region. At Indore the growing season length is about 200 days extending from June to December. Two crops can be grown in succession or an intercrop of a short duration cereal in combination with a medium duration (180 to 210 days) pulse crop has been found as a successful practice. Concurrently intercropping of soybean with pigeonpea is being adopted progressively. Provision of adequate drainage facility of excess water received in July, August, and September is

important for successful land use of Vertisols. Watershed-based land and water management systems are essential for obtaining increased and stabilized crop production in dryland in this area. Fairly high yields of crops can be harvested at least 8 years out of every 10 in this peninsular Indian region.

IV. The Sahelian SAT

The Sahelian SAT is a broad belt lying south of the great Saharan desert. The Sahalian region includes parts of the West African countries like Senegal, Gambia, Guinea Bissau, Guinea, Mauritania, Mali, Burkina Faso, Ghana, Niger, Togo, Benin, Nigeria, Cameroon, and Chad. In this region sorghum, millet, groundnut, and maize are commonly grown food crops. The crop yields are low. Dryland agriculture is common practiced. Crop failures due to recurrence of droughts is common. The past two decades or so have witnessed a drastic reduction in the amount and length of the rainy season. This region presents a serious challenge to the agricultural sciences for innovating technologies to increase and stabilize food production of this marginal agroecological zone.

A. Climatology of the Sahel

Three bioclimatic zones based on the length of the rainy period/crop growing season are recognized. These are the southern Sahelian bioclimatic zone with a growing season ranging from 75 to 90 days, the Sudan bioclimatic zone with a growing season extending to 165 days, and the northern Guinean bioclimatic zone with a growing season from 165 to 210 days. The distribution of these bioclimates in West Africa is shown in Figure 6. Data in Figure 7 depict the arrival of monsoon in higher rainfall areas of southern Sahel (Sudan bioclimatic zone) in late April, May, or June, and its move northward to the drier latitudes verging on the Sahara Desert in July, August, or early September. The pattern is unimodal (single peak in rainfall), with recession or withdrawal of the monsoon generally in late September or early October, but sometimes—especially in recent years in the Sahelian bioclimatic locations—in August. Virtually all annual rainfall is received within this season.

Evaporative rates and temperatures in the region are high during the monsoon growing season. Hargreaves and Samani (1986) indicate that evaporation rates (Class A pan equivalent) during the onset period at Niamey, Niger, are about 9 mm per day in June, declining in July to about 8 and in August to about 7, as a result of cloudiness and rains. Temperatures throughout the season average about 29°C (84°F).

The relatively high temperatures and evaporative rates tend to be compensated for by high rainfall intensities. This section shows, for two quite different rainfall zones of Niger, intensities ranging from 4 to 7 mm per day, with extremes somewhat higher and lower. With reference to lower intensities, findings on the climatic shift since 1971 are presented and discussed.

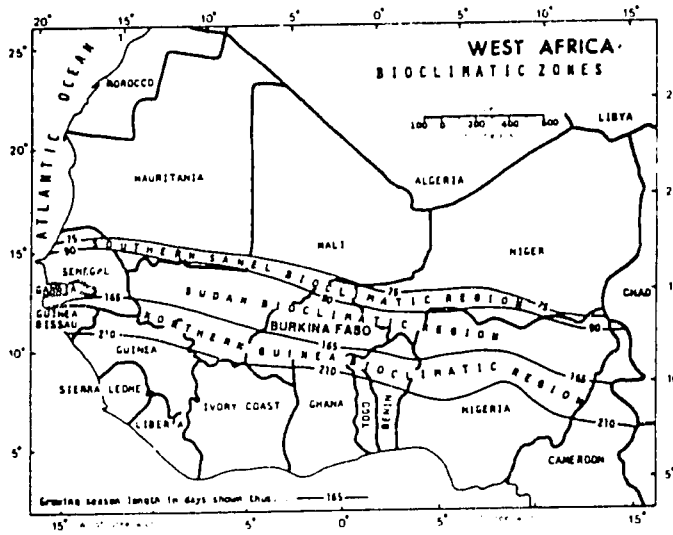


Figure 6. Bioclimatic regions in West Africa, adapted from Comité Interafricain d'Etudes Hydrauliques, Ouagadougou, Burkina Faso.

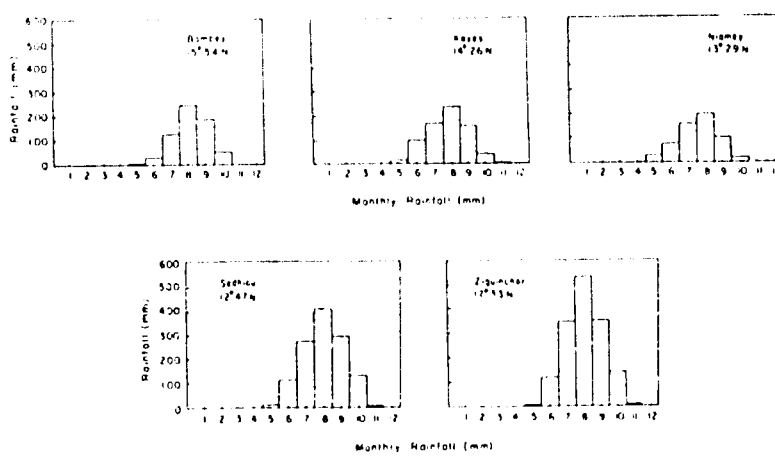


Figure 7. Distribution of monthly rainfall in five selected locations of Sahelian West Africa.

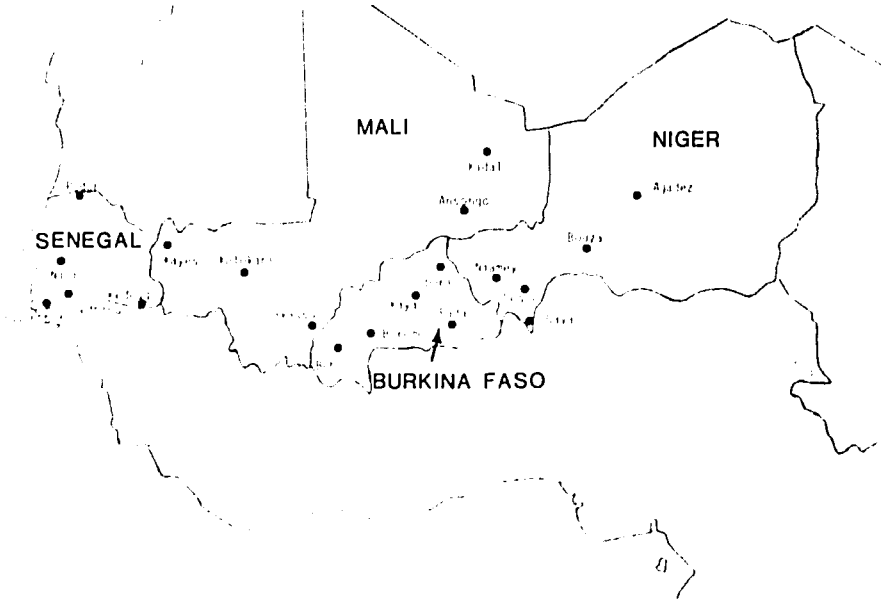


Figure 8. Location of Sahelian rainfall stations used in this chapter.

Daily climatological data for this chapter were obtained from ICRISAT, AGRHYMET, and the Royal Meteorological Institute of Belgium.

B. Onset of the Rainy Season as Rainfall Predictor

1. Niamey, Niger

The first example comes from Niamey, the capital of Niger, located in the southwest corner of the country along the Niger River somewhat east of the border of Burkina Faso (see Figure 8). Figure 9 shows the rainfall occurrences in the 30-year period of 1954–1983. This is not the entire record available for Niamey, but it is the period of special interest for this presentation, for two reasons:

1. It matches the period of records available from Bouza, Niger, which is the other West Africa example to be discussed in detail. This permits direct comparisons of the two locations.
2. In 1971 (arguably, as early as 1968), a major reduction in rainfall took place throughout the Sahelian zone. For 50 years before, the rainfall averaged markedly higher. To include the entire longer record would distort the averages in a way that would mask the effects of the recent climatic shift. The 30-year record creates a reasonable balance, with 17 years before the climatic shift and 13 years after.

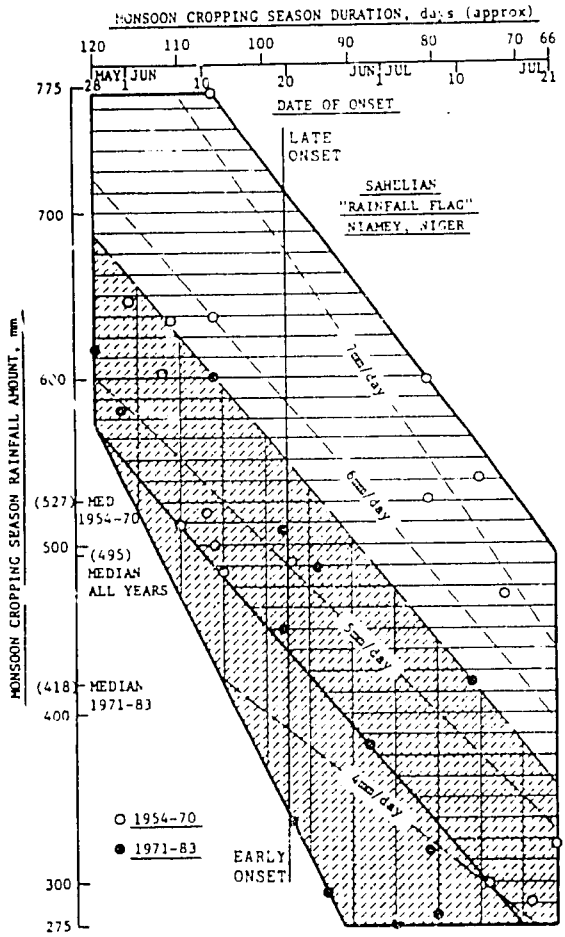


Figure 9. Thirty-year relationships of monsoon rainfall amount, duration, and intensity to date of onset: Niamey, Niger. Note the effects of the climatic shift from 1971 onward.

Figure 9 is a scatter diagram in the form of a "rainfall flag," relating seasonal rainfall amount to date of onset of the monsoon. It is not crop specific, but the major food crop in the area is pearl millet (*Pennisetum americanum*), although many other crops and cultivars with different maturities are grown. Onset is defined as 40 mm of rainfall stored in the surface soil – a somewhat stringent requirement due to the high evaporation rates and temperatures. A year with an early onset is expected to have longer dry spells in the beginning of the rainy season, which might affect the crop negatively. Therefore, the onset definition uses a "critical date," before which onset is not allowed, unless a more demanding criterion is satisfied: for each day before the critical date, an extra 2 mm of stored rainfall is required. For example, with a critical date of May 30 and a potential onset date of May 20, 40 + 10*2 = 60 mm of stored rainfall is required.

Table 3. Niamey, Niger: Median values of monsoon cropping season rainfall characteristics, including date of onset and consequent rainfall amount, duration, and intensity, for all years[a] and for early onset versus late onset years

		Monsoon cropping season rainfall, median values			
No. years	Onset period	Onset (date)	Amount (mm)	Duration (days)	Intensity[b] (mm/days)
30	ALL, May 28–Jul 21	6-20	494	99	4.68
14	EARLY, to June 19	6-10	590	113	4.91
16	LATE, June 20 on	7-06	351	82	4.07

[a] Thirty-year record from 1954 to 1983 inclusive
[b] Intensity from actual data, not calculated from median amount/duration.

The final rainfall date in this instance is identified by summing daily rainfall backward in time from the last rainfall event in October (November rainfall seldom occurs and is not considered for this purpose) until a total of 10 mm or more is reached. That date is taken to be the final rain date in the season for practical purposes. This procedure avoids the problem of, say, reasonable rainfall to September 10, then nothing until October 20, when a final rainfall of 2.0 mm occurs. Effectively, this would be outside of the cropping season.

The final rain date changes from year to year, but less than the date of onset. Figure 9 displays a horizontal scale at the top labeled Monsoon Cropping Season Duration, which means number of days from onset to final rain date, inclusive. Because of the relatively small changes in final rain date, the durations shown are approximate, as noted in the figure. For the same reason, the intensities are also approximate when related to any given data point, but are correct overall and are representative.

The Niamey rainfall in Figure 9 may be viewed as a single record or as two separate records, one from 1954 to 1970, and the other from 1971 to 1983. We will do both, starting with the view that it is a single record. This means the open circle and blackened circle data points are each representative of one year in the record and are all to be viewed equally. The shading in the lower portion of the flag is to be ignored and the whole is to be seen as one.

Overall, Figure 9 provides an excellent example of the ways in which date of onset can impact on seasonal rainfall characteristics. It is clear that the range of expected rainfall amounts as well as the duration of the rainy period are both diminishing with each day that onset is delayed. Table 3 provides details on median values of the agriculturally pertinent characteristics, first for the 30-year record as a whole, then as if it were two separate records—one confined to years that had early onset, and the other containing late-onset years. Note that this division of the record is not the same as that described.

The first line in Table 3 provides an overall look at Niamey rainfall. It shows that onset may occur as early as May 28 or as late as July 21, a span of 55 days. The median date in this range is June 20. The final rain date (not in the table) has a lesser range, and more important, a strong tendency to cluster around the median date of September 26. The median cropping season rainfall amount is 494 mm, ranging from as little as 275 mm to as much as 771 mm. Median duration of the rainy period is 99 days, but the actual duration has ranged from 71 to 154 days. This is dealt with shortly in more detail. Intensity of rainfall at Niamey has a median value of 4.68 mm/day, with a range from 3.02 to 8.08 mm/day.

However, if we divide the Niamey rainfall record into two records, simply on the basis of whether onset occurs before the median date or thereafter, major differences are revealed in all of the season characteristics of interest to the farming community. These differences may be seen in the second and third lines of Table 3, which contain characteristics of early versus late seasons, respectively.

First, we see that the median rainfall amount in early seasons is high (590 mm), whereas that of late seasons is very low (351 mm). To the farmer, this means emphasis on different crops and provision of different levels of inputs. It means different land preparation and tillage practices, probably different row spacings, and certainly different plant populations.

Next, we see that the median season duration is much longer (113 days) in early seasons than late ones (82 days). This again calls for emphasis on different crops and cultivars with different maturities. Rainfall intensities at Niamey have also been higher (median values) in early than late seasons, by nearly 1 mm per day, being 4.91 mm/day (0.19 in./day) in early seasons versus 4.07 mm/day (0.16 in./day) in late seasons.

In most instances, rainy period duration correlates with date of onset much better than does rainfall amount. Sivakumar (1988) quantifies the duration relationship for 57 locations in Niger (including Niamey) and Burkina Faso. In each case, the rainfall records used were more than 25 years long, ranging from 26 to 78 years. Thirty of the stations analyzed are in the drier zone more to the north, with 27 in Niger and 3 in Burkina Faso. The mean annual rainfall here ranges from 330 to 640 mm. Throughout this zone the correlations are excellent, with coefficients (r) ranging from 0.81 to 0.95. An additional 27 stations (all in Burkina Faso) in the zone more to the south have higher rainfall means from 650 to 1160 mm. Here the correlations are somewhat lower, but still very good. All are statistically significant at the 1% level, with correlation coefficients ranging from 0.52 to 0.90.

Stewart (1987) finds virtually the same correlation between duration and date of onset at Niamey as does Sivakumar (1988). This is of interest because the latter used somewhat different criteria for both date of onset and final rain date. Sivakumar (1988) defines the onset of rains as the date after May 1 in which rainfall had accumulated over three consecutive days of at least 20 mm, and when no dry spell occurred (>7 days of no rain) over the next 30 days. The ending of the rains is taken as the date after September 1 in which no rainfall occurs for 20 consecutive days. Additionally, he analyzed 78 years of record whereas Stewart analyzed only 30 years.

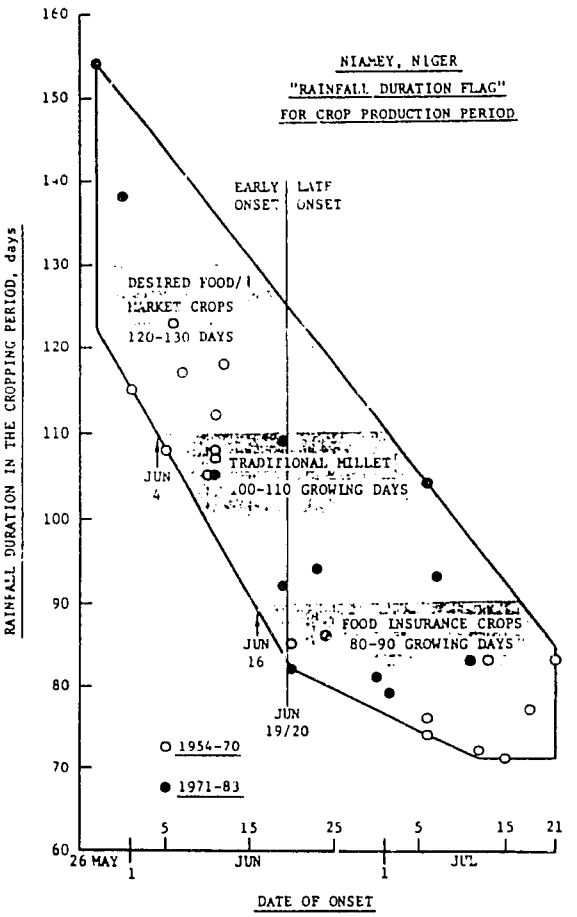


Figure 10. Duration of monsoon cropping season rainfall, as related to date of onset. Illustrative example of crop and cultivar selection based on this relation.

One important difference between the onset definitions of Stewart and Sivakumar is that, in Stewart's case, the predictor is the onset date and in Sivakumar's case the onset date plus one month! In the latter definition, a possible onset is prevented from being a false one, up to one month afterwards. It is false if there is a long dry spell within this first month. This difference in definition might explain why Sivakumar's correlation coefficients are better on average than ours for the 11 Sahelian locations, presented later in this chapter.

The relationship developed by Stewart is presented in Figure 10 in the form of a "rainfall duration flag." An example of how information of this type can be interpreted to assist farmers in selecting crops and cultivars to emphasize in seasons with different onset dates is based on the figure.

a. Crop/Cultivar Selection Based on Predicted Duration

Using the duration-versus-onset information to guide farmers requires consideration of (a) lengths of growing seasons (maturities) of different crops and cultivars in the planning site environment, (b) rapidity of planting (number of days it takes to plant following onset), (c) soil depths and water-holding capacities, (d) crop coefficients for estimation of water requirements, and (e) evaporative rates through the season.

The goal of the planning exercise is to select crops/cultivars that will reach maturity within the rainy period, or within a time period following the final rain date but before extractable soil water completely runs out. The first question is, what is the assured duration of the rainy period in relation to date of onset?

The assured, or minimum, duration of the rainy period on any given onset date is defined by the lower boundary of the flag in Figure 10, which is drawn through all of the lowest data points in the record. Of course, the actual duration may range anywhere from the number of days indicated by the lower boundary up to that indicated by the upper boundary of the flag. However, Figure 10 shows that the season durations at Niamey tend to lie in the lower half of the flag. Five of the 30 years analyzed (i.e., 1 year in 6) are on the lower boundary, and another 5 years are within 4 days of the lower boundary, so the risk of overestimating season duration climbs quickly as one increases the estimate above the minimum.

For the sake of illustration, let us assume that planting can be accomplished within 5 days after onset. We will estimate the rainy period duration to be the lower boundary value plus 5 days. From germination onward, this makes our effective estimate the lower boundary value. Two-thirds of the seasons will be of longer duration and one-third shorter than estimated, but only slightly shorter. If we further assume that the soil can (and will) store sufficient extractable water to provide the minimum needs of the crop in the final 20 days before maturity, then our illustrative case takes the form created by the three shaded bands across the flag in Figure 10. First, there is the middle band representing traditional millets around Niamey, which require a growing period of 100 to 110 days. If, in fact, it is 110 days, and the soil holds water for the final 20 days, the rain should not cease until 90 days into the growing period, that is, 90 days after crop germination. This is conservative because the actual growing period may be only 100 days. However, the conservatism is somewhat offset by risking the 5 planting days. The conclusion is that traditional millets should be deemphasized, and shorter maturity cultivars should be substituted to ensure the family food supply, if onset of the rainy season occurs later than the date when the lower boundary of the flag equals 90 days duration. In our illustration, this is the case when onset is after June 15.

On the other hand, when onset is quite early and the lower boundary of the duration flag equals or exceeds 110 days (June 4 or earlier), the indication is that longer-maturity crops can and probably should be grown. Such crops require more water as well as a longer rainy period, but hold the potential for higher

Table 4. Eleven locations in four countries of Sub-Saharan Africa listed by latitude from the dry north with a late monsoon to the relatively wetter south where the monsoon arrives earlier.[a]

Location	North latitude	Mean annual to 1970	Rainfall mm 1971 on	Ranges of onset dates Earliest	50%	Latest
Podor (S)[b]	16° 38′	292	156	7-07	8-08	9-21
Ansongo (M)	15° 40′	334	214	6-02	7-27	8-27
Kayes (M)	14° 26′	749	546	5-21	6-23	7-28
Bouza (N)	14° 25′	489	313	6-12	7-18	8-16
Dori (BF)	14° 02′	536	455	6-04	7-06	8-13
Nioro (S)	13° 44′	875	590	6-08	7-01	7-26
Kolokani (M)	13° 35′	848	724	5-11	6-20	8-09
Niamey (N)	13° 29′	603	504	5-28	6-20	7-21
Kaya (BF)	13° 09′	700	673	4-30	6-15	7-24
Gaya (N)	11° 59′	829	774	4-30	6-03	8-01
Boromo (BF)	11° 44′	957	875	4-27	5-20	6-28

[a]Mean annual rainfall to 1970, then for 1971 onward. Ranges on onset dates showing earliest, 50% of years and latest onsets.
[b]Countries are Senegal (S), Mali (M), Niger (N), and Burkina Faso (BF).

yields and more desirability and value in the marketplace, which are needed to break the poverty syndrome.

This illustration of crop selection based on the duration versus date of onset relationship is not intended to be definitive as it stands. It is just one example of a field application of the new information about rainfall. However, little additional information would be required to adapt it for use on the ground to provide guidance to farmers. The principal need is to conform the recommendations to the major soil types of the area, which will differ in their depths and water-holding capacities. Thus, a shallow sandy soil would require emphasis on shorter-term, food insurance crops at an earlier onset date than would a deeper soil with loamy or clayey texture.

2. Broadening the Findings

Relationships of rainfall amount and duration such as those at Niamey, Niger, are found throughout the Sahelian zones. The application of these findings to farm-level decision making is further enhanced by the broader, better known climate relationships of the area. Table 4 provides a first look at the broader aspects of the situation and an initial blending of the longer-known information with that more recently developed.

In Table 4, information is shown for 11 locations in sub-Saharan West Africa (see Fig. 8), including the one already discussed. Four countries are involved, from Senegal on the west reaching the Atlantic Ocean, eastward through Mali, and Burkina Faso to Niger. All 11 locations lie in the belt between 11° and 17°N latitude,

above which is virtually rainless desert. Table 4 lists the locations by latitude in descending order from north to south. The northernmost location is Podor, Senegal, at 16° 38′, and the southernmost is Boromo, Burkina Faso, at 11° 44′. These are also the driest and wettest locations, respectively, with long-term, mean rainfall amounts (prior to 1971) of 292 mm at Podor and 957 mm at Boromo.

The intermediate nine locations have intermediate rainfall, increasing with descending latitude. This relationship of annual rainfall to latitude is well known and much documented. The relation is nearly perfect for 8 of the 11 locations that lie to the east in Niger (3), Burkina Faso (3), eastern Mali (1), and northern Senegal (1). More westerly locations in Senegal (Nioro) and Mali (Kayes, Kolokani) follow a similar pattern but with approximately 35 to 50% higher rainfall at a given latitude. The mean rainfall figures at all locations prior to 1971 can be seen in column 3 of Table 4.

Table 4 shows the results of additional analyses on the long-term rainfall records (all years) of when onset of the monsoon for cropping purposes has occurred at the 11 locations. Columns 5, 6, and 7, respectively, show the earliest dates of onset, the dates by which 50% of all years had onset, and the latest dates. Since it is always possible to have a freak onset event, which might throw the "earliest" and "latest" onset columns out of line, it is most informative to look at the 50% onset dates. There we see a nearly clear progression of onset, starting early in the south at Boromo and 80 days later reaching Podor in the north. The reader should not infer that this type of progression occurs cleanly each year. These are long-term means, and in any given year, the progression of the monsoon front can be erratic, making it difficult to predict the onset at a given location from the onset of a location more to the south. Correlation analysis of onsets at different locations show this. Even locations close to each other often show bad correlation. There are a few exceptions, so possibly predictions of this kind can be made locally.

Unlike the onset, the recession or withdrawal of the monsoon occurs (on average) almost simultaneously at all latitudes being discussed. There is a mild tendency for later withdrawal in the south, perhaps 4 days later than in the north. Thus, in 50% of years, the monsoon rains depart at 17°N latitude by September 24, and at 11°N latitude by September 28.

Figure 11 provides a graphical representation of the relationship of onset to latitude, based on columns 5, 6, and 7 of Table 4. The vertical scale shows north latitude in degrees and minutes, from 11° to 17°, inclusive. The horizontal scale is a calendar showing both ordinary dates and day of year (days are numbered from 1 on January 1). The onset dates from each of the 11 locations are drawn in at the appropriate latitude, in each case showing the earliest date of onset analyzed from the long-term rainfall record, the 50% date, and the latest date. The three dates for each location are linked by dashed lines.

The shaded area of Figure 11 represents the result of regression analyses in which the three sets of onset dates are related to latitude mathematically. The purpose of the analyses is to enable estimation of the dates of onset for any other

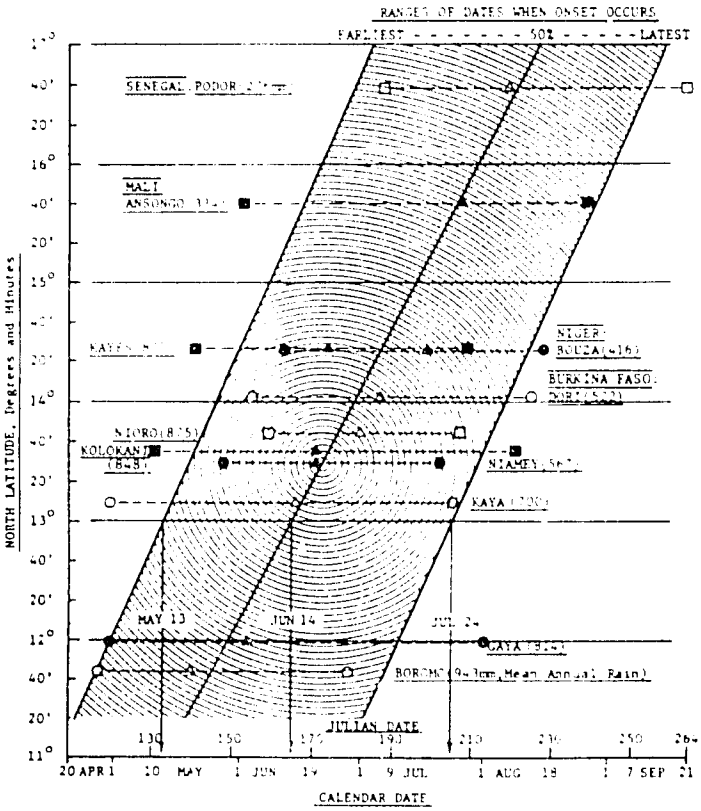


Figure 11. Western Africa, Sudano-Sahelian zone (Senegal, Mali, Burkina Faso, and Niger). The ranges of dates of onset of the monsoon cropping season are shown as a function of latitude

location not analyzed, in the sub-Saharan zones covered. Estimates of earliest onset dates are based on the line forming the left side of the shaded area. Fifty percent onset dates are based on the heavy line up through the middle of the shaded area, whereas the line on the right side estimates latest onset dates. For example, the three arrows dropped from 13°N latitude in the figure indicate that locations at that latitude should have earliest onset on May 13, 50% onset by June 14, and latest onset by July 24. Such estimates are shown for 11°N latitude through 17°N latitude in the last three columns of Table 8. These estimates were derived from the same types of regression analyses that were used to construct Figure 11.

The relationships of principal interest—those of (1) cropping season rainfall amount and (2) duration versus date of onset—are quantified by regression equations for all 11 locations in Table 5. Whenever data were sufficient, these relationships were analyzed separately for the years before 1971, and for 1971

Table 5. Relation of monsoon cropping season rainfall to date of onset at eleven locations in Sub-Saharan Africa described in Table 4

			Monsoon cropping season[b]					
			$R = a1 + b1$ (Onset)			DUR $= a2 + b2$ (Onset)		
Station	Data[a] base (yr)	Mean annual rainfall (mm)	($a1$)	($b1$)	$R2$	($a2$)	($b2$)	$R2$
Podor	46	292	1190	−4.31	(.44)	269	−0.98	(.56)
	6	156						
Ansongo	40	334	851	−2.98	(.41)	295	−1.14	(.73)
	ND	(214)[c]		ND			ND	
Kayes	41	749			(.10)	275	−0.95	(.52)
	3	546						
Bouza	17	489	1149	−3.89	(.17)	270	−1.00	(.65)
	12	313	1037	−4.14	(.73)	218	−0.80	(.46)
Dori	43	536	1347	−4.76	(.38)	274	−0.89	(.64)
	9	455	1135	−3.99	(.58)	298	−1.12	(.68)
Nioro	33	875			(.10)	296	−1.04	(.70)
	4	590		ND			ND	
Kolokani	41	848	1550	−4.73	(.28)	289	−1.03	(.85)
	3	724		ND			ND	
Niamey	17	603	1382	−4.95	(.47)	269	−0.98	(.83)
	13	504	1693	−7.32	(.62)	334	−1.35	(.64)
Kaya	48	700			(.12)	284	−1.01	(.71)
	8	673			(.05)	308	−1.18	(.69)
Gaya	36	829			(.10)	289	−1.07	(.80)
	13	774	1505	−5.16	(.51)	298	−1.14	(.82)
Boromo	45	957			(.06)	301	−1.14	(.78)
	9	875	1391	−4.24	(.59)	282	−0.95	(.77)

[a] Upper number is years to 1970, lower number is years from 1971 onward.
[b] Regression equations show how monsoon cropping season rainfall amount and duration relate to the date of onset. R = rainfall (mm), DUR = duration (days), and Onset is the Julian date of onset of the monsoon cropping season.
[c] Estimated value = annual rainfall data unavailable.

onward. In each case, the degree of closeness or fit of the relationship is represented by the coefficient of variation (r^2).

Table 5 shows the following:

1. A strong relationship exists between rainfall season duration and date of onset at all 11 locations. This is shown by r^2 values that range from a low of 0.46 in recent years (since 1971) at Bouza, Niger, to a high of 0.85 in years before 1971 at Kolokani, Mali. Statistically speaking, these are all highly significant relationships at the 1% level. Practically speaking, they are highly useful relationships on which to base advice to farmers on crop types and cultivars to emphasize in their plantings in different seasons.

Table 6. Niamey, Niger: Past situation – median values of monsoon cropping season rainfall characteristics, including date of onset and consequent rainfall amount, duration, and intensity, for all years from 1954 to 1971 (17 years), and for early-onset years (9) versus late-onset years (8)

		Monsoon cropping season rainfall, median values			
No. years	Onset period	Onset (date)	Amount (mm)	Duration (days)	Intensity (mm/days)[a]
17	All, June 01–July 21	6-12	519	107	5.16
9	Early, to June 16	6-10	603	112	5.16
8	Late, June 17 on	7-12	480	76	5.44

[a]Intensity from actual data, not calculated from median amount duration.

2. A less strong but equally valid and useful relationship exists between cropping season rainfall amount and date of onset. Coefficients of variation (r^2) range from a low of .07 at Nioro in the years before 1971 to a high of 0.73 at Bouza since 1971.
3. The relationship between rainfall amount and date of onset is nearly always useful for guiding farm decisions even when the r^2 values are low. For example, at Kaya, Burkina Faso, before 1971, the r^2 was only 0.11. The probability of season rainfall amount being less than 600 mm is 15% with an onset on April 30 (the earliest onset date in the historical record), whereas it is 66% with an onset on July 24 (the latest onset date in the record). Expressed differently, if a year with less than 600 mm seasonal rainfall is arbitrarily defined as a bad year, only 1 or 2 years out of every 10 are bad when onset is on April 30 and as much as 6 or 7 out of every 10 are bad when onset is on July 24.

3. Impact of the Climatic Change

a. Niamey, Niger

Returning to Figure 9, the lower shaded portion of the flag is seen to contain all of the data points representing the more recent years from 1971 onward. Earlier years (1954–1970) are in the unshaded portion of the flag and also the upper part of the shaded area, in effect creating two separate flags that overlap each other. Each flag shows clear relationships between farm-relevant rainfall characteristics and date of onset, in fact, each of these relationships is stronger than when considering the whole as a single record. The important point made by the shading and separation into two records is that past rainfall (1954–70) was markedly better in every respect than current rainfall (1971 on). This has continued to be true since 1983, but additional data are required for definitive relationships.

Table 6 duplicates the data of Table 3, but covers only Niamey rainfall as it used to be, that is, prior to 1971. Table 7 characterizes Niamey rainfall as it is today and may be tomorrow. Whereas average annual rainfall over the 50-year period

Table 7. Niamey, Niger: Current situation – median values of monsoon cropping season rainfall characteristics, including date of onset and consequent rainfall amount, duration, and intensity, for all years from 1971 to 1983 (13 years), and for early-onset years (7) versus late-onset years (6)

		Monsoon cropping season rainfall, median values			
No. years	Onset period	Onset (date)	Amount (mm)	Duration (days)	Intensity[a] (mm/days)
13	All, May 28–July 11	6-23	418	93	4.20
7	Early, to June 23	6-19	508	105	4.66
6	Late, June 24 on	7-04	306	84	3.45

[a]Intensity from actual data, not calculated from median amount duration.

1921–70 was 594 mm, and in the more recent 17 years of that period (1954–70) was 603 mm, it then fell to 504 mm in the 13-year period of 1971–83. The significance of this change is elaborated here.

There has been a general shift to later onset of the monsoon, of approximately 11 days, from a median date of June 12 in the pre-1971 period to June 23 thereafter. Compounding this problem is a slight tendency for earlier recession of the monsoon, from September 26 before 1971 to September 24 thereafter. These shifts have reduced the median rainy period duration from 107 days before 1971 to 93 days in recent years. The relative drop in rainfall amount for cropping has been greater, with median values of intensity falling sharply, from 5.16 mm/day before 1971 to 4.20 mm/day thereafter.

The effects of the climatic change on early-onset seasons is important, but not dramatic. In the present period, onset is a bit later, resulting in a reduction in rainy period duration of 1 week (median), from 112 to 105 days. There has been a corresponding and relatively larger reduction in cropping season rainfall amount from 603 mm to 508 mm, which has reduced median intensity from 5.16 mm/day to 4.66 mm/day.

Late-onset seasons have suffered much more from the climatic change, not simply in relative terms but in absolute reduction in rainfall amount. Prior to 1971, late seasons tended to be like early seasons, except greatly shortened. The result was a short season with daily rainfall (average) greater than that in early seasons. Now the situation is much different. In the period from 1971 onward, late seasons have been somewhat earlier in onset and, therefore, of somewhat longer duration than before, but the total rainfall and average intensity have declined catastrophically. Median late-season rainfall amount used to be 480 mm but now is only 306 mm. The average intensity was formerly 5.44 mm/day and is presently only 3.45 mm/day. These facts mean that the traditional ways of farming in late seasons require radical change, just for the sake of survival. Because the traditions have been developed in the better rainfall period from

1922 to 1970, the need presently is to provide farmers with the rainfall information and ways to deal with it—particularly in seasons that start late.

In Figure 10 the first thing to notice is that the years before 1971 and the more recent years all fall nicely into the same pattern—unlike Figure 9, where they effectively form two different flags (albeit overlapping). This reflects the fact that the changes, that took place at Niamey in 1971 were in the amount of rainfall and the onset dates, but not significantly in the final rain dates. Figure 9 shows the change in amount of rainfall relative to onset date. Figure 10 shows that onset dates since 1971, except for two in May, are clustered in the late, middle period from June 11 to July 11. Pre-1971 onsets tend to cluster both earlier and later than that, from June 1 to 12 and from July 6 to 21, with only one of the 17 years between (on June 20). Whether or not the new tendency for onset to occur in the mid-June to early July period will persist remains to be seen, because it is not clear whether it is simple coincidence or has some physical cause.

b. Bouza, Niger

The second location discussed in more detail, is Bouza, Niger—more northerly than Niamey and, therefore, closer to the Sahara Desert and drier. At Bouza the impact of the climatic shift at the start of the 1970s was greater than at Niamey, absolutely as well as relatively. Figure 12 shows a still more startling separation than that shown in Figure 9 for Niamey—more nearly complete and of greater magnitude. As at Niamey, the Bouza rainfall flags show that rainfall amount declines with later onset. But the lower shaded area, labeled "Today's Flag," shows that the reduction in expected rainfall (compared to 1954–70) with any given date of onset is severe, ranging from approximately 160 mm with the earliest onset (June 12) to about 170 mm with the latest onset (August 16) for an average of 165 mm.

There are three important differences between Figure 12 and Figure 9. First, the range of dates of onset in Figure 12 (Bouza) is from June 12 to August 16, markedly later than that at Niamey on average. However, onset has been earlier at Bouza in some individual years. Second, the scales showing approximate monsoon cropping season duration at the top and bottom of the figure are not identical. The lower scale, representing "today's" situation, shows that the rainy period duration associated with any given date of onset has decreased by about 10 days compared with the pre-1971 situation. More detail on this will come with discussion of Figure 13. Third, Figure 12 shows that 1974 was an exception at Bouza, with high rainfall, near the top of the former pattern. In practical terms, this is of little consequence because it stands alone. However, if it happens in several years, reevaluation of the situation would be in order.

Figure 13 shows the rainfall duration flag for Bouza, equivalent to that seen in Figure 10 for Niamey. But again there are noteworthy differences. First, the duration of rains at Bouza is much less than at Niamey, ranging from about 20 to 100 days, versus approximately 70 to 150 days at the latter. The average is about 50 days longer at Niamey. Second, the lower shaded portion of Figure 13 shows that the climatic shift of 1971 strongly affected season duration.

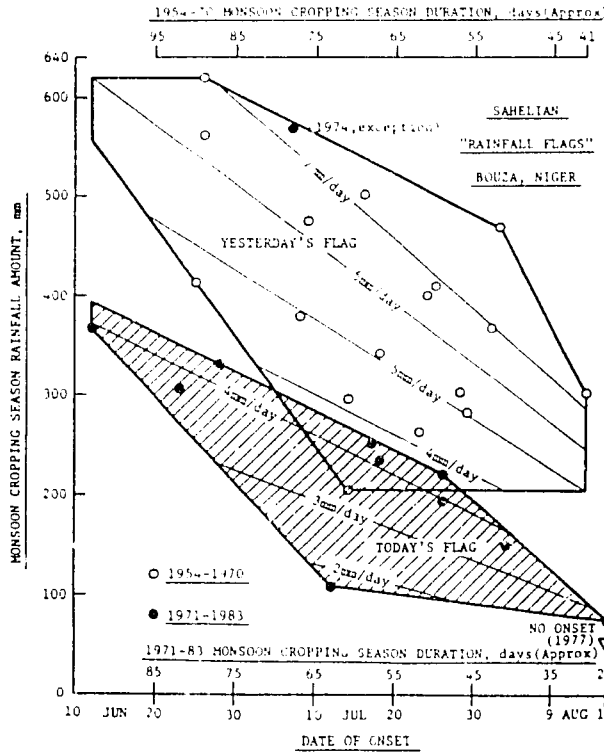


Figure 12. Two rainfall flags over Bouza, Niger. The upper flag shows how the monsoon season rainfall amount, duration, and intensity related to the date of onset prior to 1971. The lower flag (shaded) shows the effects of the climatic shift in subsequent years.

Until 1970, data from all years at Bouza were in the upper clear portion of the flag, meaning the expected duration is greater. Since 1971, of the total of 12 years (1971-83, with 1982 missing), 8 years have formed a completely different and poorer pattern (shaded) including one year with no onset at all (1977). The other 4 years remain in the pre-1971 pattern. The practical meaning of this is that since 1971, in 2 out of every 3 years, the monsoon has withdrawn from the area approximately 10 days earlier on average than previously.

It is the earlier recession of the monsoon at Bouza that required two different duration scales for "yesterday's" versus "today's" flags in Figure 12. This shift is also responsible for there being two lines in the figure labeled 4 mm/day intensity. And with reference to rainfall intensities, note that they ranged mostly from 4 to 7 mm/day, comparable to that of Niamey before 1971, after which they have ranged from 2 to 4 mm/day, much less than at Niamey, and, as previously indicated, over a much shorter season.

The inescapable conclusion is that although Bouza was at least a marginal crop production area before 1971, it is no longer suited to that usage. If crops are

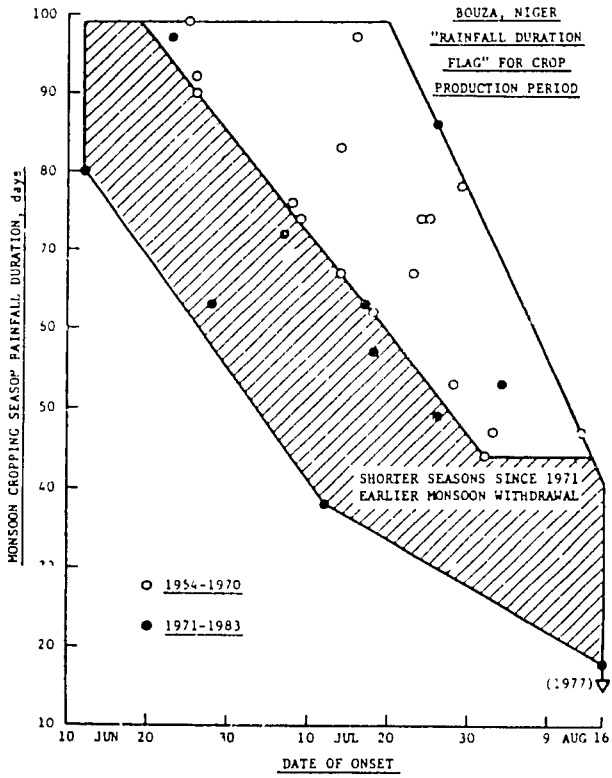


Figure 13. Duration of the monsoon rainy period for crop production, as related to date of onset at Bouza, Niger. The shaded area shows the climatic shift since 1971, manifested by earlier recession of the monsoon (Bouza, Niger, 1954-1983.)

attempted in today's rainfall conditions, only those grown in seasons with onset by mid-July offer any reasonable hope of satisfactory production.

c. Senegal, Mali, Burkina Faso, and Niger

Column 4 in Table 4 shows mean rainfall from 1971 onward at 10 of the 11 locations for which data are available at this writing—plus an estimate for the remaining one (see footnote of table). These are limited data with different numbers of years at different sites. The post-1970 rainfall means are not offered as precise values, but simply as representative of the situation now being faced by farmers of the region. As more data become available, improved analyses will be made.

Table 8 shows estimates of mean annual rainfall at each parallel both before 1971 and from 1971 onward. Rainfall figures used in the analyses are those shown earlier in Table 4. The estimates of rainfall in columns 2 and 3 of Table 8

Table 8. Generalized values for monsoon cropping season onset date and mean annual rainfall amounts for latitudes 11° to 17°N in Burkina Faso, Niger, eastern Mali, and the northernmost area of Senegal[a]

Latitude North (degrees)	Estimated pre-1971	Rainfall (mm) 1971 onward	% Reduction 1971 onward	Estimated onset dates Earliest	50%	Latest
17	177	32	81.9	7-04	8-16	9-16
16	310	182	41.3	6-21	7-31	9-03
15	444	331	25.5	6-08	7-15	8-20
14	577	481	15.1	5-26	6-30	8-07
13	711	630	11.4	5-13	6-14	7-24
12	844	780	7.6	4-30	5-29	7-11
11	977	929	4.9	4-17	5-14	6-27

[a]Rainfall amounts are shown to 1970 and from 1971 onward, with percentage reductions of the latter.

were in turn used to estimate the percentages by which rainfall has been reduced in this region in the years from 1971 onward.

The estimates of percentage reduction in rainfall in column 4 of Table 8 do not form a linear function with latitude, as do rainfall amounts and dates of onset. Instead, we see small reductions of 10% or less in the wetter southern areas, becoming ever greater percentagewise (and also in absolute rainfall amount) as one proceeds to the drier northern latitudes. Detailed examples of this phenomenon were discussed earlier for Niamey and Bouza, at latitudes 13° 29′ N and 14° 25′ N respectively. Niamey rainfall has fallen from 603 mm before 1971 to 504 mm thereafter—a drop of 99 mm, or 16.4%. Bouza started at 489 mm and fell to 313 mm—a drop of 176 mm, or 36%.

Another interesting phenomenon is that the r^2 values for the onset versus season rainfall amount relationship have increased markedly since 1971 at five of the six locations where data are available. The recent mean is 0.51 whereas the pre-1971 mean was 0.24.

V. Botswana SAT

Botswana is a land-locked country situated in southern Africa. It has experienced food deficits in the recent past. Major improvements in agricultural management in Botswana are required to increase its production. During the period 1979 to 1984, the average farmer's yield for sorghum was 175 kg/ha. Even large commercial farms frequently record yields less than 500 kg/ha. The low productivity is a result of physical, biological, and economic factors. In the traditional agricultural system, there is little or no application of chemicals or hybrid seed. Because of the low and variable rainfall, water availability is the limiting resource; therefore, the farmer is not willing to risk the additional expense of fertilizer and chemicals. Development of on-farm water resources for securing adequate water

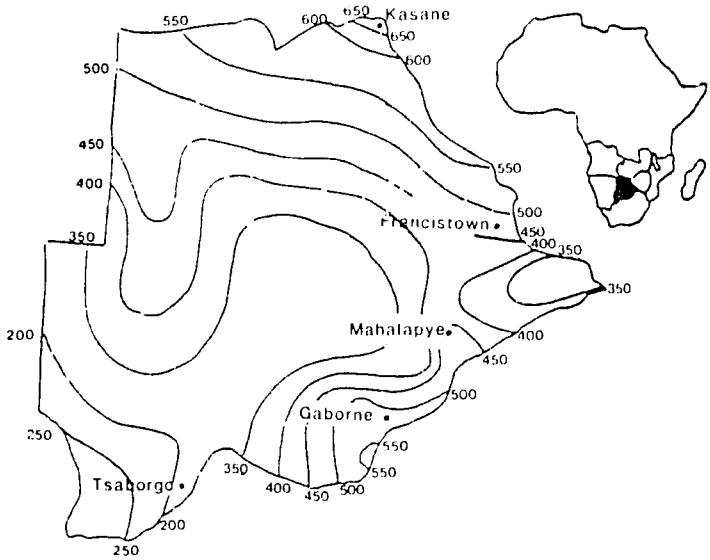


Figure 14. Location of the selected Botswana rainfall stations used in this chapter, and the mean annual rainfall in Botswana.

availability during the growing season has been identified as one of the key factors to increased agricultural production.

The annual rainfall in Botswana is 650 mm in the north to 250 mm in the southwest (Fig. 14). In general, 90% of the rainfall is received in the period October to April. The rainy season is November to January. The rainfall is unimodal with a peak during January. Thus the climate borders on being arid subtropical. However, the Botswana climate and agriculture provide an illustration of an agroclimatological approach to dryland agriculture.

To illustrate the moisture and thermal regimes of Botswana, Virmani (1985) studied the agrometeorological features of two contrasting locations to evaluate variability of rainfall and the thermal regime. Mahalapye is located in eastern Botswana with a mean annual rainfall of about 500 mm, while Tsabong is located in southern Botswana with a mean annual rainfall slightly above 250 mm. At Mahalapye the rainy, pre- and postrainy, and dry seasons are well defined. The rainy season extends from November to March. During this period, in terms of thermal regime, some 400 thermal units are accumulated.

The data for Tsabong showed that the rainy season there was not well-defined. The rainfall has a tendency toward bimodality, with the first peak in December and the second in February. However, the amount of rainfall received in any of the months is less than 50 mm which meets only a fraction of the PE needs.

Virmani's analysis based on the rainfall and thermal regimes of about 30 locations of Botswana have indicated that areas receiving above 400 mm mean annual rainfall follow the trend of rainfall distribution and temperatures exhibited by

Mahalapye station, and areas receiving less than 400 mm mean annual rainfall exhibit rainfall and thermal characteristics as those of Tsabong.

A. Crop Production Potential of Different Regions of Botswana

1. High Potential Areas

This region is located in northern Botswana with mean annual rainfall of at least 550 mm. To estimate potential for productivity, a sorghum yield model (SORGF) was run using climatic data of Kasane. It showed that under medium management conditions (adequate fertilization, 60,000 to 70,000 plants/ha) sorghum yields in excess of 4 tons/ha can be achieved in 5 years out of every 10 in this agroecological zone. Three years in every 10 years will record a crop failure (less than 500 kg/ha), while in 2 years out of every 10 the sorghum yields may be around 1000 to 2000 kg/ha.

The results also showed that for a 120- to 130-day sorghum cultivar the drought stress in deep soils of the region is likely to be encountered at the GS3 stage, whereas in the shallow soils, it will be encountered at both GS2 and GS3 stages. Maize is likely to do well in deeper/fertile soils. In terms of moisture conservation and crop management agronomic research, the following are some agenda points for research:

1. Increased emphasis on in situ soil moisture conservation through efficient weed control, deep ploughing, stubble-mulch farming, micro-watershed water harvesting by growing crops on ridges, and establishment of key lines for providing a reference point for farmers to follow contour cultivation.
2. Intercropping of maize and sorghum may be tried in soils with high (150 mm) moisture storage capacity, and intercropping of millet and sorghum in soils with medium (100 mm) moisture storage capacity.
3. Adequate fertilization with nitrogen and phosphorus is essential to optimize rainfall use efficiency. Research on split application of nitrogen fertilizer and basal application of P in relation to crop phenology and soil moisture is essential.

2. Medium Potential Areas

This region of Botswana receives between 400 and 550 mm of annual rainfall. Two main soils predominate in this region, the Aeronosols in the west and the Alfisols in the east. Since the water-holding capacities of these soils are quite different, the issues related to crop production in this region varies with the soil type. We are therefore presenting the agenda points for improved soil moisture conservation separately for the two soil groups:

1. Aeronosol areas: In this region, our model simulation results for crops show that the probability of harvesting a crop of sorghum yielding over 1000 kg/ha under adequate management conditions is 1 in every 3 years. The risks to dependable crop production are high. In addition, in situ soil moisture conserva-

tion is not likely to be of much help because of the low moisture-holding capacity of the soil. The yields in drylands can be stabilized by providing irrigation.

2. Alfisol areas: In the Alfisol region which is located in the Francistown-Mahalapye-Gaborone transect of eastern Botswana, application of improved land and water management techniques is likely to help stabilize and increase crop production. In the current dryland farming system, it is possible to mature a sorghum crop in 3 or 4 years out of every 10. Following are some suggestions for improved dryland farming:

a. In soils with 150 mm of available water storage capacity in the root profile, zonal water harvesting systems may be tried. Such a practice has been successful in stabilizing yields of millet crop at Bellary station of the All India Coordinated Dryland Agriculture Research Project of the Indian Council of Agriculture Research (Randhawa and Venkateswarlu, 1987).

b. A watershed-based water harvesting/recycling system that has been developed at ICRISAT in Hyderabad, India, may prove useful for stabilizing dryland production. Part (30 to 50%) of the watershed can be left bare or uncultivated. This uncultivated land is treated to encourage runoff which could be stored in a reservoir. The stored water could be applied to the cultivated area of the watershed. Our simulation results showed that using Mahalapye climatic data that moisture from rainfall plus irrigation from the reservoir would be adequate to successfully mature a sorghum crop for 6 to 7 years in every 10. Under adequate fertilization and with proper agronomic management yields in excess of 3000 kg/ha could be expected. There would be 2 to 3 years in every 10 when the rainfall would be too meager to mature a crop of sorghum. Under this system water will have to be lifted out of the reservoir and applied uniformly over the cultivated area.

3. Low Potential Area

A very large part of Botswana (about 50% of the total area of the country) where rainfall is 400 mm or less forms a low crop production region of the country. It is not suitable for arable farming. Pasture-based programs should be developed in this region.

B. The Relationship Between Onset of Rains Versus Season Duration and Rainfall Amount

We selected the three locations (Francistown, Mahalapye, and Gaborone) to evaluate the relationships between onset of the growing season versus the duration of growing season and onset versus growing season rainfall amount, using the same definitions used for the Sahelian analysis. The three locations have about the same mean annual rainfall (see Fig. 14).

The results of the analysis are shown in Table 9. In the regression equations, the day of year should be used to calculate expected duration and amount. If the onset is so late that it falls in the beginning of the next year, then the day of year + 365

Table 9. Regression equations showing how monsoon cropping season rainfall amount and duration relate to the date of onset. Three locations in Botswana, described in Figure 15

	Gaborone	Francistown	Mahalapya
Number of years	30	49	53
Mean onset (Julian date)	321	338	333
Duration			
$R2^a$	0.15	0.82	0.78
$a1$	346	536	432
$b1$	0.67	1.24	0.91
Mean (days)	130	118	127
Amount			
$R2$	0.09	0.25	0.31
$a2$	973	1485	1147
$b2$	1.76	3.25	2.28
Mean (mm)	407	386	348

[a] $R2$ = coefficient of variation.

should be used. For example, one year in Francistown the onset is on January 15. The expected duration equals $a1 - b1*(15 + 365) = 536 - 1.24*380 = 65$ days.

The correlations seem to be as useful as in the Sahel, because for both onset versus duration and onset versus amount the r^2 values are about the same magnitude. Even Gaborone is not as hopeless as it looks. When two extremely abnormal years (1957 and 1959) of the 30 years are left out of the regression analysis, the r^2 for the onset-duration correlation increases to .76 and for the onset-amount correlation to .25!

In Botswana, the rainfall is less concentrated in the rainy season than it is in the Sahel. A larger percentage of the rain falls outside the rainy season. In addition, the season duration is significantly longer, compared to Sahelian locations with about the same mean annual rainfall, like Bouza and Dori. Thus, the season rainfall intensity (= amount/duration) in Botswana is rather low. This suggests that long dry spells have a higher probability of occurrence and that the growing season, although longer, will be less reliable.

VI. Summary and Conclusions

A. Role of Agroclimatic Studies

The studies reported in this chapter improve our understanding of the agroclimatic environment, and summarize the state of the knowledge on the subject. They also provide broad indications of directions of interventions for growth and stability of agriculture in this agroclimatic region. However, they relate to some

selected locations, and it is important to extend such studies, to cover larger areas and a greater variety of farming systems in the SAT.

The logical and practical means to facilitate the agroclimatic approaches requires the development of both hardware and software, as well as an expanded data base. The prospects for achieving this now appear quite encouraging. In Sahelian Africa great international effort is expended in collecting weather data and monitoring crop conditions and warning of food shortage. Remotely sensed data, especially by aircraft, would provide important information. In India, the government is giving major emphasis to computerization of agricultural information systems, which contain rainfall data for more than 350 locations, information on soils for different regions, data on crop and resource-centered technologies available with central and regional research/development organizations, and information from farm surveys. In the section on Indian study we have therefore emphasized interyear and intrayear variations in rainfall for understanding the need for and direction of introducing greater flexibility in cropping strategies for improved crop production. New farming systems based on agroforestry or agropastoral systems are suggested in areas of high risk of droughts to cope with rainfall variability.

B. Sub-Saharan Agriculture

In this region early warning of weather conditions is critical because the growing season is very short and most of the cropping is done by several farmers with limited means producing staple cereal (millet) of low value. This chapter describes a new methodology termed "Response Farming." It is based on rainfall records of several Sahelian stations. The potential for its application in the Sahelian and Sudan bioclimatic regions is evaluated. The farm manager makes a series of decisions throughout the season from planting, fertilization, thinning, cultivation, weeding, and harvest. With an expectancy of the rainfall pattern, he can make decisions as to the crop, planting density, and fertilization that will optimize his economic output.

The attempt has been made to predict essential characteristics of the approaching monsoon season and to match crop decisions, farm practices, and levels of inputs to expected rainfall. The key point is that an early onset of the rainy season means a longer growing season and a higher total amount of rainfall, whereas delayed onset of the rainy season means a shorter growing season and less than average rainfall. Sivakumar (1988) suggests that by a careful choice of crops (e.g., millet gives high yields in years when planting is delayed) the crop yields can be increased and stabilized.

Since about 1970 the rainfall has dropped considerably in the Sahel, most dramatically in the northern parts.

C. Botswana

The agroclimatic analyses presented here delineate areas of high, medium, and low productivity. Suggestions for testing various improved land, water, and crop

management practices for increasing and stabilizing agricultural production are discussed. The agroclimatic survey shows that about half the country is not suitable for arable agriculture. The concept of advance prediction of growing season duration and seasonal rainfall amount from the date of onset of the rainy season has been tested for Botswana. The analysis show that here too, as in the Sahel, the date of onset of the growing season could be used for predicting the expected length of the growing season.

D. Outlook for Future

Current indications are that in the semiarid areas the rainfall variability is on the increase. This would lead to changes in the length and the quality of the growing season. The improved farming systems of the future would have to be more flexible and broad-based. The research available today shows that in the Indian SAT, food production can be increased through improved technology. The agronomist and the agroclimatologist will have to work together to make strategic and tactical decisions for the farmer for adopting cropping systems and crop management practices as of the onset and progress of the rainy season. The results of application of improved practices in the farmers' fields managed by researchers have consistently showed that crop yields of major rainfed cereals and grain legumes can be easily increased to 1500 to 2000 kg/ha against their average yield of 300 to 800 kg/ha.

In Africa food production increases in the next decade may come mainly by increasing land area under cultivation. However, the situation in the Sahel and other SAT areas of West Africa is less promising. Finally, it should be mentioned that the productivity of traditional agriculture is declining, and that the threat of serious food shortages is rising in the rainfed semiarid tropics, but potential for increased food production does exist. By properly evaluating the agroclimatic resources and transferring and adapting improved technologies, the yet underexploited potential of semiarid tropical regions can be realized for sustained and improved agriculture.

References

Hargreaves, G.H., and Zohrab A. Samani. 1986. World water for agriculture—precipitation management. International Irrigation Center, Department of Agricultural and irrigation Engineering Center, Utah State University.

Huda, A.K.S., and S.M. Virmani. 1987. Effects of variations in climate and soil water on agricultural productivity. In Parry M.L. et al., eds. The impact of Climatic Variations on Agriculture. Dordrecht, The Netherlands: Reidel.

Randhawa, N.S., and Venkateswarlu. 1987. Farming system research: Indian experience. *In* Proc. of Internatl. Agric. Res. Centers Workshop on Farming System Research, 17-21 Feb. 1986, ICRISAT Center, India. Patancheru, pp. 110-112. A.P. 502324. India: Internatl. Crop Res. Institute for Semiarid Tropics.

Robertson, G.W. 1976. Dry and wet spells. UNDP/FAO Tun Razah Agriculture Research Centre, Sungh: Tekam, Malaysia, Project field Report, Agrometerology A-6.

Sivakumar, M.V.K. 1988. Predicting rainy season potential from onset of rains in the Southern Sahelian and Sudanian climatic zones of West Africa. Agri. For. Meteorol. 42:295–305.

Stewart, J. Ian. 1987. Potential for response farming in sub-Saharan Africa. Proceedings, INRAN-ICRISAT-TROPSOILS-USAID-USDA Workshop on soil and water management systems for rainfed agriculture in the Sudano-Sahelian zone, Niamey, Niger. January 11–16, 1987.

Troll, C. 1965. Seasonal climates of the earth. *In* Rodenwaldt, E. and H.J. Jusatz, eds. World Maps of Climatology, 2nd ed. pp. 2–25. Berlin: Springer-Verlag.

Virmani, S.M. 1985. Agroclimatic assessment of Botswana: An agenda for dryland farming research. Mimeo (for limited circulation). p. 22. ICRISAT, Patancheru, A.P., 502 324, India.

Virmani, S.M., M.V.K. Sivakumar, and S.J. Reddy. 1982. Rainfall probability estimates for selected locations in semi-arid India, 2nd enlarged ed., Research Bulletin No. 1, ICRISAT, Patancheru, A.P. 502 324, India.

An Economic Analysis of Farm Management Practices and Improved Technologies in the Sahel*

J.C. Day, W.R. Butcher, and D.W. Hughes

I. Introduction 311
II. Farming Conditions in Mali 313
A. Land Use 313
B. Soils 313
C. Climate and Weather 313
D. Farming Practices 316
III. Technological Options for Dryland Farming 318
IV. Soil, Water, and Crop Management Case Studies 319
A. The Typical Rainfed Farming System 320
B. Rainfall, Soil Moisture, and Crop Yields 320
C. Soil Erosion and Declining Productivity 323
D. Management Strategies Examined 324
V. Case Study Results 325
VI. Conclusions 328
Appendix 329
References 330

I. Introduction

The seven West African countries of the Sahel (Senegal, Gambia, Mauritania, Mali, Burkina Faso, Niger, and Chad) are among the poorest in the world. In these countries, per capita income in 1981 averaged just over $300 (U.S. dollars), food intake was below the minimum requirements, falling as low as 1500 calories

*This research is supported by the U.S. Agency for International Development, Science and Technology Bureau, Technology of Soil Moisture Management Project (TSMM) under USDA PASA No. BST-4021-P-AG 108D-00.

1990 by Springer-Verlag New York Inc.
Advances in Soil Science, Volume 13

Preceding Page Blank

Table 1. Average annual growth rates, 1962–1983 (%): Cropped area, yield per hectare, and per-capita production of the principal food crops for the Sahel Region and selected countries

Country and commodity	Cropped area	Yield per hectare	Per-capita production
Sahel region	−0.3	−1.3	−1.6
Mali			
Maize	−1.01	−2.46	−3.47
Rice	−0.27	0.32	0.05
Millet	0.28	−1.96	−1.68
Niger			
Sorghum	4.18	−1.89	2.29
Rice	5.15	−1.38	3.77
Millet	3.51	−1.56	1.95
Senegal			
Rice	−1.83	−0.50	−2.33
Millete	−0.85	1.67	0.82

Source: Jayne et al., 1989.

per day in some locations, and life expectancy was about 44 years (FAO, 1986a; MacDonald, 1986). The GNP growth rate for the region during the 1960–81 period was essentially zero (MacDonald, 1986).

Agriculture is the dominant economic sector in the Sahel, supporting roughly 80 to 90% of the present population (World Bank, 1985). About 80% of the total land area is located in arid and semiarid zones where annual rainfall is less than 25 inches and over 98% of all cultivation is carried out under strictly rainfed conditions (World Bank, 1985; FAO, 1985; MacDonald, 1986).

Total food grain production in the region grew by approximately 1% per year from 1970 to 1984, predominantly because of cultivated area expansion; however, yield per hectare generally fell. During this same period population growth rates in the various countries ranged between 2 and 3% with the result that production per capita also declined (Table 1). Average grain yields are very low: 400 to 700 kg per hectare compared with 2000 to 4000 kg per hectare in developed regions (FAO, 1985). If current trends continue, the carrying capacity of the land in the year 2000 will be exceeded by about 30 million people (World Bank, 1985).

Given the limited potential for large gains in output from the irrigated sector (Biswas, 1986a) and the difficulty of attaining dramatic reduction of population growth in traditional societies, the rainfed systems of the Sahel must achieve sustained increases in productivity and production for positive changes in general well-being to take place.

A number of factors (biological, environmental, managerial, and socioeconomic) are responsible for the low agricultural productivity. Among the most important are adverse climatic conditions and poor soils (Sivakumar, 1988). In this study we evaluate several improved soil, water, and crop management strate-

Table 2. Land use in Mali and the Sahel (m/ha)

Region	Total land area	Arable cropland[a]	Permanent pasture	Forest woodland	Other land[b]	Irrigated land[c]
Mali	122.0	2.0	30.0	9.0	81.0	.1
		(1.6)[d]	(24.6)	(7.4)	(66.4)	(neg)
Sahel	525.2	16.9	139.3	59.9	308.9	.4
		(3.2)	(26.5)	(11.4)	(58.8)	(neg)

Source: FAO, 1984.
[a] Arable cropland is land under cultivation, including tree crops.
[b] Other land is unused land, wasteland, and barren land.
[c] Irrigated land area is also included in other land-use categories.
[d] Figures in parentheses are percentages.

gies in the context of a typical farming situation in Mali. The objective is to estimate potential farm income, production, and resource conservation impacts of innovative farming practices. Given the similarity between conditions in Mali and other Sahelian countries, the results of the analysis are relevant to those locations as well.

II. Farming Conditions in Mali

A. Land Use

Only a very small proportion of the total land area of Mali (1.6%) is used for the cultivation of crops (Table 2). On the other hand, a relatively large share (32%) is devoted to permanent pasture, range, or woodlots. The largest share (66.4%) is land generally unsuited to food and fiber production. Irrigated land is a minor component in the total land use picture. This distribution of land use, very much the same for the Sahel as a whole, is largely due to the nature of the soil resources and the rainfall patterns of the area.

B. Soils

As in West Africa generally, Malienne soils are diverse and soil types are widely scattered. Within arable regions the predominant soils are Alfisols (32%), Entisols (28%), Aridosols (16%), and Ultisols (10%) (TAMS, 1983). The balance are stony, gravelly, and lateritic soils. All soils are highly weathered and of low inherent fertility. Organic matter is generally lacking, and soils are deficient in natural nitrogen, phosphorus, and sulfur. Acidity and aluminum toxicity are common problems. Weak soil structure and the presence of clay in many soils leads to crusting, compaction, and sealing during and following rains. The combination of soil crusting and intense storms typical of the rainy season cause high runoff and low infiltration. Water-holding capacities are low, particularly in the deep sandy soils so prevalent in much of the country. Water erosion on steeper slopes, wind erosion, and sand encroachment are common problems.

Table 3. Land distribution by climatic zones, Mali and Sahel

Region	Saharan Sahelo-Saharan (<NLC)(%)[a]	Sahelo-Sudanean and Sudanean (NLC – 800 mm)(%)	Sudano-Guinian (>800 mm)(%)	Total land area (million ha)
Mali	66.7	20.8	12.5	122.0
Sahel	66.4	26.1	7.5	525.2

Source: World Bank, 1985.
[a] NLC is the northern limit where rainfall is sufficient for crop cultivation, that is, about 300 mm.

C. Climate and Weather

Two-thirds of the country receives insufficient rainfall for crop production (Table 3). In the remaining area, over 99% depends on rainfall as its source of moisture. The spatial distribution of mean rainy-season precipitation in Mali is shown in Figure 1.

Climatological studies have shown a continuous decline in total annual rainfall since the 1950s (Fig. 2). Droughts are common. The most recent case, extending from the late 1960s to the early 1980s, was a severe, but not an unusual, occur-

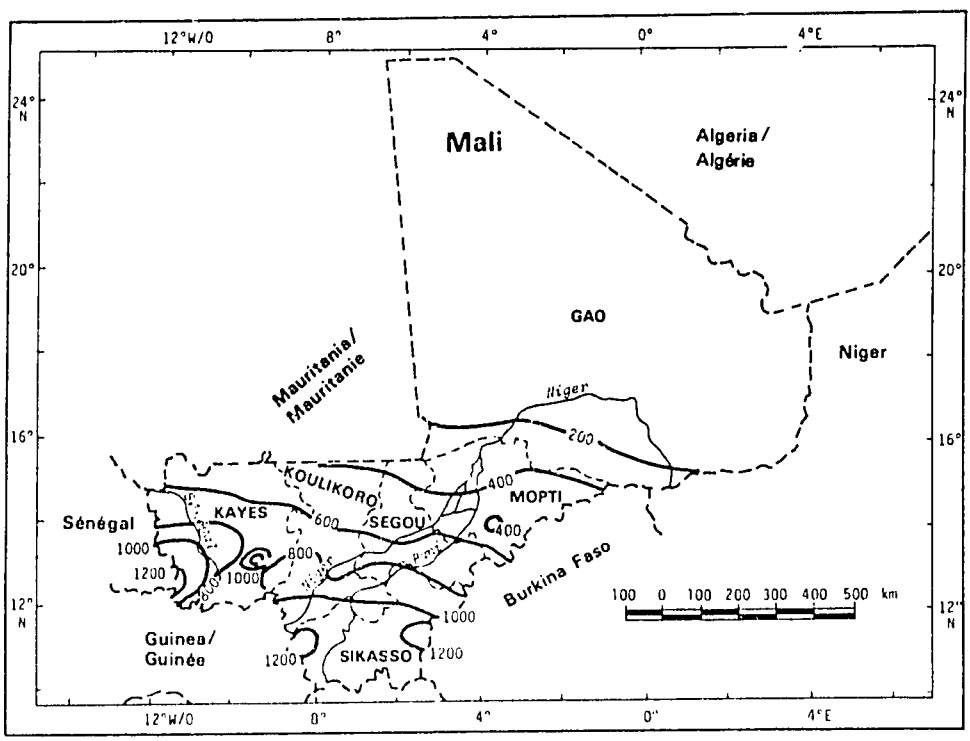


Figure 1. Spatial distribution of mean rainfall, rainy season, Mali. (From Sivakumar et al., 1984.)

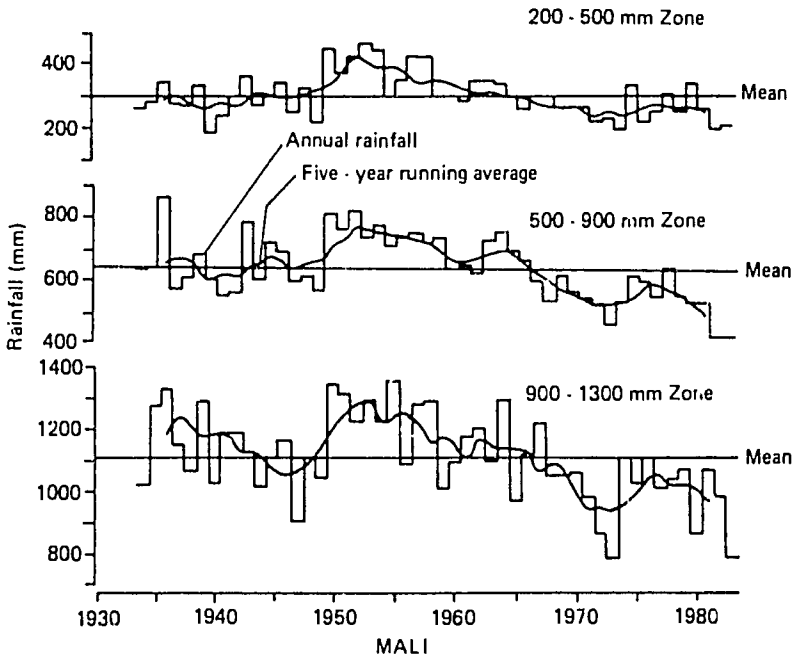


Figure 2. Annual rainfall, five-year running average and mean annual for last 50 years, Mali. (From Biswas, 1986b.)

rence in the long-term weather record. Of major significance is the year-to-year variability in rainfall that exists all across the country: coefficients of variation in total annual rainfall for 81 weather stations (30 to 70 years of record) range from 20 to as high as 50% (Sivakumar et al., 1984).

As in other Sahelian countries, rainfall in Mali is also highly variable in terms of date of onset and length of rainy season (Table 4). Rainy seasons generally begin in late spring–early summer and last 2 to 3 months in the north and 4 to 5 months in the south. Late onset is highly correlated with short rainy seasons and low total seasonal precipitation. The use of crop cultivars with short growing season requirements can be an effective response to late onset of rain (Stewart, 1987; Sivakumar, 1988).

Table 4. Mean annual rainfall and variation in onset, three locations in Mali

Location	North latitude	Mean annual rainfall (mm) to 1970	Mean annual rainfall (mm) from 1971	Range of onset dates Earliest	Range of onset dates Median	Range of onset dates Latest
Ansongo	15°40′	334	214	6/02	7/27	8/27
Kayes	14°26′	749	546	5/21	6/23	7/28
Kolokani	13°35′	848	742	5/11	6/20	8/09

Source: Kanemasu et al. (Chapter 14 of this publication).

Year-round high temperatures and solar radiation levels exacerbate the low rainfall situation. Elevated temperatures, coupled with high solar radiation, means that potential crop water use (potential evaporation) is high and often exceeds rainfall at critical times during the growing season (Table 5). Whenever potential crop water use exceeds precipitation, optimum plant growth is not achieved because of water stress. Low infiltration rates and low soil water-holding capacity make the already poor crop water demand-rainfall situation even worse.

D. Farming Practices

Malienne farmers tend to rely on local cereal varieties tolerant of low moisture, low nutrient levels, and high pest infestations. But the traditional varieties are also of low productivity under good or even average weather conditions and are generally less responsive to higher input levels than improved cultivars (Matlon, 1986). Eighty-five percent of all cultivated land is in food grains, primarily sorghum, millet, maize, and rice. These cultivars tend to be long-season varieties. Planting occurs in late May, June, or early July depending on location, and takes place only after sufficient rain (about 40 mm) has fallen to provide enough moisture in the upper soil profile to ensure seed germination. False starts in the rainy season may mean that farmers lose their initial planting and must reseed; hence farmers tend to plant late rather than early.

Fertilizer and manure applications are too small to replace nutrients withdrawn through crop growth, and long rejuvenating bush fallow is being shortened or eliminated altogether because of land use pressure. Erosion of topsoil and failure to return organic matter contributes further to soil deterioration. Many of the tillage, cultivation, and harvesting operations are done manually. Crusting makes it difficult to work the soil and land preparation must wait until early rains soften the ground. The need to both till and plant as soon as possible after the rains begin creates special demands on labor that may delay the planting. Labor is usually in short supply not only during planting/land preparation, but also during weeding and harvest periods.

Farm prices are typically low relative to production costs, and can fluctuate widely depending on the size of the harvest, which in turn is a function of rainfall. Marketing channels for both farm inputs and outputs are poorly developed except in scattered areas and for state-supported cotton and groundnut production. Producing for home consumption is a primary objective, and farmers are reluctant to risk scarce capital and needed food supplies on new and costly practices with uncertain returns.

Of all the difficulties farmers face, the generally low and always unpredictable rainfall is probably the most serious. Farmers cannot be certain when first rains will occur or when there will be sufficient moisture in the soil for land preparation, planting, and seed germination. Likewise, they cannot be sure of the amount of rain they will receive for the season nor its distribution throughout the season. Coping with the rainfall situation is, therefore, a fundamental concern to

Table 5. Climate in selected locations in Mali, average conditions over 37 years

Station	Mean monthly data													Mean annual PET[a]	Mean annual temperature
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	12-month total		
	Millimeters														
Mopti:															
Rain	0	0	0	3	24	61	139	169	95	24	0	0	515	NA	NA
PET[a]	152	166	215	220	224	199	177	154	147	159	157	140	NA	2,151	NA
Sikasso:															
Rain	1	3	15	45	106	152	253	326	217	84	19	4	1,225	NA	NA
PET[a]	173	177	211	192	185	163	152	142	147	163	164	165	NA	2,003	NA
Tessalit:															
Rain	1	0	1	0	2	7	23	55	27	1	1	0	118	NA	NA
PET[a]	114	126	181	205	234	236	237	227	201	173	131	103	NA	2,774	NA
	Degrees Celsius														
Temperature:															
Mopti	32	35	38	40	40	38	34	32	32	34	35	31	NA	NA	27.8
Sikasso	34	36	38	37	36	33	31	30	31	33	34	33	NA	NA	27.2
Tessalit	27	30	34	37	41	43	42	40	40	38	33	26	NA	NA	28.6

NA = Not applicable.
[a]PET = Potential evapotranspiration.
Source: Hargreaves and Samani, 1986.

Table 6. Strategies to overcome major limitations in production of sorghum and millet

Limitation	Strategy
Crop establishment	Planting technique, timely planting, superior varieties
Nutrient stress	Timely planting, fertilizers, rotations, weed control, efficient varieties
Moisture stress	Timely planting, appropriate plant densities, mixed cropping, weed control, efficient varieties, soil erosion control, water conservation
Pests/diseases	Seed treatment, insecticides/pesticides, good husbandry, genetic resistance, rotations
Birds	Uniform maturity, short plant height, tannins/pearling (sorghum)
Postharvest losses	Good storage techniques, rodent/insect control
Market stability	Government policies, support prices, infrastructure

Source: D.J. Andrews et al., 1984.

farmers and a paramount concern for researchers, extension workers, and policy officials searching for ways to help these farmers.

III. Technological Options for Dryland Farming

Strategies do exist to increase agricultural productivity in the Sahel (Table 6). Soil and water conservation measures that enhance productivity include bunds, microcatchment basins, mulching, small-scale soil erosion and runoff retention devices (diguettes), and tied-ridges, that is, ridges with cross-ties to form furrow dikes. Other productivity-increasing technologies include chemical and organic fertilizer, various conservation-oriented tillage and cultivation schemes with and without animal traction, and better crop selection and scheduling of crop calendars (Lal, 1987b; Steiner et al., 1988). Experimental research and on-farm trials indicate that crop yields can be increased with these methods.

Economic studies of soil and water management alternatives (Delgado and McIntire, 1982; Nicou and Charreau 1985; Roth and Sanders, 1984; Sanders et al., 1985) have shown that farm-level benefits of animal traction, chemical fertilizer, and tied ridges can be quite high. Gains of 50 to 70% in both farm income and food production have been reported. While either tied ridges or fertilizer can be economically profitable, when both are combined the interactive effect increases yield by more than the sum of the yields when the two techniques are used alone (Roth and Sanders, 1984). However, with insufficient soil moisture, fertilizer may not be profitable.

Traditional cereal cultivars in West Africa are becoming less satisfactory in the face of the tendency toward lower and more variable rainfall, shorter rainy seasons, and the extension of farming onto marginal land (Matlon, 1986). Breeding programs currently underway emphasize short-season varieties (ICRISAT, 1984), which allow farmers more flexibility in planting, replanting, intercrop-

ping, and relay-cropping rotations. However, variety selections must be made relative to other production practices and the seasonal rainfall pattern.

As Stewart (1987) and Sivakumar (1988) have shown, the amount of rain and the duration of the rainy season can be strongly correlated with date of onset. For that reason important farming decisions, such as planting date, varietal choice, and fertilizer applications, should be made in response to onset date and the early season pattern of rain. In a similar vein, Krause et al. (1987) demonstrate that significant economic benefits can be obtained by choosing appropriate plant densities in combination with sole-cropping, intercropping, and fertilization. Few if any published studies, however, have evaluated short-cycle versus long-cycle crops in combination with soil and water management options.

The literature review also revealed that economic research on technological innovations for the Sahel has addressed the rainfall variability issue mainly from the year-to-year perspective. Yet, as we have seen, the intraseasonal variation in rainfall is also very important. It is the intraseasonal pattern of rainfall (timing and amount) together with soil water infiltration rates and soil water-holding capacities that determine the amount of moisture actually available to crops at different stages of their growth cycles. For example, if infiltration rates are 40% of rainfall, and 20% of infiltration is lost to deep percolation, then no more than 32% of rainfall is available for plant use.

If the amount of moisture in the root zone during any particular stage in a plant's phenological growth process falls below water requirements during that same stage, yield will be reduced. Even if there is excess moisture in later stages, the loss in yield is not likely to be recovered. Adjusting planting dates and crop variety can bring water requirements more into line with water availability. This interaction between rainfall, timing of crop planting, and soil properties must be taken into account when evaluating soil, water, and crop management practices.

The principal conclusions from the literature review are that (1) appropriate combinations of soil, water, and crop management practices offer the best chance of improving productivity and income in the Sahel, and (2) evaluation of the economic feasibility of such measures requires the use of data and analytical methods that reflect both soil characteristics and weather-related variability within a crop growing season.

IV. Soil, Water, and Crop Management Case Studies

Farming systems research underway by the authors is focused on soil, water, and crop management technologies for dryland areas. A major objective in this work is to be able to produce more accurate estimates of farm-level impacts of improved resource management by better integration of soils, weather, agronomic, and economic information. To that end an analytical procedure combining soil water balance–crop yield response relationships and whole-farm economic models has been developed. This method was tested in case studies of one or two management options drawing on data from Mali (Butcher and Day,

Table 7. Farm characteristics

Agroclimatic zone	: Sudano-Guinean	Technology	: Traditional with no modern inputs
Rainfall zone	: 800–1000 mm	Home consumption	: Per capita – food grains 185 kg; vegetables 20 kg
Farm size	: 8 hectares	Crops	: Sorghum, millet, groundnut, maize, vegetables, rice, sorghum–groundnut intercropped
Family size	: 12 members		
Family labor pool	: 5 adults (FTE)		

Source: Flemming, 1981

1987; Day and Aillery, 1988; Day, 1988). This particular analysis uses the same basic methodology but examines a much wider range of options – soil moisture conservation, erosion control, short-season and long-season cultivars, alternative planting dates, animal traction, and fertilizers. The focus remains that of a typical nonirrigated farm in western Mali. The procedures followed and the results obtained in this latest case study are described in this section.

A. The Typical Rainfed Farming System

In 1978 and 1979, Fleming conducted a series of farm interviews on 55 farms in 9 villages in the Kita Region of western Mali (Fleming, 1981). These surveys generated information on farm family characteristics, farm size, input utilization, equipment complements, cropping patterns, crop calendars, and crop yields of farms in the area. The basic characteristics of a representative traditional farm are shown in Table 7. Published summaries of the farm surveys and other secondary information formed the data base for construction of a linear-programming model of the typical farm. A mathematical statement of the farm model appears in the Appendix.

B. Rainfall, Soil Moisture, and Crop Yields

The relationship between rainfall, soil moisture levels, and crop yield is a fundamental consideration when evaluating soil and water conservation options. Given rainfall, infiltration rates, and the water-holding capacity of the soil determine soil moisture availability. Plant response to soil moisture (or the lack thereof), in turn, plays a significant role in crop yield. The basic purpose of on-farm water management practices is to raise crop yields by improving soil water balance, that is, by bringing soil water availability more into line with plant water requirements. Timing of planting and of management practices in relation to rainfall and available soil moisture is, therefore, extremely important. If plant demand for water exceeds available soil moisture levels, plants will experience moisture stress, and in most cases yields will be negatively affected.

According to methods described by Doorenbos and Pruett (1975) Doorenbos and Kassam (1979) and FAO (1986b) soil water balances and resulting crop yield response to moisture stress can be estimated by the following equations:

$$SWB^t = (R^t \times I^t) - (ET_0^t \times k_c^t) + \Sigma_t[(R^{t-1} \times I^{t-1}) - (ET_0^{t-1} \times k_c^{t-1})] \quad (1)$$

$$MD_f^t = \frac{|SWB^t|}{ET_m} \qquad \text{when } SWB^t < 0 \quad (2)$$

$$y_r^t = MD_f^t \times k_y^t \quad (3)$$

$$CY_r = \Sigma_t(y_r^t) \times (CY_m) \quad (4)$$

$$CY_a = CY_m - CY_r \quad (5)$$

where

SWB^t = soil water balance in time period t, that is, the amount of moisture in the root zone,
R^t = rainfall in time period t,
I^t = rainfall infiltration rate in time period t,
ET_0^t = reference crop evapotranspiration in time period t,
k_c^t = proportion of ET_0^t required by the crop of interest,
MD_f^t = soil moisture deficit factor in time period t,
ET_m = total evapotranspiration demand of crop,
y_r^t = crop yield reduction factor for moisture stress in time period t,
k_y^t = crop stress factor for moisture deficits in time period t,
CY_r = total yield reduction per unit of land due to moisture stress in all time periods,
CY_m = maximum potential yield of crop per unit of land, and
CY_a = actual crop yield per unit of land.

The first equation says that the amount of moisture in the soil (SWB^t) during any period is equal to infiltration less plant water loss during the period plus carryover moisture from previous periods. Within the root zone, SWB^t is bounded by the water-holding capacity of the soil to that depth. Equation 2 indicates that for any period in a plant growth cycle, a moisture deficit factor (MD_f^t) can be defined equal to the ratio of the absolute value of SWB^t for that period and the total plant water requirements (ET_m) for the entire season when SWB^t is less than zero. The moisture deficit factor indicates the degree to which water was insufficient for plant needs. In Eq. 3, the product of a moisture deficit factor and a crop stress factor, k_y, gives a yield reduction factor for each period of stress. Equation 4 means that the total reduction in crop yield per unit of land (CY_r) is equal to the summation of the periodic yield reduction factors, times the maximum potential yield (CY_m) per unit of land. Last, Eq. 5 shows that actual yield (CY_a) is maximum yield less the stress-induced reduction in yield. The time steps in these calculations are arbitrary; for example, these steps can be daily, weekly, or monthly, depending on data availability and the precision desired.

Table 8. Rainfall, Kita Station, Mali (mm per time period)

Time period	Average rainfall (43 years) Amount	St. deviation	Average-yield rainfall (1968)	Lowest-yield rainfall (1972)
5/16-31	29	24	43	14
6/01-15	74	33	73	141
6/16-30	79	39	38	83
7/01-15	109	52	81	27
7/16-31	141	46	192	164
8/01-15	160	55	114	147
8/16-31	180	71	161	100
9/01-15	128	50	198	55
9/16-30	88	42	52	34
Total season	988	-	952	765
Total annual	1103	205	1069	825

Source: Rainfall data was supplied by the Evapotranspiration Laboratory, Kansas State University, Manhattan, Kansas.

Equations 1 through 5 become a simple model of soil water balance and crop response relationships that can be used to estimate changes in crop yields resulting from various soil and water conservation measures. This model may also be used to evaluate crop management alternatives such as different planting schedules (crop calendars) or crop cultivars that alter plant water demand in the soil water balance equation.

A LOTUS 1-2-3 spreadsheet routine was developed to solve the soil water balance-crop yield response model for the soils, weather, cropping alternatives, and improved soil and water technologies examined in the Kita case study. The data used to calibrate Eqs. 1 through 5 are now outlined.

1. Rainfall Patterns

For any location with high interseasonal and intraseasonal variability, the number of possible rainfall patterns that might occur could be extremely large. For that reason, in technology appraisal one must select a particular pattern or some reasonable number of alternative patterns to analyze.

In this study we use two rainfall patterns: one that could conceivably produce average yields and one that could produce only the lowest yields for a reference crop, in this case 130-day sorghum with traditional technology. Equations 1 through 5 were employed to estimate potential sorghum yields for each annual weather pattern in 43 years of record at the Kita Weather Station. Average and poor seasonal rainfall, per se, were not used because neither parameter takes into account the distribution of the rain throughout the season: a year with low rain, for example, could still produce good yields if the moisture fell during critical plant growth stages.

Table 9. Crop water requirement coefficients (K_c), by crop growth stage

	Crop[a]							
	Sorghum		Millet		Maize		Groundnut	
Growth stage	S-S	L-S	S-S	L-S	S-S	L-S	S-S	L-S
Establishment	.30	.30	.30	.30	.30	.30	.30	.30
Vegetative	.50	.40	.50	.40	.70	.60	.60	.50
Flowering	.80	.70	.70	.60	1.00	1.10	.90	1.00
Yield formation	.90	1.00	.80	.90	.80	.90	1.00	1.10
Ripening	.50	.70	.50	.70	.60	.70	.70	.70

Source: Doorenbos and Pruett, 1975; FAO, 1986; Hatfield, 1988.
[a] S-S refers to short-season (90 day growth) crops and L-S refers to long-season (130-day growth) crops.

The two chosen rainfall patterns, therefore, represent average and poor *production* years. The average production year embodies a rainy season which could be expected to result in average crop yields, and thus becomes an approximation of the weather pattern farmers are most likely to plan for at the beginning of the season. The poor production year, on the other hand, is the worst-case rainfall scenario with which the farmer may have to cope. To ensure food supplies, farmers must also plan for this rainfall pattern. Our farm model actually takes these two weather possibilities into account simultaneously to identify farm plans that are optimal under average yield conditions as well as satisfy food needs should the worst year occur. The two rainfall scenarios examined along with the long-term seasonal average and its standard deviation are shown in Table 8.

2. Soil Moisture and Crop Yield Response

Estimates of infiltration were generated from rainfall–runoff curve data, which reflect the soil characteristics, ground cover, and rainfall intensities in the Kita area (USDA/SCS, 1986). Three alternative infiltration rates were considered: 40, 60, and 80% of rainfall. For a given soil and climate, alternative infiltration rates arise from different soil conditions and soil water conservation practices. Traditional farm practices in the study area result in low (about 40%) infiltration rates.

Crop water requirements were based on water requirements for a reference crop (ET_0) and k_c coefficients for the crops examined in this study (Table 9). K_y coefficients reflecting crop yield response to moisture stress during plant growth stages are shown in Table 10. Assumed levels of maximum potential crop yield (kg/ha) in the Kita area for 90-day and 130-day cultivars, respectively, under traditional practices with no water stress were sorghum – 1130/1250; millet – 820/1000; maize – 1080/1200; and groundnuts – 1290/1400.

C. Soil Erosion and Declining Productivity

Soil erosion, which can reach high levels in the Kita area, can have a sizable impact on crop productivity (Stocking and Peake, 1986). Since it would be too

Table 10. Crop yield-moisture stress coefficients (K_y), by crop growth stage

Growth stage	Crop			
	Sorghum	Millet	Maize	Groundnut
Establishment	.20	.20	.40	.20
Vegetative	.20	.20	.40	.20
Flowering	.55	.55	1.50	.80
Yield formation	.45	.20	.50	.60
Ripening	.20	.20	.20	.20

Source: Doorenbos and Kassam, 1979; FAO, 1986; Hatfield, 1988.

time-consuming and expensive to collect primary field data on rates of soil erosion under all the various crop and land-use conditions, we turned to synthetic erosion prediction models.

There are several soil erosion estimates for West Africa, but none for the Kita area, and no method for predicting erosion is as widely accepted as the Universal Soil-Loss Equation (USLE; Wischmeier, 1959). Therefore, using Lal's soil plot data for Ibadan, Nigeria (Lal, 1987a), we assumed a maximum erosion rate of approximately 60 mt/ha for a bare fallow field of variable length with 5% slope. The effectiveness of physical erosion control structures, tillage practices, and crop cover in reducing erosion to less than the maximum value was computed using the USLE approach of multiplying the maximum potential erosion (MPE) by the factors for physical structure (P) and crop cover (C), that is, MPE $\times$ P $\times$ C. Crop cover factors in western Africa range from 0.9 in early growth stages to 0.4 for a good stand of fully grown millet, maize, or sorghum. Tied ridges, the only structural erosion control practice analyzed, are assumed to reduce erosion by 80% (P = .2) (Roose, 1977).

The effect of soil erosion on crop productivity can be estimated by comparing yields on eroded and noneroded fields, by monitoring rates of erosion and yields over time, and by using biological plant growth models that predict the effect of erosion-caused changes in the growth environment on yield (Lal, 1987a). Linearized regressions of maize and cowpea experimental plot yields and soil loss, as estimated by Lal (1981;1984), indicate an approximate decline of 0.2 metric tons in corn yields and a 0.03-metric-ton decline in cowpea yields per 10-ton loss in soil. We assume that the 1% yield decline in corn from Lal's plots applies to the much lower maize, millet, and sorghum yields realized on farms in the Kita area. We further assume that the erosion-induced yield decline for groundnuts in the Kita area is 5% of the estimated yield decline for cowpeas. The present value of the permanent economic loss from unchecked erosion is entered in the farm model as a cost of erosion.

D. Management Strategies Examined

The farm-level soil and water management strategies and related farm management decisions examined in the case studies are (1) the use of small amounts of

Table 11. Soil, water, and crop management strategies for case study

Strategy	Base case	Case I	Case II	Case III	Case IV	Case V
Fertilizer	–	X	X	X	X	X
Tied ridges	–	–	X	–	X	X
L-S cultivars	X	X	X	X	X	X
S-S cultivars	–	–	–	X	X	X
Four plant dates	X	X	X	X	X	X
Animal traction	–	X	X	X	X	X
(Long-term erosion accounted for)	X	X	X	X	X	–

fertilizer – up to 24, 8, and 32 kg per ha NPK, respectively, to improve soil fertility; (2) the use of tied ridges to increase rainfall infiltration and reduce soil erosion; (3) the choice of long-season (130 day) or short-season (90 day) cultivars for millet, sorghum, maize, and groundnut; (4) the use of alternative planting dates for all crops including rice and vegetables (May 15, June 1, June 15, or July 1); and (5) the use of animal traction. The complete set of options represent strategies that a farmer may carry out singly or in various combinations.

In summary, a soil water balance–crop yield response model was used initially to predict crop yields under various combinations of management strategies. These yield predictions became input data to the whole-farm planning model. Also included in the whole-farm model were crop production input/output coefficients and cost-return data for each management strategy. The farm model was then used to identify the most economically profitable farm production plan given farm level constraints on land, labor, capital, and the safety-first constraint of producing sufficient food to satisfy home consumption requirements under the worst rainfall-production scenario.

V. Case Study Results

The specific soil and water management strategies examined are outlined in Table 11. Farm-level impacts, including the long-term consequences of soil erosion, associated with Cases I, II, III, and IV are compared to those of the base case. The effect on farm income, production, and soil erosion whenever the farmer ignores the loss in productivity due to erosion is brought to light in a comparison of Case IV and Case V.

The analysis is designed to evaluate impacts of soil and water management options within the framework of actual fertilizer availability and use; hence, NPK fertilizer levels in each case situation were not allowed to exceed the amount typically used, as revealed in the Kita farm surveys. The impact of higher amounts of chemical fertilizer in combination with tied ridges and short-season cultivars was not examined. Animal traction (oxen) was considered an appropriate output-enhancing technological option, particularly for construction of tied ridges, in all

Table 12. Case study impacts of soil, water, and crop management strategies

Impact category	Base case	Case I	Case II	Case III	Case IV	Case V
Net farm income (1000 MF)[a]	8.4	35.5 (323)[d]	375.1 (4365)	35.5 (323)	377.1 (4389)	345.9 (4018)
Food production (kg)						
Grain	7105	7954 (12)	9605 (35)	7954 (12)	9620 (35)	9452 (33)
Groundnut	120	120	120	120	120	120
Vegetables	240	240	240	240	240	240
Erosion (tons per ha)	32	33 (5)	9 (−72)	33 (5)	9 (−72)	12 (−62)
Erosion damage (1000 MF)[b]	343	360 (5)	94 (−72)	360 (5)	94 (−72)	130 (−62)
Area planted (ha)						
With tied ridges	0	0	7.4	0	7.4	6.6
With long-season crops	8.0	8.0	8.0	8.0	7.9	7.7
With short-season crops	0	0	0	0	.1	.3
May 15	5.5	3.8	4.1	3.8	3.9	3.1
June 1	.1	3.1	3.3	3.1	3.4	3.4
June 15	2.4	1.1	.6	1.1	.7	1.5
July 1	0	0	0	0	0	0
Animal traction used (hr)						
Rented ox team	23	38	0	38	0	0
Owned ox team	0	0	400	0	351	370
Hired labor (hr)	80	88	434	88	434	278
Soil/water conservation benefits						
Damage prevented (1000 MF)	0	0	249	0	249	213
Net benefits (B-C)[c]	–	–	157	–	157	131
B/C ratio	–	–	2.7	–	2.7	2.6

[a] Net farm income equals current net returns minus future income loss caused by yield losses resulting from current soil erosion.
[b] Present value of 10 year stream of lost productivity due to erosion in current year.
[c] Costs include labor and animal feed associated with mechanical tied ridging, but not a share of the fixed costs of oxen ownership. This somewhat understates the cost of tied ridges, but benefits are also underestimated since only a 10-year time horizon was considered.
[d] Figures in parenthesis represent percentage changes compared to the base case.

cases except the base case. Another common strategy option is the choice of planting date. Farmers everywhere adjust their planting schedules to the onset of rains and other climatic variables, and also to the expected availability of labor for planting and other farm operations. This analysis examines the question of how planting date might be affected by the introduction of tied ridges, short-season crops, and soil erosion.

Given the technical and economic input data associated with each technology mix, the whole-farm model was solved for each situation to identify the production plan that maximized net farm income subject to the various farm-level constraints. As indicated, the constraints included the need to produce enough food for yearly family needs in the event a poor production year occurs. Solution values for the optimal production plan associated with each situation are shown in Table 12.

A comparison of Cases I through IV with the base case reveals that the use of fertilizer, tied ridges, and animal traction could result in beneficial changes in farm income, production, and the natural resource base. In the base case, net farm income is not very high because there is little saleable surplus beyond basic family food needs. Moreover, real farm income is further depressed by the loss in present value of future productivity caused by erosion during production of the current crop. Fertilizer (even in small amounts) plus animal traction (Case I) could increase net farm income by more than 300% and food production by 12%, but soil erosion would also increase slightly. Introducing tied ridges (Case II) significantly increases net farm income and production and at the same time decreases soil erosion by about 72%. In this case the large increase in income arises from additional current-year food production (due to higher yields), which in turn permit a large increase in saleable surplus, plus increased present value of future productivity due to less erosion with the current crop. The soil and water conservation benefits of tied ridges alone in this comparison amount to 249,000 MF in present value terms for a benefit–cost ratio of almost 3. By increasing yields, the tied-ridge strategy supports the purchase of an oxen team, makes greater use of early-season rains through earlier planting, and permits the hiring of additional labor.

Short-season cultivars (Case III) make no contribution over Case I. Short-season crops have a yield advantage over long-season varieties when late onset or early cessation of rains result in a short growing season. Given the seasonal pattern of the rainfall data used in this study, the potential advantage of the short-season varieties did not come into play as expected primarily because early-season rains under both scenarios were generally sufficient for early planting. It is likely, however, that in a year with late onset the short-season crops would be a better choice. For the same reason the new combination of short-season varieties and tied ridges (Case IV) makes no significant difference from tied ridges alone (Case II).

The production plan of Case V represents a situation in which the farmer gives no weight to the long-term benefits of soil conservation. The first-year gain in productivity due to soil moisture conservation with tied ridges is accounted for,

but the long-term loss in *future* soil productivity because of erosion caused by current farming practices is not. In Case IV, on the other hand, the long-term soil-conserving benefit of tied ridges is recognized, as are the immediate moisture-retaining advantages. Accordingly, the reduced use of tied ridges in Case V compared to Case IV results in somewhat lower profits and increased erosion rates of 4 tons per hectare. Case V represents a situation of misperception by the farmer, who ignores erosion costs. In both Case IV and Case V, however, the adoption of yield-boosting technologies results in higher profits and improved treatment of the soil resource base compared to the base case.

VI. Conclusions

This analysis evaluated various farming practices for managing soil, water, and crops to identify the most desirable combination on economic grounds. Land, labor, and capital resources available on a typical farm in western Mali helped to determine which technologies were feasible and the extent of their use. Food consumption needs of the farm family were additional constraints on the mix of productivity-enhancing measures selected. In this framework, increments of new technology and management decisions were evaluated and compared to the traditional farming situation in which options are limited. Soil moisture conservation and soil erosion control benefits of the tied-ridge technology were explicitly taken into account.

The whole-farm economic model used proved to be a simple but effective tool for integrating agronomic, agroclimatic, and socioeconomic data associated with the many alternative farm production decisions examined. Farm modeling efforts now underway, however, will attempt to reflect more directly statistical rainfall probabilities and effect of rainfall variability on crop yield and farm income. This will improve our ability to describe the "riskiness" of rainfed agriculture, how that risk can be reduced through improved resource management, and, coupled with information on farmers' attitudes toward risk, the likelihood of technology adoption.

The complex relationship between crop yields and rainfall distribution throughout the growing season, infiltration, soil water-holding capacity, and soil water management practices was simulated with a soil water balance model. The amount and timing of rain and the capacity of the soil to collect and hold water jointly determine the amount of moisture actually available for plant uptake. This water supply can be altered by appropriate technology and good management. Similarly, crop management can alter plant water demands to more closely match soil water availability. These basic relationships, and how they can be beneficially changed, are at the core of rainfed farming. The soil water balance model, therefore, played a major role in this economic analysis of the problem. The practicality of using simple crop growth models to perhaps generate more accurately this necessary physical-biological data for the Sahel region is being explored.

Even in the relatively humid Sudano-Guinean zone where our representative farm is located improved soil and water management could lead to significant

differences in farm production, income, and soil erosion. The combination of chemical fertilizer and tied ridges proved most effective, as did the long-season (130 day) cultivars of food grain crops and groundnuts. The short-season (90 day) cultivars made no significant contribution to farm output or income. In situations with less favorable seasonal distribution of rainfall, such as, later onset/earlier cessation, the short-season options would very likely replace the traditional varieties. This is particularly true as one moves northward from our study area into the arid and semiarid regions of the Sahel, where growing season length tends to be shorter.

Our analysis indicates that the benefits of public programs and policies that stimulate better soil and water management in the rainfed areas of the Sahel are potentially very large. Farms and farmers with characteristics similar to our representative case could experience similar gains; however, this depends on the extent to which the collective actions of many individual farms affects the total demand for inputs, commodity supplies, and related input/output price ratios in general. If a large number of farmers were to adopt technologies that significantly increase output, farm gate prices could be depressed. Similarly, a large shift in demand for production inpats might raise costs. The net effect on net farm income should such changes occur, therefore, depends on input–output supply and demand elasticities. Thus, although farm-level studies provide valuable insights regarding the feasibility of new practices the aggregate effects of technology adoption should be examined as well before particular policy prescriptions are made.

Appendix

A simplified description of the linear-programming model employed in this analysis may be written as follows:

$$\text{MAX } I = \sum_i P_i\,(Y_i X_i - D_i - HC_i) \tag{1}$$

$$- [\sum_f P_f (\sum_i F_{fi} X_i) + \sum_i CC_i X_i + \sum_t W_t HL_t$$

$$\sum_i L_{ti} X_i - HL_t \leq LA_t \qquad t = 1 \ldots n \tag{2}$$

$$\sum_i X_i \leq HA \tag{3}$$

$$\sum_i Y_i X_i - D_i \geq HC_i \tag{4}$$

$$\sum_i B_i X_i \geq HC_i \tag{5}$$

$$X_i \geq 0 \tag{6}$$

where

i = crop type,
t = time period,
P_i = price of the ith crop,
Y_i = expected yield per hectare of ith crop,
X_i = hectares of ith crop,
D_i = deductions (kg) of ith crop for seed, gifts, and crop loss,
HC_i = home consumption of ith crop,
P_f = price of fth fertilizer,
F_{fi} = f^{th} fertilizer use per hectare of ith crop,
CC_i = cash cost per hectare of ith crop,
W_t = hourly wage rate of labor in t^{th} time period,
L_{ti} = labor hours in t^{th} time period per hectare of ith crop,
LA_t = family labor hours available in time period t,
HL_t = hired labor in t^{th} time period,
HA = hectares of land available for crop production,
B_i = safe minimum assured yield of ith crop.

References

Andrews, D.J., et al. 1984. Sorghum and pearl millet production in Africa: Problems and prospects with new varieties. *In* Advancing Agricultural Production in Africa, pp. 85–90. Proceedings, Commonwealth Agricultural Bureaux Scientific Conference, Arusha, Tanzania, Feb. 12–18, 1984. Commonwealth Agricultural Bureau, Reading.

Biswas, A. 1986a. Irrigation in Africa. Land Use Policy, (4):269–285.

Biswas, A. 1986b. Land use in Africa. Land Use Policy, (4):247–258.

Butcher, W., and J. Day. 1987. Economics analysis of soil and moisture management on marginal croplands. Paper presented at IAAE/CAAE/CASS Symposium, Beijing, China, Oct. 1987.

Day, J. 1988. Water conservation in arid and semi-arid agriculture: A case study analysis for West Africa. Presented at the VI IWWA International Congress on Water Resources, Ottawa, Canada.

Day, J. and M. Aillery. 1988. Soil and moisture management in Mali: A case study analysis for West Africa. Agricultural Economics, Nov. 1988.

Delgado, C., and J. McIntire. 1982. Constraints on Oxen Cultivation in the Sahel. American Journal of Agricultural Economics, Vol. 64, No. 2, 1982.

Doorenbos, J., and A. Kassam. 1979. Yield response to water. Irrigation and Drainage Paper 33. Food and Agricultural Organization of the United Nations (FAO), Rome.

Doorenbos, J., and W. Pruett. 1975. Guidelines for predicting crop water requirements. Irrigation and Drainage Paper 24. Food and Agricultural Organization of the United Nations (FAO), Rome.

FAO. 1985. Production Yearbook – 1984. Rome.

FAO. 1986a. African Agriculture: The Next 25 Years. Rome.

FAO. 1986b. Early Agrometeorological Crop Yield Assessment. Plant Production and Protection Paper No. 73, Rome.

Farmer, G. 1986. Rainfall variability in tropical Africa: Some implications for policy. Land Use Policy. (4):336-341.

Fleming, A. 1981. Agricultural productivity and the use of labor in alternative enterprises in the circle of Kita Mali. M.S. thesis, Purdue University, W. Lafayette, Indiana.

Hargreaves, G., and Z. Samani. 1986. Rainfed and water requirements manual for Mali. The International Irrigation Center, Department of Agricultural and Irrigation Engineering, Utah State Unviersity, Logan.

Hatfield, J. 1988. Personal correspondence.

International Crop Research Institute for Semi-Arid Tropics. 1984. ICRISAT Cooperative Program in Mali, Annual Report, Bamako, Mali.

Jayne, T., J. Day, and H. Dregne. 1989. Technology and Agricultural Productivity in the Sahel. Economic Research Service, U.S. Department of Agriculture, AER Bulletin, October.

Krause, M., K. Maliki, K. Reddy, R. Deuson, and M. Issa. 1987. Labor management effects on the relative profitability of alternative millet-cowpea intercrop/systems in Niger. Paper presented at the Farming Systems Research Symposium, Fayetteville, Arkansas.

Lal, R. 1981. Soil erosion problems on Alfisols in western Nigeria, VI. Effects of erosion on experimental plots. Geoderma 25:215-230.

Lal, R. 1984. Assessment of tropical soils and the effects of erosion. *In* Quantification of the Effects of Erosion on Soil Productivity in an International Context. Netherlands.

Lal, R. 1987a. Effects of soil erosion on crop productivity. CRC Critical Reviews in Plant Sciences. 4:303-367.

Lal, R. 1987b. Managing the soils of sub-Saharan Africa. Science, 236:1069-1076.

MacDonald, L. 1986. Natural Resources Development in the Sahel: The Role of the United Nations Systems. The United Nations Univesity, NRTS/UNUP-422. Tokyo.

Matlon, P. 1986. Orienting millet improvement objectives to fit clients needs: Improved genotypes and traditional management systems in Burkina Faso. Paper Presented at International Pearl Millet Workshop, ICRISAT, Hyderabad, April.

Nicou, R., and C. Charreau. 1985. Soil tillage and water conservation in semi-arid West Africa. Appropriate Technologies for Farmers in Semi-Arid West Africa. West Lafayette, Indiana: Purdue University Press.

Roose, E. 1977. Use of the universal soil loss equation to predict erosion in West Africa. *In* G. Foster, ed., Soil Erosion: Prediction and Control, pp. 60-74. Ankeny, Iowa: Soil Conservation Society of America.

Roth, M., and J. Sanders. 1984. An economic evaluation of selected agricultural technologies with implications for development strategies in Burkina Faso. Paper presented at Workshop on Farming Systems, Purdue University, W. Lafayette, August.

Sanders, J., J. Nagy, and B. Shapiro. 1985. Developing and evaluation new agricultural technology for the Sahel: A case study in Burkina Faso. Purdue University.

Sivakumar, M., M. Konate, and S. Virmani. 1984. Agroclimatology of West Africa: Mali. ICRISAT Information Bulletin No. 19, Patancheru, India.

Sivakumar, M.V.K. 1988. Predicting rainy season potential from the onset of rains in southern Sahelian and Sudanian climatic zones of West Africa. Agricultural and Forest Meterology, 42:295-305.

Steiner, J., J. Day, R. Papendick, R. Meyer, and A. Bertrand. 1988. Improving and sustaining productivity in dryland regions of developing countires. Advances in Soil Science 8:79-122.

Stewart, J.I. 1987. Potential for response farming in sub-Saharan Africa. Paper presented at the Workshop on Soil and Water Management Systems for Rainfed Agriculture in the Sudano-Sahelian Zone, Niamey, Niger, January.

Stocking, M., and L. Peake. 1986. Crop yield losses from the erosion of Alfisols. Tropical Agriculture (Trinidad) 63, 5:41-45.

TAMS (Tippetts-Abbett-McCarthy-Stratton, Inc.). 1983. Mali Land and Water Resources. New York.

USDA/SCS. 1986. Hydrology for Small Watersheds. Technical Release 55. Washington, D.C.

Wischmeier, W. 1959. Cropping-management factor evaluations for a universal soil-loss equation. Soil Science Society of America Proceedings, 23:322-326.

World Bank. 1985. Desertification in the Sahelian and Sudanian Zones of West Africa. Washington, D.C.: IBRD.

Use of Crop Simulation Models in Dryland Agriculture*

C.A. Jones

I. Introduction 333
II. Evaluation of New Crops in Australia 334
A. Guayule 334
B. Sunflower 335
C. Grain Sorghum 336
D. Other Studies 336
III. Application of Grain Sorghum Simulation Models in Central Texas ... 337
A. Optimum Fertilizer Nitrogen Rates 338
B. Forecasting Drought Stress 338
C. Evaluating Usefulness of Furrow Dikes 338
D. Defining Where Ratooning Is Profitable 339
IV. Future Trends in Model Use 340
A. Research 340
B. Yield Forecasts 340
C. Strategic Decisions 340
D. Tactical Decisions 341
E. Other Advances 341
References 342

I. Introduction

Dryland agriculture is dynamic. Weather varies from year to year. Crops, cultivars, machinery, input costs, and markets for agricultural products change constantly. How, then, can a farmer design a successful cropping system for his unique and dynamic set of conditions? How can he select a crop and a management

*Contribution of the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS), Grassland, Soil and Water Research Laboratory (GSWRL), Temple, Texas.

1990 by Springer-Verlag New York Inc.
Advances in Soil Science, Volume 13

strategy to match his resources of climate, soil, labor, and capital? Agricultural research has traditionally relied heavily on field experiments to evaluate management practices. However, with their high costs and labor requirements, they can be used to sample only a fraction of the management alternatives available to farmers in only a fraction of the weather conditions he is likely to encounter. As a result, new tools are needed to supplement field experiments and to extrapolate, in time and space, the information they provide. This chapter describes how simulation models have been so used and how they might be used in the future.

During the past 15 years, simulation models have been developed for a number of agricultural processes, including weather, hydrology, soil erosion, nutrient transformations and losses, and crop phenology, growth, and yield. Models of specific processes have been combined into comprehensive crop growth models, which predict effects of environment, crop genotype, and management on yields and, in some cases, on the soil resource. These comprehensive models have been used by researchers around the world to predict the agronomic and economic impacts of modifying dryland cropping systems at specific sites.

The intention of this chapter is neither to describe the characteristics, strengths, and weaknesses of simulation models nor to review all their possible uses. Rather, I will illustrate their application to practical problems by describing two groups of studies, one conducted in Australia and the other in central Texas. This approach sets the development and practical use of simulation models in a historical context and provides the reader with two quite different examples of their use as tools for analyzing dryland agricultural systems.

II. Evaluation of New Crops in Australia

The Australian economy has long depended on export of industrial and agricultural raw materials, and high priority has been given to adaptation of export crops to the Australian environment. Homoclime analysis has been used to identify Australian sites with climatic characteristics similar to those in which the crop grows naturally or has been successfully grown (Nix, 1975, 1987; Prescott, 1943); however, it serves as only a rough guide to determine potential productivity and the optimum conditions for growth. Simulation models have been used to provide more detailed analyses and to match crop climatic and soil requirements with site characteristics.

A. Guayule

Guayule (*Parthenium argentum*) is a potential industrial (rubber) crop. Little experimental work has been done on the crop in Australia; therefore, a study was conducted of potential sites for guayule research and, ultimately, industrial production. A generalized plant growth simulation model (GROWEST) incorporating a simple water balance model and temperature and light response func-

tions was used (Nix, 1981). A growth index was calculated for each of 1000 sites in Australia for which mean weekly rainfall, potential evaporation, temperature, and solar radiation were available. Sites with high probabilities of extended periods of soil saturation or poor rubber synthesis (due to unfavorable radiation/temperature balance) were excluded. Regions with favorable climatic potential were mapped, and potential sites for future research and industrial production were selected based on availability of land with suitable topography and soils (Nix, 1987).

B. Sunflower

When sunflower (*Helianthus annuus*) production became economically attractive in Australia in the 1970s, little was known about its environmental requirements or its adaptation to the agricultural areas in the country. As a result, a coordinated set of field experiments was conducted to determine functional relationships that could be used to predict crop development, growth, and yield (Anderson et al., 1978a,b), and a sunflower growth simulation model was developed (Smith et al., 1978a,b). Phenological development was estimated from mean daily temperature, soil water, and day length. Dry matter and seed growth were simulated from temperature, solar radiation, the ratio of actual to potential evapotranspiration, frost, and estimated disease severity. Mean weekly weather data were used to estimate yields at 455 sites throughout Australia, each with 13 dates of seeding and four levels of antecedent soil water. The model predicted that frost would limit seeding dates in many areas, disease pressure would reduce predicted yields in humid regions, and yields for a particular site and seeding date would be sensitive to soil water-holding capacity and water content at seeding. The results were used to predict the optimum seeding date for each site and to produce maps of estimated average yields for the optimum planting date and for a range of soil water-holding capacities and initial soil water content.

This study improved understanding of sunflower adaptation in Australia (Lovett et al., 1979). Because the model used average weekly precipitation, it could not be used to simulate year-to-year variation in crop yields or the risks of crop failure for the different seeding dates. In a subsequent study, historical daily precipitation records (51 to 97 years) were used with mean weekly temperature, radiation, evaporation, and day length data to evaluate risk associated with different seeding dates at 13 locations (Smith et al., 1978b). The results suggested that in the southern areas of the continent early seeding was less risky than late seeding. In the central highlands of Queensland the reverse was true, and in southern Queensland risk was reduced by seeding at either the beginning or the end of the summer period.

A similar Queensland study of optimum seeding dates for short- and long-season cultivars (Hammer and McKeon, 1984) conducted with a different simulation model (Goyne and Hammer, 1982; Hammer and Goyne, 1982; Hammer et al., 1982) gave similar results.

C. Grain Sorghum

In the mid-1979s, the semiarid, tropical area around Katherine, Northern Territory, had little history of agricultural production. Some 25 years of traditional agronomic experimentation had shown that grain sorghum (*Sorghum bicolor*) could be grown but that yields were low. Researchers suspected that the proper combination of soil type, sowing date, cultivar maturity type, and canopy development rate could result in higher and more stable yields. Angus et al. (1974; cited in Nix, 1981) used the CROPEVAL model to evaluate alternative grain sorghum cropping systems in the area. The model was run with a 20-year sequence of measured weather data and combinations of cultivar maturity type, date of sowing, soil type, and rate of canopy development, which could be influenced by fertilizer rate, row spacing, and plant population. The results for a clay loam soil with 100 mm of available water indicated that early-maturing cultivars sown early in the wet season produced the highest yields and had the lowest year-to-year variation. These simulated results, consistent with previous field experimentation in the area, were obtained much more quickly and less expensively. A different management strategy was recommended for deep sandy loam soils with 150 mm of available water. For these soils, late sowing coupled with slow canopy development allowed the crop to conserve water during the vegetative phase and use it more effectively for grain filling later in the season when the radiation:temperature balance was more favorable. This combination of soil and management practices had not been tested in previous field experiments, and the study illustrates how simulation models can be used to identify promising combinations of soils, cultivars, and management strategies for further testing in field experiments.

D. Other Studies

Simulation models have been used to study adaptation of other crops to specific sites in Australia. For example, Hammer and McKeon (1984) used simulation to estimate the risk of wheat (*Triticum aestivum*) production along rainfall gradients in Queensland. Stapper et al. (1983) used a simulation model currently in use in Australia to conduct similar studies in the Middle East. Nix and McMahon (1979) conducted a study of jojoba (*Simmondsia chinensis*) adaptation similar to that described for guayule.

Simulation models have been used in novel ways to match the climatic characteristics of sites with consumer demand for fresh produce. Australia's potato-growing districts extend over wide ranges of latitude and elevation, and potatoes (*Solanum tuberosum*) are produced during different seasons at different sites (Hackett and Rattigan, 1978). In the late 1970s, changes in location of production and management practices were occurring. As a result, a potato simulation model was developed to help identify promising producing areas, to predict the effects of varying planting times to take advantage of favorable climatic and market conditions, to improve the accuracy of crop forecasting and to help

agronomists analyze the performance of experimental and commercial plantings (Hackett et al., 1979a,b; Sands et al., 1979).

The model estimated phenological development of the crop and tuber growth (bulking). The initial version required weekly mean minimum and maximum temperatures throughout the crop, solar radiation for the 3 weeks following emergence, and an estimate of the maximum soil water deficit experienced during bulking. Later versions simulated the effects of day length, plant population, and crop cultivar on bulking and estimated graded as well as total tuber yields (Sands and Regel, 1983).

The model was used to evaluate the possibility of improving yield in several potato-growing districts, the effects of altering timing of production to take advantage of seasonal price fluctuations, the potential for commercial production in several areas not producing potatoes at the time, and the potential for exporting seed potatoes to lowland tropical regions (Hackett et al., 1979b).

The studies cited earlier illustrate that crop simulation models can be used to (a) identify potential sites for production of specific crops, (b) evaluate production risks (frost, drought stress) for particular sites, (c) optimize crop maturity genotypes and seeding dates to minimize risks, and (d) select sites for off-season production of fresh produce. The studies also illustrate that all useful crop simulation models need not have the same characteristics or simulate the same processes. For example, the guayule model produces an index of crop adaptation to a site that is sufficient to identify potential sites for future research and industrial production. The model does not need to simulate phenology, biomass production, or rubber yield. The potato model predicts crop phenology and tuber growth without simulating leaf area development or biomass. Production risk analyses with sunflower models require weather, soil, and management information to simulate disease pressure, phenology, leaf area, biomass, and grain yield.

In many areas with long histories of agricultural production, optimum sowing dates and cultivar types have been established by conventional field experiments. However, simulation models are increasingly being used to evaluate other management practices. Several such studies have been conducted for grain sorghum grown in central Texas.

III. Application of Grain Sorghum Simulation Models in Central Texas

Simulation of the dryland grain sorghum cropping system in central Texas began in the early 1970s with models to predict evaporation from a grain sorghum crop with incomplete cover (Ritchie, 1972), hydrology (Richardson and Ritchie, 1973), leaf area development (Ritchie and Arkin, 1973), and eventually crop growth, development, and yield (Arkin et al., 1976; Vanderlip and Arkin, 1977). Since their development, these grain sorghum simulation models have been used for a number of studies of the dryland grain sorghum cropping system.

A. Optimum Fertilizer Nitrogen Rates

In central Texas, response of grain sorghum to fertilizer N rates varies from year to year. Much of this variation is due to differences in drought stress. Kissel et al. (1975) used simulation models of grain sorghum leaf area development (Ritchie and Arkin, 1973) and soil water (Richardson and Ritchie, 1973) to estimate the severity of drought stress (Hiler and Clark, 1971) in each of 6 years. The results of the drought stress simulations were used with data from nitrogen rate experiments to develop a statistical model of the effects of drought stress and N fertilizer rate on grain sorghum yields. The model was validated with independent data, and the probability of drought stress was calculated using 60 years of weather data from the area. Probability of drought was a function of preseason and early-season soil profile water contents, and Kissel et al. (1975) showed that soil water content could be used to estimate optimum fertilizer N rates.

B. Forecasting Drought Stress

In central Texas, rainfall is quite variable during the grain sorghum growing season, and drought stress often limits yields. The SORGF model (Arkin et al., 1976, 1980; Vanderlip and Arkin, 1977) was developed to simulate the effects on growth and yield of weather (rainfall, temperature, and solar radiation), plant-available soil water (ASW), and crop genotype.

Arkin et al. (1978) used the model to assess the effects of ASW and early crop growth on grain yields. A 20-year sequence of measured weather data was used to simulate crop growth and yields for six levels of ASW at seeding. When ASW was greater than 9 cm at seeding, simulated grain yields exceeded 4000 kg/ha in 80% of the 20 years. However, with less than 9 cm ASW at seeding yield exceeded only 1500 kg/ha in 80% of the years.

Further simulations were used to estimate grain yields from measured crop leaf area and ASW at 60 days after emergence (DAE). For example, when leaf area at 60 DAE was greater than 0.27 m^2/plant and the soil was wet (ASW $>$ 11.4 cm), median simulated yields were 7500 kg/ha. However, if early growth was good but the soil was dry (ASW $<$ 3.8), median simulated grain yields were only 2600 kg/ha. This study provided a good basis for early- and midseason yield forecasting for farmers, lending agencies, and grain merchants.

C. Evaluating Usefulness of Furrow Dikes

Dryland farmers cannot alter the amount or timing of precipitation received by the crop, but they can often manage its utilization. Proper tillage and residue management can improve infiltration and minimize evaporation losses from the soil surface. Fallow can be used to increase stored soil water, and furrow dikes (also known as tied ridges, row dams, or basin listing) can trap runoff until it infiltrates.

Yield response to furrow dikes depends on the soil's water-holding and infiltration characteristics, initial soil water content, and within-season precipitation amounts and timing. The benefits of furrow dikes may be small in years with little potential runoff or with adequate rainfall. However, they may be large in years in which dikes increase infiltration and the water is later used by the crop.

In Texas, several studies of the effects of furrow dikes on crop yields have been conducted (Bilbro and Hudspeth, 1977; Gerard et al., 1983, 1984; Lyle and Dixon, 1977). The results varied greatly among sites and years, and it has been difficult to make site-specific recommendations. Simulation models have recently been used to supplement the experimental data and to estimate the probability and magnitude of increased yields due to furrow diking. Krishna et al. (1987) used the SORGF model (Arkin et al., 1976) and runoff algorithms from the Erosion-Productivity Impact Calculator (EPIC) (Williams et al., 1984) to simulate grain sorghum yields. The models were first validated using experimental runoff and crop yield data for diked and undiked situations in the few years and sites with adequate data. Effects of furrow diking were then simulated for three sites in central, southwest, and northwest Texas using 20 years of daily weather records. Results indicated that furrow diking would increase mean grain sorghum yields for all three locations, but the amount of increase depended on the year, the site, and whether the dikes were maintained all year or only during the growing season. The central Texas site had the highest annual precipitation (854 mm) and the lowest simulated mean yield response to furrow diking (490 kg/ha) because of the relatively low probability of severe drought stress. The southwest Texas site (618 mm) had the highest mean yield response (1160 kg/ha). The northwest Texas site (467 mm) had an intermediate yield response (720 kg/ha) because, even though drought stress severely limited yields, furrow dikes trapped relatively little runoff in this dry environment.

Studies of this type, using validated simulation models, can provide farmers with valuable information concerning the benefits of water conservation practices such as furrow diking. A farmer might even base his decision to install dikes on soil hydrologic characteristics and the amount of ASW at planting.

D. Defining Where Ratooning Is Profitable

When rainfall and temperatures are adequate, as in the southeastern United States and some tropical areas, grain sorghum can produce good ratoon yields (Duncan, 1981). However, the practice is less feasible in regions where the probability of adequate rainfall during the ratoon crop is low. Central Texas is an area with erratic late-season rainfall, and little data on ratoon sorghum yields are available. Consequently, Stinson et al. (1981) conducted a feasibility study using the SORGF crop model in conjunction with the HYMO hydrologic model (Williams and Hann, 1978). Results were validated by comparing simulated ratoon yields with those obtained by farmers in the area. Subsequent simulations using historical weather records from the area (Stinson et al., 1981) suggested that,

though no ratoon yields would be produced in some dry years, yields as high as 3500 kg/ha were possible. Median ratoon yields were 500 kg/ha. The low investment required to produce the ratoon crop and its high potential returns have encouraged more farmers to consider ratooning sorghum and have stimulated research to optimize varietal selection and cultural practices (G. F. Arkin, 1986, personal communication). Subsequent field and simulation studies have better-defined areas in Texas, with good potential for production of ratoon grain sorghum (T. J. Gerik, 1986, personal communication).

IV. Future Trends in Model Use

In the future, simulation models will be more widely used to analyze complex cropping systems. They will be used for research, yield forecasting, and strategic and tactical decision making. They will increasingly be adapted to microcomputers and included in comprehensive decision support systems containing extensive natural resource and economic data bases and expect systems.

A. Research

Agricultural research will increasingly be influenced by simulation models. When scientists express their understanding of a process in a mathematical model, they often discover areas of ignorance. This leads to experiments that ultimately increase both their understanding of the process and their ability to simulate it.

B. Yield Forecasts

Simulation models are convenient tools for integrating site-specific weather, soil, and crop management data to produce regional crop yield forecasts (Hodges, 1985). Typically, measured weather data are used to simulate crop growth from seeding until the current date. One or more hypothetical weather sequences are used to simulate growth from the current date until maturity. Such simulations are conducted for representative sites with a region, and the results are aggregated to produce a regional yield estimate or a distribution of probable yields.

C. Strategic Decisions

Several examples of strategic decision making were given in the preceding sections describing evaluation of alternative sites, seeding dates, and management practices. More complex models will permit evaluation of more management practices. In a recent study, a comprehensive cropping systems model was used to simulate a variety of management options for a rice-based dryland cropping system in India (Jones and O'Toole, 1987). Crop maturity group, plant type (traditional, semi-dwarf, intermediate), fertilizer nitrogen rate, control of runoff, and seeding a grain legume following the rice harvest were evaluated. The study illustrated how simu-

lation models can be used to select management practices (cultivars, planting dates, fertilizer rates, runoff control practices, crop rotations, etc.) that take full advantage of the environment without damaging the soil resource.

D. Tactical Decisions

Simulation models will be used to aid within-season decision making. They will be used for a variety of purposes including prediction of harvest maturity, estimating fertilizer N requirements from fertilizer N reserves and crop N requirements, and scheduling irrigation and insecticide applications.

E. Other Advances

Rapid advances are being made to develop (a) natural resource, management, and economic data bases used by agricultural simulation models (Jones et al., 1987; Williams et al., 1984), (b) models of specific agricultural processes, and (c) combination of specific models into comprehensive models of cropping systems (Shaffer and Larson, 1987; Williams et al., 1984). For example, the Nitrogen-Tillage-Residue-Management (NTRM) model (Shaffer and Larson, 1987) simulates physical, chemical, and biological processes in the soil-water-crop continuum using integrated submodels for soil temperature, soil carbon and nitrogen transformations, unsaturated flow of water, crop (maize) and root growth, evaporation and transpiration, tillage, interception and infiltration, chemical equilibria processes, solute transport, and crop residues. The Erosion-Productivity Impact Calculator (EPIC) model (Williams et al., 1984) simulates weather, hydrology, soil erosion by wind and water, nitrogen and phosphorus cycling, residue decomposition, soil temperature, growth and development of a variety of crops, and management practices including tillage, lime application, irrigation, and fertilization. It is capable of simulating complete crop rotations and evaluating a wide variety of crops, soils, and management alternatives using microcomputers. In the future, such comprehensive simulation models will be more widely used in analyzing complex cropping systems.

Crop simulation models are increasingly available as independent programs for microcomputers (e.g., Arkin and Jackson, 1983; Jackson and Arkin, 1984; Jones and Kiniry, 1986) and as parts of network-based decision support systems. For example, COMAK is a comprehensive crop management package developed in the Netherlands (Stapper et al., 1986). It operates on an independent microcomputer and consists of packages that help (a) record farming activities; (b) optimize use of machinery, labor, and capital; (c) warn of impending management requirements; (d) recommend fertilizer application rates; and (e) aid financial management. AGVISER is a computerized farm management, information, and communications service developed in the United Kingdom (Poole and Causton, 1985). Farmers can choose to operate at three levels of complexity according to their needs. The simplest provides access through a telecommunications link to agricultural information, communications, and computing. The most

sophisticated level includes access to central computer facilities. SIRAGCROP is a computer network-based crop management system for irrigated wheat and associated summer crops in Australia. It includes a simulation model of wheat growth (Stapper, 1984), development, and water use, which is used to predict soil water contents and schedule irrigation and other crop management practices (Stapper et al., 1986).

Such decision support systems will increasingly be used to aid within-season crop management, including prediction of crop development, estimating soil N reserves and crop N requirements, and scheduling irrigation and pesticide applications, which may be sensitive to both crop development stage and environmental conditions. The long-term commercial success of such systems will depend on their ability to provide farmers with useful information in an economical and easily accessible form. Agricultural researchers are often poor judges of what information farmers want and need. Therefore, system developers should work closely with users to provide not only accurate information, but the most useful information displayed in the most appropriate way. Only then will information technology and simulation models play the role they are capable of in agriculture.

References

Anderson, W.K., R.C.G. Smith, and J.R. McWilliam. 1978a. A systems approach to the adaptation of sunflower to new environments. I. Phenology and development. Field Crops Res. 1:141-152.

Anderson, W.K., R.C.G. Smith, and J.R. McWilliam. 1978b. A systems approach to the adaptation of sunflower to new environments. II. Effects of temperature and radiation on growth and yield. Field Crops Res. 1:153-163.

Angus, J.F., J.J. Basinski, and H.A. Nix. 1974. Weather analysis and its application to production strategy in areas of climatic instability. Report to the IAD/UNDP Internat. Expert Consultation on the Use of Improved Technol. for Food Production in Rainfed Areas of Tropical Asia. Food and Agriculture Organization of the United Nations, Rome.

Arkin, G.F., and B.S. Jackson. 1983. User's guide to SORG-AP: A grain sorghum growth model for an Apple computer. Texas Agric. Exp. Sta., MP-1541.

Arkin, G.F., S.J. Maas, and C.W. Richardson. 1980. Forecasting grain sorghum yields using simulated weather data and updating techniques. Trans. Am. Soc. Agric. Engin. 23:676-680.

Arkin, G.F., C.W. Richardson, and S.J. Maas. 1978. Forecasting grain sorghum yields using probability functions. Trans. Am. Soc. Agric. Engin. 21:874-877, 880.

Arkin, G.F., R.L. Vanderlip, and J.T. Ritchie. 1976. A dynamic grain sorghum growth model. Trans. Am. Soc. Agric. Engin. 19:622-626, 630.

Bilbro, J.D., and E.B. Hudspeth, Jr. 1977. Furrow diking to prevent runoff and increase yields of cotton. Texas Agric. Exp. Sta., PR-3436.

Duncan, R.R. 1981. Production principles. *In* R.R. Duncan, ed. Ratoon Cropping of Sorghum for Grain in the Southeastern United States. pp. 1-6. University of Georgia, College Agric. Exp. Sta., Res. Bull. 269, Nov. 1981.

Gerard, C.J., P.D. Sexton, and D.M. Conover. 1984. Effect of furrow diking, subsoiling, and slope position on crop yields. Agron. J. 76:945-950.

Gerard, C.J., P.D. Sexton, and D.M. Matus. 1983. Furrow diking for cotton production in the Rolling Plains. Texas Agric. Exp. Sta., PR-4174.

Goyne, P.J., and G.L. Hammer. 1982. Phenology of sunflower cultivars. II. Controlled environment studies of temperature and photoperiod effects. Aust. J. Agric. Res. 33:251-261.

Hackett, C., and K. Rattigan. 1978. The location and timing of potato production in Australia. CSIRO Aust. Div. Land Use Res. Tech. Pap. No. 38.

Hackett, C., P.J. Sands, and H.A. Nix. 1979a. A model of the development and bulking of potatoes (*Solanum tuberosum* L.) II. Prediction of district commercial yields. Field Crops Res. 2:333-347.

Hackett, C., P.J. Sands, and H.A. Nix. 1979b. A model of the development and bulking of potatoes (*Solanum tuberosum* L.) III. Some implications for potato production and research. Field Crops Res. 2:349-364.

Hammer, G.L., and P.J. Goyne. 1982. Determination of regional strategies for sunflower production. Proc. Tenth Internat. Sunflower Conf., Surfers Paradise, Australia, March 1982.

Hammer, G.L., P.J. Goyne, and D. R. Woodruff. 1982. Phenology of sunflower cultivars. III. Models for prediction in field environments. Aust. J. Agric. Res. 33:263-274.

Hammer, G.L., and G.M. McKeon. 1984. Evaluating the effect of climatic variability on management of dryland agricultural systems in northeastern Australia. *In* E.A. Fitzpatrick, ed. Need for Climatic and Hydrologic Data in Agriculture of Southeast Asia. Canberra, 12-15 December 1983. Symposium sponsored by United Nations University.

Hiler, E.A., and R.N. Clark. 1971. Stress day index to characterize effects of water stress on crop yields. Trans. Am. Soc. Agric. Engin. 14:757-761.

Hodges, T. 1985. Using the CERES-Maize model to estimate production for the U.S. Cornbelt. (Abstract) Agron. Abst. 77:12.

Jackson, B.S., and G.F. Arkin. 1984. User's guide to CORN-AP: A maize growth model for an Apple computer. Texas Agric. Exp. Stn., MP-1571.

Jones, C.A., W.W. Fuchs, and P.T. Dyke. 1987. Use of soil characterization data in simulation models. *In* Proc. IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) Symposium. Vol. VI. pp. 970-974. Trans. XIII Internat. Soc. Soil Sci., August 13-20, 1986. Hamburg.

Jones, C.A., and J.R. Kiniry, eds. 1986. CERES-Maize: A simulation model of maize growth and development. Texas A&M Press, College Station.

Jones, C.A., and J.C. O'Toole. 1987. Application of crop production models in agroecological characterization: Simulation models for specific crops. *In* A.H. Bunting, ed. Agricultural Environments: Characterization, Specifications, and Mapping. Commonwealth Agricultural Bureau International, London.

Kissel, D.E., J.T. Ritchie, and C.W. Richardson. 1975. A stress day concept to improve nitrogen fertilizer utilization: Dryland grain sorghum in the Texas Blackland Prairie. Texas Agric. Exp. Stn., MP-1201.

Krishna, J.H., G.F. Arkin, J.R. Williams, and J.R. Mulkey. 1987. Simulating furrow-dike impacts on runoff and sorghum yields. Trans. Am. Soc. Agric. Engin. 30:143-147.

Lovett, J.V., H.C. Harris, and J.R. McWilliam. 1979. Sunflower. *In* J.V. Lovett and A. Lazenby, eds. Australian Field Crops. Vol. 2: Tropical Cereals, Oilseeds, Grain Legumes, and Other Crops. pp. 137-160. Sydney: Angus and Robertson.

Lyle, W.M., and O.R. Dixon. 1977. Basin tillage for rainfall retention. Trans. Am. Soc. Agric. Engin. 20:1013-1017.

Nix, H.A. 1975. The Australian climate and its effects on grain yield and quality. *In* A. Lazenby and E.M. Matheson, eds. Australian Field Crops, Vol. I. Wheat and Other Temperate Cereals. pp. 183–226. Sydney: Angus and Robertson.

Nix, H.A. 1981. Simplified simulation models based on specified minimum data sets: The CROPEVAL concept. *In* A. Berg, ed. Application of Remote Sensing to Agricultural Production Forecasting. pp. 151–169. Rotterdam: A.A. Balkema.

Nix, H.A. 1987. Land evaluation for potential guayule rubber production in Australia. *In* G.A. Stewart and S.M. Lucas, eds. The Potential Production of Natural Rubber from Guayule in Australia. CSIRO Monograph, Canberra. (in press).

Nix, H.A. and J.P. McMahon. 1979. Jojoba in Australia: Where? *In* Proc. First Australian Jojoba Conf., Bathurst N.S.W. Sydney: AAAT.

Poole, K.A.K., and A.E. Causton. 1985. "AGVISER" farm computer system. *In* G.H. Jackson, ed. Farm Electronics and Computing. pp. 375–376. Royal Agr. Soc. of England, Monograph Series No. 4, Stoneleigh, United Kingdom.

Prescott, J.A. 1943. Australian homoclimes of the zone of natural occurrence of *Parthenium argentatum*. Trans. R. Soc. S.A. 67:312–318.

Richardson, C.W., and J.T. Ritchie. 1973. Soil water balance for small watersheds. Trans. Am. Soc. Agric. Engin. 16:72–77.

Ritchie, J.T. 1972. A model for predicting evaporation from row crop with incomplete cover. Water Resources Res. 8:1204–1213.

Ritchie, J.T., and G.F. Arkin. 1973. Simulating the seasonal variation in leaf area index of grain sorghum. Agron. Abstracts, Madison, Wisc.: Am. Soc. Agron.

Sands, P.J., C. Hackett, and H.A. Nix. 1979. A model of the development and bulking of potatoes (*Solanum tuberosum L.*). I. Derivation from well-managed field crops. Field Crops Res. 2:309–331.

Sands, P.J., and P.A. Regel. 1983. A model of the development and bulking of potatoes (*Solanum tuberosum* L.). V. A simple model for predicting graded yields. Field Crops Res. 6:25–40.

Shaffer, M.J., and W.E. Larson, eds. 1987. NTRM, a soil-crop simulation model for nitrogen, tillage, and crop residue management. U.S. Department of Agriculture, Agricultural Research Service, Conservation Research Report 34-1.

Smith, R.C.G., W.K. Anderson, and H.C. Harris. 1978a. A systems approach to the adaptation of sunflower to new environments. III. Yield predictions for continental Australia. Field Crops Res. 1:215–228.

Smith, R.C.G., S.D. English, and H.C. Harris. 1978b. A systems approach to the adaptation of sunflower to new environments. IV. Yield variability and optimum cropping strategies. Field Crops Res. 1:229–242.

Stapper, M. 1984. SIMTAG: A simulation model of wheat genotypes. Model documentation. Department of Agronomy and Soil Science, University of New England, Armidale, New South Wales and International Center for Agricultural Research in the Dry Areas, Aleppo, Syria.

Stapper, M., H.C. Harris, and R.C.G. Smith. 1983. Risk analysis of wheat yields in relation to cultivar maturity type and climatic variability in semi-arid areas, using a crop growth model. *In* E.A. Fitzpatrick, ed. Need for Climatic and Hydrologic Data in Agriculture of Southeast Asia. Canberra, 12–15 December 1983. Symposium sponsored by United Nations University.

Stapper, M., R.C.G. Smith, R.E. Speed, and R. Colomb. 1986. Framework for implementation and commercialization of SIRAGCROP. Tech. Rep. No. 3. Centre for Irrigation Research, Griffith, New South Wales, June 1986.

Stinson, D.L., G.F. Arkin, T.A. Howell, C.W. Richardson, and J.R. Williams. 1981. Modeling grain sorghum ratoon cropping and associated runoff and sediment losses. Trans. Am. Soc. Agric. Engin. 24:631-635, 642.

Vanderlip, R.L., and G.F. Arkin. 1977. Simulating accumulation and distribution of dry matter in grain sorghum. Agron. J. 69:917-923.

Williams, J.R., and R.W. Hann. 1978. Optimal operation of large agricultural watersheds with quality constraints. Tech. Rep. No. 96. Texas Water Resources Institute, Texas A&M University, College Station, Texas.

Williams, J.R., C.A. Jones, and P.T. Dyke. 1984. A modelling approach to determine the relationship between soil erosion and soil productivity. Trans. Am. Soc. Agric. Engin. 27:129-144.

Strategies for Increasing the Productivity and Stability of Dryland Farming Systems

C.E. Whitman and R.E. Meyer

I. Introduction 347
II. Successful Dryland Regions 349
A. Southern Great Plains 349
B. Southern Australia 351
C. General Considerations 352
III. Dryland Technologies 353
A. Germplasm Improvements 353
B. Developing Appropriate Soil, Water, Crop, and Livestock Production Practices 354
IV. Research and Technology Transfer 354
V. Research Needs 356
VI. A Strategy for Achieving Improved Dryland Production 356
References 357

I. Introduction

Most of the world's food production is achieved under rainfed conditions. That part of the rainfed sector where precipitation is generally limiting to crop production is an important and essential part of the agricultural sector in many countries. These same areas have serious environmental problems and poverty. Drylands are of particular importance in South and West Asia, the Near East, and North Africa. They are also major grain-producing areas in the United States, Australia, and Canada.

Over the last 50 years, development in semiarid and arid regions has been largely the result of irrigation projects. Although the cost of these projects has been quite high ($20,000 ha^{-1} is not unusual), potential grain yield has been

1990 by Springer-Verlag New York Inc.
Advances in Soil Science, Volume 13

Preceding Page Blank

increased twelvefold, from 0.5 (rainfed, no inputs) to 6.0 Mg ha^{-1} (irrigated, inputs). However, there are many cases of underachieving irrigation projects in developing countries, with grain yields of only 2.0 Mg ha^{-1}. This can be attributed to the lack of investment in improved market infrastructure, dependable and timely supply of agronomic inputs (improved seed, fertilizer, and equipment), well-trained farmers, effective technical support, efficient on-farm water management, effective and efficient whole system management, and appropriate governmental polices and pricing mechanisms.

While irrigation projects have substantially increased production in semiarid lands such as the U.S. Great Plains and India, the long-term sustainability of irrigation has always been problematic. Examples of this are the Tigres/Euphrates River Valley about 4000 B.C., the Southwest United States about A.D. 900 to 1200, and more recently the Central and Imperial Valleys of California. Often this is due to the lack of adequate drainage. Although it is well-known that drainage systems should be an integral part of all irrigation projects, they are frequently overlooked or omitted entirely because of the tremendous additional costs involved. This contributes to the observation in some countries, for example India, that as much agricultural area is lost to salinity and drainage problems over a given time span as is gained by irrigation (R. P. Singh, personal communication).

Given these problems with irrigation, how would equivalent production be obtained in dryland agriculture? A 10,000-ha irrigation scheme would cost at least $100,000,000, probably twice that in Africa. The production potential would be 60,000 Mg per harvest for the entire area (6.0 Mg ha^{-1}), and realistically, 25,000 Mg (2.5 Mg ha^{-1}). With two harvests per year (this seldom occurs), we could expect grain production of 50,000 Mg per year. Under dryland conditions, potential production would be 2.0 Mg ha^{-1} (optimal management and inputs), and realistically, 1.0 Mg ha^{-1}. To produce 50,000 Mg per year, 50,000 ha of land must be farmed. If one expected complete crop failure in 1 out of 5 years and 50% failure for another 1 in 5 years, 65,000 ha would be required for 5 years to produce grain equal to that from 10,000 ha of irrigated land over the same period, all other risks remaining zero in both cases. The question then becomes, how could $1500 ha^{-1} ($100,000,000 per 65,000 ha) be spent to improve the land resource and reduce risk in dryland farming?

The answer to this question is necessarily location specific and the soil and climatic resource inventories required for the answer are unavailable in many regions. However, studies from Sudan, Niger, and Mali have shown that minimal amounts of phosphate fertilizer can increase the efficiency of water use, doubling yields. Other studies indicate that as much as 50% of rainfall is lost as runoff. If conservation practices were instituted, this loss could be realistically reduced by half, and water available for crop production could be increased by 50%. Yield increases would be substantial, given known water production functions. It is unlikely that these minimal investments would exceed $1500 ha^{-1}. Likewise, the social equity would be considerably greater as a result of improving the dryland systems.

It seems axiomatic that long-term improvement in world food production will depend on enhanced, sustainable productivity in dryland areas. Increased investments to improve the living conditions of inhabitants of these areas are essential to prevent the escalating calamities we have witnessed with the droughts in Africa. The current population growth in India indicates that the Green Revolution has merely bought some additional time to improve food production under rainfed/dryland conditions (Indo-U.S. Subcommission on Agriculture 1987). From a scientific standpoint, the major question is how to use the natural resources more effectively without their further degradation. It is essential to sustain the natural resources of the drylands while increasing their food production potential.

A more complete understanding of the environment must be integrated with developmental activities such as forestry, fisheries, and agriculture. Improving our ability to predict the impacts of natural resource utilization on the environment will help minimize the adverse effects of development activities and enhance their success. The knowledge required to achieve these objectives can be gained primarily through research. Ideally, research should precede intervention rather than follow it. The objective of this chapter is to review the experiences of two successful dryland regions and to develop a strategy for research and technology to increase the productivity and stability of rainfed agricultural systems.

II. Successful Dryland Regions

Dryland farming can be highly productive, although the system tends to be extensive rather than intensive. With similar agroclimatic resources, wheat yields in the U.S. Great Plains and southern Australia are two to four times that of the Near East and North Africa – 2.0 and 0.5 Mg ha^{-1}, respectively. Drylands in both the Great Plains and Australia experienced serious declines in productivity in the early part of this century. There are some lessons to be learned from the way in which their productivity was restored. Unfortunately, little attention has been given to the transfer of this knowledge and associated technologies to other regions.

A. Southern Great Plains

One of the best examples of improving dryland productive capacity is the Great Plains area of the United States. During the early to mid-1920s, rainfall was favorable in the southern Great Plains; farmers intensively cultivated and grazed their land. Then came the devastating drought of the 1930s. By 1932, the southern Great Plains was experiencing drastic declines in production and severe wind erosion. Farmers were ill-equipped to deal with this harsher environment. Many of them abandoned their land.

The U.S. government responded with its Land Utilization Program. Under this program, the most severely eroded land was purchased by the USDA and

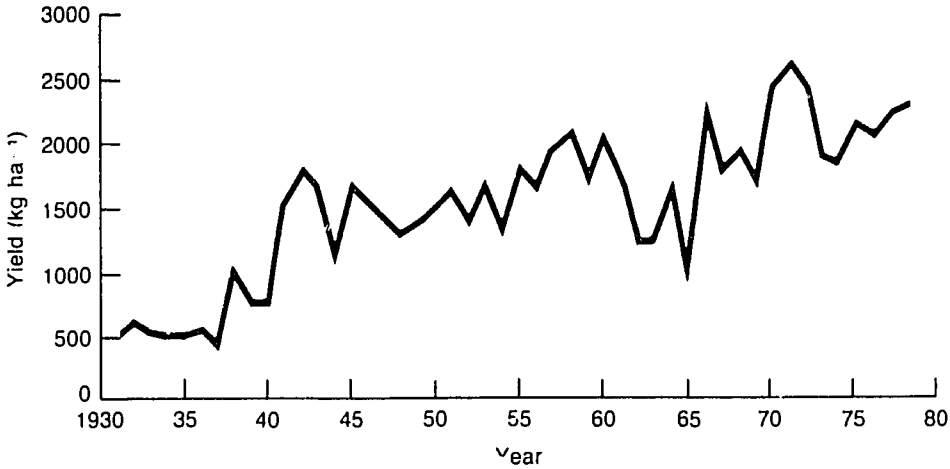


Figure 1. Average winter wheat yields in western Nebraska over time. (From Papendick, 1989.)

removed from production. The USDA's Soil Conservation Service (SCS) instituted a technical program to stabilize these blow lands. With the help of the USDA's Civilian Conservation Corps, they listed the land with deep furrows to catch soil and water, and drilled drought-resistant cover crops to reestablish the grasslands. Eventually these lands were returned to grazing. Federal land-use policies helped convert agriculture on marginal land in the southern Great Plains from crop production and overgrazing to controlled livestock raising, and sound range management (Hurt, 1985).

In addition to the land utilization projects, the U.S. government recognized the need for increased research on wind erosion control and the adoption of conservation practices by farmers. From the onset of the Dust Bowl, institutions were in place to address these needs. Under the state land-grant university system, state agricultural experiment stations and state extension services were poised to conduct relevant research and to transfer new technologies and conservation practices to farmers. The U.S. Department of Agriculture, through the SCS and the Agricultural Research Service, provided regional continuity to these activities. As a result of the combined efforts of federal and state research, extension, and action agencies, new cultivars and technologies were developed specifically for dryland farming systems. Federal legislation also assisted farmers who could not afford to implement soil and water conserving practices by making financial assistance available in the form of federal cost-sharing payments and subsidies.

Following the ecologic and economic devastation of the 1930s, the southern Great Plains has been transformed into one of the most efficient and productive grain-producing areas in the world. Although this was largely due to the expansion of irrigation, dryland productivity has also increased as a result of improved cultivars, and soil and water management (Fig. 1). Ironically the area has

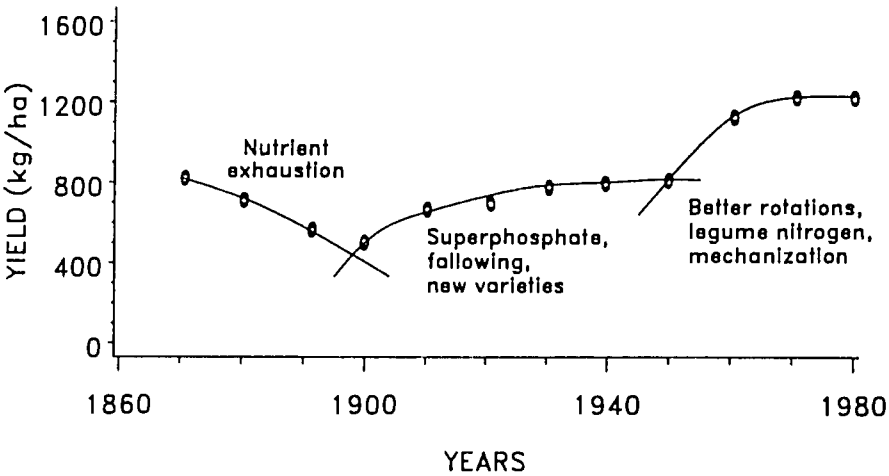


Figure 2. Australian wheat yields from 1860 to 1980. Each point indicates the unweighted mean of annual yields in the preceding 10 years. (From Donald, 1981.)

become a victim of its success and an increasingly global economy. Low world grain prices and increased production costs have reduced the profitability of farming. This simply illustrates that technology is not the ultimate solution; governmental policies and national and international linkages are also very important. The severe drought years of 1950–1956 in the southern Great Plains were potentially more severe than that of the 1930s, and wind erosion at times has been more devastating to localized areas. But the devastation has never recurred on such a large scale. Government policy, research, and farmers' application of conservation practices have continued to ensure against another Dust Bowl.

B. Southern Australia

In southern Australia, dryland productivity has increased dramatically since the turn of the century (Fig. 2). Initially (1900–1930), crop yields were increased by the use of superphosphate and wheat (*Triticum aestivum*)–fallow rotations. Continued use of these practices eventually depleted soil organic matter and resulted in deterioration of soil structure. Erosion became widespread.

From 1930 to 1950, rotations shifted toward wheat–oat (*Avena sativa*)–fallow systems, but yields remained the same. This was mainly because of nitrogen limitations. Then in the early 1950s, as a result of large increases in the price of wool, farmers shifted their emphasis from cropping to livestock. As a result, pastures of annual legumes were widely grown. The ley farming system evolved in which a self-seeding annual legume is grown in rotation with a cereal. Increases in cereal yields after 1950 are commonly attributed to nitrogen from annual legumes and improved soil structure. Superphosphate applications remain necessary to sustain

legume growth; however, it has been estimated that the value of the nitrogen added to the soil more than offsets the cost of phosphate (Carter, 1974).

The ley farming system is a natural outgrowth of the existing socioeconomic structure of rural Australia. The wheat farmer also raises sheep. Including a legume ley in the cereal rotation not only improved cereal production, but sheep numbers and wool production also increased (Puckridge and French, 1983). As a low-input, highly productive crop/livestock system, ley farming is now viewed as having enormous potential for countries in the Near East and North Africa.

Although the use of ley rotations began in the 1920s, the ley farming system was not widely adopted until after World War II. Donald (1981) has concluded that this was due to inadequate extension services. And while the U.S. government has pursued aggressive policies to protect its drylands since the 1930s, the Commonwealth of Australia has been slower to intervene (Bradley and Cornish, 1987). In 1983, however, the Commonwealth formally recognized the necessity for more coordinated land-use management within the country.

C. General Considerations

Government policies and both the availability and suitability of agricultural technologies have played important roles in the recovery of dryland productivity in the southern Great Plains and southern Australia. Today, particularly in the United States, the high costs of intensive production and concerns for the environment (e.g., soil erosion and groundwater quality) are causing some farmers to look for alternatives such as low-input farming systems. Farmers who have already undergone the transition from high- to low-input farming have reported that the process takes from 3 to 8 years to accomplish (Parr et al., 1989). With better scientific input, farmers may be able to shorten this transition period, as well as to ameliorate any adverse effects. Federal and state agricultural research institutions need to provide farmers with improved technologies that lower their production costs, sustain their production, and protect the environment. Government policies need to be modified to allow adoption of sustainable farming methods by farmers (Parr et al., 1989).

At least one consideration that may have important implications is the need to conduct priority research on-site (i.e., on-farm), and not at some distant location. Tools such as simulation modeling can provide powerful direction to basic research but cannot completely substitute for it. Even with all the important tools developed over the last 50 years, there is still the need to conduct site-specific research to derive appropriate technological solutions.

Achieving long-term, sustained growth in the productive capacity of low rainfall areas will require sound decisions based on accurate assessments of resource problems and potentials, and on careful analysis of alternative policies, programs, and projects. Hence, the capacity of governments and donor agencies to make the necessary technical evaluations and rigorous analyses must improve if the desired changes are to occur.

III. Dryland Technologies

Dryland agriculture is a rainfed crop production system in which a major limitation is the deficiency of water. However, insects and diseases, hail, high winds, and intensive rains are other hazards that can destroy crops in a matter of minutes. Many dryland areas also have severe soil problems. Consequently, dryland farming is, at best, a risky enterprise. This situation is further exacerbated because farmers in dryland regions are often resource poor, and these regions are usually of low priority when national budgets are drafted. Improving the productivity of dryland regions requires that constraints be clearly defined and programs developed to alleviate these constraints so that farmers can cope with them.

Crop productivity is a function not only of the genetic potential of the crop, but also of the agroclimatic, topographic, and soil environment in which the crop is grown. Man can modify both the crop genotypic potential and the physical environment to increase production. In dryland areas, however, it is usually the environment that limits crop yields.

A. Germplasm Improvements

Improved germplasm for wheat and rice (*Oryza sativa*) production was the foundation for the Green Revolution in Asia. Because of this tremendous achievement, many hopes have been placed on plant breeding and improved cultivars for other geographic areas. It is very important, however, to keep this in proper perspective when comparing dryland agriculture to the Green Revolution in Asia.

The Green Revolution occurred largely in irrigated regions or in areas of generally ensured rainfall. This ensured soil moisture reduced risk levels sufficiently to make investments in fertilizers, pesticides, and improved agronomic practices feasible. Thus, the interaction between the high yielding potential of the cultivars and favorable agronomic conditions was realized, leading to substantial net returns. Under dryland conditions, risk to the farmer remains high because of low and erratic rainfall; water supply is a major limiting factor in crop production. The emphasis, then, should be on soil and water conserving practices and stabilization of crop yields.

Another characteristic specific to dryland areas is that livestock is usually an important part of the production system. As a result, crop residues are, in many cases, as important to the farmer as the harvested grain. In this situation the emphasis should be on increasing the biological yield or biomass. In the short run this can be done by improved soil water storage and other soil management practices. In the longer term, crops may be bred or engineered for a number of yield stabilizing traits including (1) enhanced water use efficiency, that is, the ratio of biomass produced to water transpired by the growing crop; (2) remobilization of stored carbohydrate during grain filling; (3) chilling tolerance and early flowering for crop growth during periods of low evaporative demand; (4) crop

adaptation to optimum temperature ranges (thermal kinetic window); and (5) plasticity in root/shoot partitioning.

Improving germplasm for disease and insect resistance is another matter, and this activity is extremely important in dryland regions, as well as developing cultivars that are tolerant to soil constraints such as aluminum toxicity. Plants growing in tropical and subtropical areas are subject to a wide variety of disease and insect problems. For example, as crops are introduced into new areas, resistance to new pests and diseases is often lacking. Traits that improve the nutritional quality of food crops such as high lysine content in maize (*Zea mays*), or those that are advantageous from an agronomic or marketing perspective should likewise be of high priority in breeding programs.

B. Developing Appropriate Soil, Water, Crop, and Livestock Production Practices

The most immediate and significant improvements in dryland crop production will result from improved management practices. The first priority should be to identify existing technologies and adapt them to specific environments and economic and social conditions. Indigenous management practices and technologies should not be overlooked. The focus should be on soil and water conservation, increased biomass production, and cropping systems that maintain adequate soil cover and organic matter levels. Agronomic practices are much more effective when two or more are used in concert because of the positive interactions. For example, the maximum benefit of chemical fertilizers will not be achieved without improved water conservation. Even then, yield increases may not be realized without adequate weed control.

Specific examples of agronomic practices that could bring about immediate positive results in many dryland areas include (1) weed control, (2) improved crop geometry and population rates, (3) improved crop calendars linked to seasonal precipitation probabilities, (4) runoff-reducing practices including tied ridges and contour planting, (5) conservation bench terracing and mechanical and vegetative bunding, (6) maintenance of soil cover, (7) water harvesting systems, (8) improved tillage systems including minimum, ridge till, or no-till, (9) improved fertility practices including legumes and sod-based rotations, and (10) improved forage/livestock systems including forage legumes.

IV. Research and Technology Transfer

The research institutions in many developing countries of the world's arid and semiarid regions are lacking in the human and physical resources to implement effective research programs on dryland agriculture. Often the resources allocated to dryland agricultural research and development are minimal because primary attention has focused on irrigated agriculture or on higher rainfall areas. Although such inequitable allocation of resources does occur, and in some cases

might even be justified, recent experience has shown that successful development of dryland regions has happened only after research institutions were established to develop, adapt, and transfer these technologies.

In the less developed countries, the first priority should be to develop and adopt indigenous practices that will increase crop production and protect the resource base. Second, new and proven technologies from other regions should be evaluated to determine whether or not they can be easily adapted by farmers. Sound data bases are either nonexistent or inadequate on agroclimatology and soil resources. Yet these are essential for the evaluation of technologies for possible transfer and the development of dryland regions. Practices from other regions cannot always be transferred directly, but if the principles are applicable, specific practices can be altered to fit local environments and socioeconomic conditions.

As research institutions are developed, technology transfer capabilities (extension services) must also be improved and strengthened. In many countries, there are no existing links between researchers and farmers and this deficiency must be corrected. Even in developed countries where there are some strong linkages, technology adoption often lags behind research and development by as much as 10 or more years. Since time is critical in many developing countries, it is essential that technology transfer programs be established that effectively link the research scientist, the extension worker, and the farmer. This on-farm assistance may be critical to farmer adoption. Much of the adaptive-type research should be conducted on farmers fields and involve participation by the farmers themselves. In the United States, a particular type of technology transfer institution (Soil Conservation Service) provides much more technical service to the farmer than a traditional extension service.

Sustainable dryland agricultural systems are management intensive and information requiring. Information can be substituted for certain inputs. Or information can increase the efficiency of inputs assuming that it can be communicated to the farmer in an understandable and appropriate form. It follows, therefore, that educational, research, extension, and service institutions must become more effective and should have a high priority in governmental planning and implementation.

Dryland agricultural production systems can be thought of as the interaction of three domains—the biophysical or ecologic, the economic, and the sociocultural. Biophysical and economic principles are the most easily transferred. The sociocultural aspects of dryland systems are more difficult to quantify. This would seem to indicate that developmental agencies should put particular effort into understanding the biophysical domain since outside experts can readily provide input. The economic domain is less certain, but because of the influence of international marketing and pricing on the most remote farmer, outside individuals can also assist with these studies. It is questionable whether foreigners can sufficiently understand the sociocultural aspects. Integration of this domain would probably require indigenous or host country professionals and the investment in human capital by development agencies is thereby strongly justified.

Ultimately, prediction of farmer response is very difficult, even in the most developed countries where past behavior is well-documented.

V. Research Needs

The development of productive, profitable, and sustainable dryland agricultural systems necessitates a better understanding of the biophysical system to define, plan, and implement technologies that fit with, or require minimal changes in, the socioeconomic system. This includes a more complete characterization of the soil resource – physically, chemically, and biologically. It also requires an understanding of climate as a resource rather than as a constraint. Both of these issues are necessary for an improved system of agrotechnology transfer.

Specific examples of the agricultural and economic research needed to accomplish this include (1) biological dynamics of N cycling and availability; (2) microbiological research on biological N fixation and mycorrhizae; (3) relationships between particular soil characteristics and cropping systems; (4) integration of soil–water–plant relationships with developmental plant physiology; (5) understanding of cropping systems (e.g., trees, legumes, and forage/livestock), in relation to nutrient cycling, sinks, and supply; (6) understanding of agronomic systems (e.g., rotations, tillage, risks, and input/output costs), in relation to weed and pest control; (7) importance and value of crop residues in relation to maintenance of soil productivity, nutrient pools, livestock feed, water conservation, erosion control, and risk management; (8) relationship of soil characteristics to nutrient bioavailability and human/livestock nutrition; (9) integration of technologies on a whole-farm basis; (10) increasing yields faster than costs by changing production functions; (11) relationship of unitary costs of food production to farmer objectives (e.g., risk and other factors); (12) relationship of sustainable dryland agricultural production potentials to income factors, urbanization, and world marketing; and (13) developing means of providing more options and better understood options to the farmer so that he can select the alternatives that best fit his particular objectives and natural resources. These research needs are not limited to dryland systems.

VI. A Strategy for Achieving Improved Dryland Production

A scientific strategy for improving dryland production in areas with different levels of capability would involve the linkage of the scientific communities in countries with common research objectives. This would lead to a better understanding of dryland resources, the production potentials of those resources, and a sufficient understanding of the economic system to simulate possible production systems.

Primary steps would include the development of the following:

1. A data base of existing research information concerning the soil and water resources and the production systems;
2. Workshops with participants from the host country, international research organizations, and both developed and developing country scientists to outline priorities for research activities; and
3. Research activities linked by common research objectives and methodology and conducted in both developing and developed countries for improved understanding and extrapolation of results to areas of need.

The scientist-to-scientist linkages developed by these steps would provide a powerful network of researchers resulting in a synergistic increase of research information and utilization. Taking any one of these steps without committing the financial resources to complete all three provides only a limited impact on dryland development.

The lack of developmental success in the drylands of some regions, as illustrated by the negative per capita food production trends in Africa, makes it imperative to take a second look at dryland successes. It seems evident that in dryland areas experiencing declines in production, cropping systems are mining the soil resource (Fig. 2). With current production potentials at the left of the curves in Figures 1 and 2, the challenge for science is to shorten the time it takes to get from the left to the right. In the cases of the U.S. Great Plains and Australia, the recovery processes took more than 50 years. Today, with the current body of scientific knowledge and tools such as simulation modeling, global geographic information systems, and remote sensing, the time needed to increase dryland productivity (as in Figs. 1 and 2) should be greatly reduced. These same scientific resources can also ensure that production increases in an environmentally sustainable manner.

Certainly science and technology alone will not result in the elimination of poverty, environmental degradation, or inadequate food production. Dryland recovery also depends on political and financial commitment by donors and governments. Equally essential are infrastructure and institutions for the provision of basic education, extension and technical services, research, and appropriate governmental policies. Ultimately we may find that there is more plasticity in the sociocultural and economic aspects of agricultural systems than in their biophysical aspects.

References

Carter, E.D. 1974. Stocking rate and the ecosystem: Some soil-plant-animal interrelationships in South Australia. Proc. XII Int. Grassl. Congr., Moscow, USSR, 1974.

Donald, C.M. 1981. Innovation in agriculture. *In* D.B. Williams, ed. Agriculture in the Australian economy. pp. 57-86. Sydney: Sydney University Press.

Hurt, R.D. 1985. The national grasslands: Origin and development in the Dust Bowl. *In* D. Helms and S.L. Flader, eds. The History of Soil and Water Conservation. pp. 144-157. Washington D.C.: The Agric. History Soc.

Indo-U.S. Subcommission on Agriculture. 1987. Combined report of the U.S. Dryland Farming Team and the Economics Team Visits to India, March/April and June 1987.

Papendick, R.I. 1989. Storage and retention of water during fallow. *In* C.E. Whitman, J.F. Parr, R.I. Papendick and R.E. Meyer, eds. Proc. of the Workshop on Soil, Water and Crop/Livestock Management Systems for Rainfed Agriculture in the Near East Region, Amman, Jordan, Jan. 18-23, 1986. pp. 260-269. U.S. Gov. Printing Office, Washington, DC.

Parr, J.F., R.I. Papendick, I.G. Youngberg, and R.E. Meyer. 1990. Sustainable agriculture in the United States. *In* Proc. Int. Conf. on Sustainable Agric. Sys., Columbus, Ohio, Sep. 19-23, 1988. pp. 50-67. Soil and Water Conservation Society, Ankeny, IA.

Pratley, J.E., and P.S. Cornish. 1987. Responsible land use: The role of government. *In* P.S. Cornish and J.E. Pratley, eds. Tillage: New Directions in Australian Agriculture. pp. 420-434. Melbourne: Inkata Press.

Puckridge, D.W., and R.J. French. 1983. The annual legume pasture in cereal-ley farming systems of southern Australia: A review. Agric. Ecosystems Environ. 9:229-267.

Index

A
Abiotic
  constraints, 217
  factors, 134
Acidification, 5
Actinomycetes, 55, 244, 246-247
Acuff loam, 56
Adaptive research, 267
Aeration, 56, 105, 134-135
Aerobic processes, 137-138
Aeronosols, 304
Africa, 1, 7, 11, 54, 71, 74, 132, 156, 165, 188, 193, 257, 274, 285-287, 293, 295-296, 302, 307-308, 311, 324, 347-349, 357
Aggregate stability, 242
Aggregates, 32, 47, 49-50, 55-56, 60, 73, 76-77, 92, 105, 139, 185, 188
  water stable, 94, 242-243
Aggregation, 69, 85, 112, 136, 139
Agricultural chemicals, 178, 269, 302
Agroclimatic
  characteristics, 279
  constraints, 274
  potentials, 170
  zone, 320
Agroclimatology, 9-24, 170, 303, 355
Agroecosystems, 245, 247
Alabama, 116
Alfalfa, 144, 232, 245
Alfisols, 122, 167, 284, 304-305, 313
Algae, 178-179
Algeria, 82
Aluminum toxicity, 313, 354
Ammonia volatilization, 135, 146
Ammonification, 137-138, 245
Ammonium
  nitrate, 146
  oxidizers, 244
Anaerobic
  conditions, 222
  processes, 137-138
Animal
  traction, 318, 320, 325-327
  wastes, 178
Aquatic life, 187
Arachis hypogaea, 71
Argentina, 11
Arid regions, 1, 4, 22, 192-193, 197, 329, 347
  map, 194
Arid zones, 311
Aridic Paleustoll, 56
Aridisols, 71
Aridity index, 21-22
  arid zone, 21
  hyperarid zone, 21
  semiarid zone, 21
  subhumid zone, 21

Aridosols, 313
Arthopods, 244–245
Asclepias syriaca L., 31
Ascochyta spp., 215
Asia, 54, 71, 132, 193, 347, 353
Aspergillus, 244
Atmospheric warming, 241
Atrazine, 31, 41–43, 58
Australia, 22, 29, 71, 77–80, 132, 139, 144, 155, 166, 189, 192–193, 219, 277, 334, 335, 336, 347, 349, 351–352, 357
Available soil water, 223, 338
Available water supply, 254
Avena sativa, 226, 351
Avocado, 54
Azotobacter, 244
Azotobacter sp., 242

B
Bacteria, 55, 137, 230, 232, 243–244, 246–247, 270
  aerobic, 244
Barley, 29, 221, 224–226, 229–230, 232, 245, 264, 268
Base saturation, 71
Basin listing, 37, 94, 114, 338
Beans, 71, 220–222
Beijerinckia indica, 242
Belgium, 287
Bench terracing, 354
Benin, 295
Bioclimatic regions
  Sahel, 307
  Sudan, 307
Bioclimatic zones, 285
  northern Guinean, 285
  Sahel, 285
Biodiversity, 241–242, 246
  dynamics, 243
  microbial, 244
  soil, 244–245, 247
Bioindicators, 242–243, 247
Biological activity, 122, 134–135, 143
Biotechnology, 3
Biotic
  activity, 123
  factors, 134, 264
Birds, 318
Botswana, 39, 279, 302–308
Brazil, 71
Bromegrass, 133, 139
Bromus inermis L., 139
Buffer action, 73
Buffering capacity, 72
Bulk density, 55, 77–78, 81, 85, 92, 94
Burkina Faso, 17, 19, 23, 165, 285–287, 290, 293–295, 297, 301–302, 311
Bush fallow, 57

C
C. gramineum Fusarium oxysporum, 218
C:N ratios, 75
Cajanus cajan Millsp., 57
Calcium, 232
California, 161, 348
Cameroon, 285
Canada, 29, 78, 84, 116, 262, 347
Canadian prairies, 71, 78, 80
Canopies, 55, 169
Canopy, 151, 164
  development, 336
Carbon cycling, 241
Carbon-nitrogen ratios, 243
Castor, 284
Cation exchange capacity, 73
Cenchrum sp., 31
Cephalosporium gramineum, 224
Cephalosporium spp., 215
Chad, 285, 311
Chickpea, 1, 220, 284
China, 11, 193

Chloropicrin, 217
Citrullus vulgaris, 222
Climatic generation, 181
Climatic zones
  Mali, 314
  Sahel, 314
Clods, 92, 95, 105, 113, 167, 195
Clovers, 224
Cobalt, 135
Cochliobolus sativus, 221
Collembola sp., 245
Colorado, 36, 40, 43, 167
Compaction, 5, 34, 55-56, 99-100, 106, 112, 114, 118, 122, 124-125, 313
Conservation
  bench terrace, 168
  benefits, 326-327
  practices, 4-5, 348, 350
  Reserve Program, 246
  tillage, 3-4, 7, 28-60, 93, 95, 98, 105, 176, 229, 255, 269
  tillage, definition, 28, 226
Contour
  cropping, 93
  cultivation, 304
  farming, 5
  planting, 354
  tillage, 34
Contouring, 50
Conventional tillage, 34, 37, 46, 54, 59, 78-80, 219, 224, 225, 242-243, 245, 254, 263-264, 269
  definition, 28
Copper, 132, 135, 223
Corn, *see also* Maize, 33-34, 81-82, 91, 113, 120, 142, 143, 225-227, 324
Cost return data, 325
Cotton, 31, 48, 70, 92, 164-165, 221, 284
Crop
  calendars, 155, 318, 320, 322, 354
  coefficients, 19, 292, 323
  geometry, 354
  management factor, 179
  management practices, 307-308
  management strategies, 312, 326
  phenology, 334
  productivity, 353
  residues, 4-5, 7, 28, 30-39, 42-43, 45-53, 55-57, 59-60, 70, 72, 74-77, 79-80, 82-85, 91-92, 94, 98-100, 105, 109, 112-113, 118, 124, 133, 135, 138-141, 143-146, 166-167, 176, 195, 197, 215, 218-219, 228-229, 243, 253-270, 356
    burning, 70, 80, 98, 219-220, 228-229, 258
    densities, 36
    irrigated, 42-43
    orientation, 36
  rotations, 3-5, 30-32, 41, 50, 82-84, 124, 144, 217, 223-226, 229, 230-233, 243, 267, 268, 270, 318-319, 341, 351, 352, 356
Cropping systems, 37, 70, 72, 79-80, 85, 143-145, 151, 170, 216, 245, 263, 320, 333, 336, 341, 354, 356-357
Crusting, 5, 34, 50, 56, 84-85, 91, 94, 99, 105, 122, 124-125, 136, 254, 313, 316
Cultural practices, 145, 165

D

Deep plowing, 188, 304
Deep tillage, 96
Degradation, 1, 4, 46
  potential, 248
  processes, 5
Degradative processes, 4
Dehydrogenase, 243
Denitrification, 135, 137-138, 181, 269

Desertification, 5, 197
Developing countries, 1, 23, 169, 176
Disease, 335, 337
Disease resistance, 165-166, 354
Diseases, 1, 7, 23-24, 46, 52, 60, 89, 144, 163, 169, 176, 215-233, 264, 281, 318, 353
  resistance, 165-166, 354
DNA probes, 231
Drainage, 5, 122, 151, 222, 348
Drought, 1-2, 314
  stress, 338
  year, definition, 280
Dry savanna, 275
Dryland
  farming, definition, 90, 151
  regions, 13
Drylands, 1-2
Dust
  mulch, 43
  storm rating system, 192
Dust Bowl, 189, 226, 350-351

E
Earthworms, 55-56, 245, 254
Ecofallow, 29, 120, 144, 231
Ecological disturbance, 242
Ecology, 134, 232, 245
  soil, 247
Economic
  conditions, 170
  pressure, 183
Ecosystems, 144, 241-242, 246, 248
Electrical conductivity, 136
Energy
  conservation, 233
  inputs, 226
England, 193
Entisols, 313
Environment, 3, 193, 222
Environmental
  degradation, 241, 357
  factors, 232, 312
  quality, 47, 51
Enzyme activity, 243
Erosion, 1-2, 4-5, 46-57, 60, 71-72, 74, 77, 78, 80-81, 91, 93-94, 113-114, 125, 144, 146-147, 181, 183, 241-242, 247, 268, 323-329, 334, 352
  accelerated, 175, 183
  control, 141-142, 166-167, 269, 318, 320, 324, 328, 356
    measures, 52
    practice factor, 179
    practices, 176-177
  geological, 175
  gulley, 50, 181
  interill, 181
  prediction, 177, 179-180
  rill, 50, 181
  topsoil, 316
  water, 5, 7, 38, 47, 49, 51, 55, 69-70, 82-85, 91, 99, 105, 112, 123, 146, 175-183, 225, 254, 264-266, 341
    USLE equation, 50, 324
  wind, 5, 7, 47-49, 51, 55, 60, 69-70, 82, 83, 84-85, 91-92, 94-95, 99, 105, 112, 123, 167, 187-197, 225, 254, 264-266, 341, 349-351
    control, 187-188, 195, 265
    equation, 48, 188
Ethanol, 222
Ethiopia, 276, 278
Euclidean matrix, 23
Euphrates River, 348
Eurasia, 71
Europe, 54, 193
Eutrophication, 178-179
Evaporation, 19, 22, 24, 32, 35-40, 45, 53-54, 77, 80, 89, 91-92, 105, 123, 141, 145-146, 151, 163, 166-169, 188, 256, 262, 264, 266, 337, 341

control, 258
losses, 338
open-pan, 278
potential, 335
rates, Class A pan, 285
reducing, 255
reduction, 143
stages, 35, 258, 260
Evaporative rate, 292
Evapotranspiration, 15, 18, 152, 155, 159-164, 166-168, 268, 284, 321
Exchangeable sodium percentage, 136
Experimental designs, 203

F
F. culmorum, 221-222, 231-232
F. graminearium, 221-222
F. moniliforme, 222, 231
F. solani f.sp. *phaseoli*, 222, 232
F. solani f.sp. *pisi*, 221
Faba bean, 144
Fallow, 31-34, 39, 41-44, 54, 58, 75, 80-83, 96, 106, 123, 137-138, 141-142, 144, 157, 166-167, 220, 224-226, 255, 262, 266, 268, 351
efficiency, 167, 254, 256
definition, 254
weedy, 143, 268
Fallowing, 143
Farming systems, 2-7, 70, 83, 133, 319
Fauna, 56, 225, 245
Faunal activity, 134
Feldspars, 136
Fertilizer applications, 319
Fertilizer practices, 145
Fertilizer, 2, 4-5, 51-52, 70, 75-76, 80, 82-83, 85, 89-90, 132-133, 141, 143, 146, 156, 168-169, 179, 201, 206-210, 243, 245, 247, 254, 263, 269, 281, 302, 316, 318, 320, 325, 327, 329, 336, 338, 340-341, 348, 353-354
application, 319
liquid, 109
placement, 83-84, 121, 123, 145, 206, 266-268
practices, 145
Fescue grass, 245
Field capacity, 161, 260
Fish habitat, 178
Foot rot, 221, 223, 231-232
Foxtail millet, 284
Fragile lands, 242
Fragipan, 95
Fulvic acid, 243
Fungal hyphae, 242
Fungi, 55, 74, 137, 215-216, 218, 220, 224, 225, 227, 244, 246-247
Fungicides, 229
Furrow *see also* Tied ridges
dams, 168
dikes, 34, 37, 50, 114, 116, 318, 338-339
Fusarium, 244
Fusarium culmorum, 218, 224
Fusarium oxysporum, 221, 232
Fusarium solani f.sp. *pisi*, 219
Fusarium spp., 215, 218, 220-221

G
G. graminis var. *tritici*, 224, 230, 233
Gaeumannomyces graminis var. *tritici*, 220, 228
Gaeumannomyces spp., 215
Gaeumanonmomyces graminis var. *Tritici*, 53
Gambia, 285, 311
Gene manipulation, 233
Geographic information systems, 357
Ghana, 285
Global weather patterns, 193

Glycine max, 225
Glycine max (L.) *Merr.*, 165
Glycine max L., 51
Goats, 143
Gossypium hirsutum, 71
Gossypium hirsutum L., 31, 164
Governmental policies, 357
Graded furrows, 34
Grasses, 132, 224
Great Plains, 2, 18, 35, 38, 42, 48, 58, 77–78, 90–96, 105, 112, 144, 157–158, 164, 167–168, 188–189, 195, 197, 261–263, 266, 348–349, 352, 357
Green Revolution, 349, 353
Greenbug, 52
Groundnut, 1, 71, 284–285, 320, 323, 325–326, 329
Groundwater, 176, 179–180
  contamination, 182, 269
  quality, 352
Growing
  period, 22
  season, 284, 328
    length, 278, 292
Guayule, 334
Guinea, 285
Guinea Bissau, 285
Guinea grass, 57
Gypsum, 96, 136

H

Hail, 353
Hardpan, 95
Harvest index, 112, 152–155, 165, 169
Hawaii, 232
Helianthus annuus, 166, 335
Helianthus annuus L. 37
Herbicide-resistant weeds, 31
Herbicides, 30–32, 39, 41–43, 45, 58–59, 81, 89–90, 95, 97, 99, 113–114, 116, 118, 124–125, 143–144, 176, 224, 245, 263, 266, 269–270, 274
  2,4-D, 43
Heterodera avenae, 221
Hordeum vulgare, 224, 264
Hordeum vulgare L., 29
Household wastes, 178
Humic
  acid, 243
  substances, 69, 72
Humid
  month, definition, 275
  regions, 1, 18, 120, 139, 193, 335
  savanna, 275
Humus, 74
Hydraulic conductivity, 56–57, 136
Hydrology, 337

I

Idaho, 38, 219, 223, 227
Illinois, 101–103, 108, 115
Immobilization, 79, 81, 124, 269
India, 2, 10, 16, 22–23, 54, 71, 78, 80–81, 90, 122, 132, 156, 161, 167, 188–189, 257, 276, 278–280, 282, 284, 305, 307–308, 340, 349
  irrigated agriculture, 274
Indian desert, 244, 247
Infiltration, 32–34, 37, 39–40, 45, 47, 50, 55–57, 60, 77, 80, 83–85, 91–92, 94–96, 105–106, 114, 117, 122, 124, 136, 151, 168, 181–182, 219, 243, 254–255, 257, 269, 313, 321, 323, 325, 328, 338–339, 341
  rate, 20, 319–320
Infrastructure, 348
Inoculum
  density, 219, 224
  potential, 223, 225–226, 229, 232
Input costs, 333
Input/output
  coefficients, 325
  costs, 356
  ratios, 329
Insecticides, 176, 274, 341

Insects, 24, 46, 52, 60, 89, 144, 163, 264, 353
  control, 318
  problems, 176
  resistance, 165–166, 354
Intercropping, 124, 144, 284, 304, 318–320
Intertropical convergence zone, 278–279
Iowa, 270
Iran, 18
Iraq, 83
Iron, 132, 135, 223
Irrigated
  agriculture, 2, 169, 274, 354
  land, 313
  regions, 353
Irrigation, 44, 58, 70, 96, 133, 139, 141, 152, 178, 188, 231, 244, 350
  projects
    costs, 347
    developing countries, 348
  scheduling, 341–342
  supplemental, 82, 305
  sustainability, 348
Israel, 161, 193
Ivory Coast, 16

J
Jojoba, 336

K
Kansas, 38, 77, 161, 227
Kenya, 277–278

L
Land
  degradation, 242
  leveling, 93
Lateritic soils 313
Law of the Limiting, 132–133
Leaching, 5, 73, 96, 146, 269
  nitrate, 269
Lebanon, 18
Lentil, 144
Ley farming, 351–352
Liebig, 132
Lime, 341
Livestock, 7, 268, 350–351, 354, 356
  production, 3, 6
Long rains, 278–279
Lupin, 224
Luvisols, 71, 84
Lysine, 354

M
Macroorganisms, 135
Macrophomina phaseoliola, 222
Magnesium, 223
Maize *see also* Corn, 23, 28, 32, 51, 54, 57, 165, 220, 284, 285, 304, 312, 316, 320, 323–325, 341, 354
Mali, 13, 257, 285, 293–296, 301–302, 311–315, 317, 319–320, 322, 328, 348
Manganese, 135, 223
Manure, 133, 138, 179, 245, 316
  animal, 3–5, 81, 269
  farmyard, 244
  feedlot, 142
  green, 3, 81–83, 133, 138, 144
Markov chain procedure, 281, 283
Matric potential, 46, 57
Mauritania, 285, 311
Medicago sativa, 232
Medicago sp., 82–83
Mediterranean
  climate, 10, 156
  Sea, 10
Metalaxyl, 216, 227
Methemoglobinemia, 178
Methyl bromide, 216
Mexico, 71
Microbes, 254

Microbial
activity, 72, 77, 79, 81-82, 105, 134-135, 137, 139, 143, 242-243, 245
diversity, 242
Microbiology, 137
Microconidia, 221
Micronutrients, 72-73, 132, 135, 138
Microorganisms, 74-76, 134, 216-218, 228-229, 232, 248
Millet, 19-20, 41, 70, 90, 93, 165, 257, 259, 285, 292, 304-305, 307, 312, 316, 318, 320, 323-325
Mineralization, 70, 73-75, 81, 84, 105, 124, 137-138, 179, 181, 243, 245
Minimum tillage, 37, 78-79, 246, 263, 354
Mites, 245
Model
ACTMO, 180-181
AGNPS, 181
agronomic, 170
AGVISER, 341
ARM, 180
CMLS, 181
COMAK, 341
CREAMS, 180-181
crop, 14, 17, 161
growth, 24, 170, 334
management, 264
production, 264
simulation, 333-345
CROPEVAL, 336
CSU, 180
disease, 17
empirical, 179
EPIC, 177, 339, 341
erosion, 183
prediction, 264
evaporation, 17
evapotranspiration
Blaney-Criddle, 19
evaporation pan, 19
Jensen-Haise, 19, 21
Penman, 19
Penman-Monteith, 19
Priestly-Taylor, 19
Thorntwaite, 19
GLEAMS, 180-181
GROWEST, 334
hydrologic, 180-181, 339
HYMO, 339
insect, 17
leaching, 181
LEACHM, 181
MUSLE, 179-180
NTRM, 341
planning, 17
process based, 179, 182
process-driven, 180
PRZM, 181
SHAW, 260
simulation, 7-24
SIRAGCROP, 341
Smith's, 180
SORGF, 304, 338-339
SORKAM, 180
Stanford, 180
USLE, 179-183
water
balance, 15, 322, 328, 334
quality, 182-183
WEPP, 180-183
wheat growth, 341
whole-farm, 325, 327
yield, 170
Moisture
availability index, 158
conservation, 328
Moldboard, 47, 53, 56, 77, 99-101, 112-113, 219, 264
Mollisols, 71, 73, 132
Molybdenum, 132
Montana, 38, 40, 145, 167, 227
Montmorillonite, 71
Morocco, 156
Mucor, 244

Mulch, 33, 35–36, 40, 51, 53, 72, 77–78, 80–81, 91–92, 118, 122, 164, 167–168, 225–227, 229, 231, 254, 263, 266, 318
Mulching, 176
Municipal wastes, 5
Mycorrhizae, 356
Mycorrhizal infections, 135

N
N^{15}, 79
N^2 fixation, 142, 144
Natural resource base, 1, 3, 176, 327
Near East, 1–2, 17–18, 156, 268–269, 347, 349, 352
Nebraska, 38–40, 109, 113, 142, 167, 227, 231, 263, 350
Nematodes, 216, 221
Net radiation, 15, 54
New Zealand, 267
Niger, 12, 16–17, 276, 278, 285, 287–290, 293–299, 301–302, 311–312, 348
Nigeria, 32, 34, 285, 324
Nitrate, 112, 137, 146, 178, 181
Nitrification, 82, 137–138, 181
Nitrite, 137, 178
Nitrobacter, 137
Nitrococcus, 137
Nitrogen, 53, 70–73, 75–78, 80–85, 105, 132, 133, 137, 139–143, 146, 169, 178–179, 181, 206, 218, 226, 230, 243, 269, 304, 313, 325, 338, 340–342, 351–352
  ammonium, 137
  availability, 135
  cycling, 356
  deficiency, 124
  fixation, 356
  transformations, 135
Nitrosomas, 137
Nitrosomonas sp., 244
No-tillage, 29, 31–34, 37, 39, 42–44, 46–48, 53, 55, 56–59, 78–79, 90, 116, 118–125, 138, 167, 176, 225, 243, 245, 260, 263–264, 266–267, 269, 354
Nodulation, 135
North America, 10–11, 54, 71, 90, 132, 166, 193
North Dakota, 17–18, 111, 140, 262
Nutrient
  cycling, 5, 7, 81, 85, 131–147, 268, 356
  depletion, 1
  pools, 356

O
Oats, 226, 232, 351
Off-site damages, 178, 182
Ohio, 33
Oklahoma, 227
Opportunity cropping, 157
Oregon, 109, 219, 227
Organic
  matter, 2, 4–5, 7, 37, 49–50, 52, 55, 57, 69–85, 105, 132, 136–140, 179, 241–247, 313, 316, 351, 354
  wastes, 3, 5
Orthents, 284
Orthids, 283
Oryza sativa, 29, 353
Oryza sativa L., 165
Osmotic potential, 135–136, 145
Overgrazing, 268

P
P. irregulare, 224–225
P. ultimum, 224–225
P^{32}, 145
Pacific Northwest, 2, 46, 230, 232, 254–257, 266
Panicum dichotomiflourum Michx., 31

Panicum maximum, 57
Panicum miliaceum, 257
Parthenium argentum, 334
Pasture, 284, 305, 313
Pearl millet, 1, 156, 283, 288
Peas, 71, 81, 144, 219–220, 222–223, 225, 268
Penicillium, 244
Pennisetum americanum, 70, 288
Pennisetum typhoides, 156
Percolation, 35, 37, 52, 182, 257, 319
Pergamenus sp., 245
Persea americana L., 54
Pest
  control, 133, 356
  infestations, 316
Pesticides, 2, 4, 51, 73, 90, 178–179, 181, 254, 269, 342, 353
  degradation, 181, 269
  washoff, 181
Pests, 281
pH, 79, 136–137, 206–210, 230
Phenology, 337
Phenols, 72
Phosphate, 136–137, 243, 348, 352
Phosphorus, 53, 70–73, 78, 80, 84, 132, 138, 143, 179, 181, 206, 223, 226, 304, 313, 325
  availability, 81, 137, 145
  cycling, 341
  extractable, 82
  organic, 135, 140
  placement, 83, 85
Photosynthesis, 138, 168
Physical
  conditions, 92, 226
  properties, 77–78, 81, 85, 123, 248
Phythophthora spp., 220
Phytoxicity, 227
Pigeonpea, 1, 57, 284
Pisum sativum, 268
Pisum sativum L., 219
Plant
  available water, 37, 57, 159
  breeding, 165–166, 253
  canopies, 35
  geometry, 145, 152
  population, 46, 145, 153–154, 156, 290, 336–337, 354
Plowpan, 95
Pollutants, 51–52
Pollution, 60
  environmental, 246
  groundwater, 2, 4, 52
  nonpoint source, 178
  surface water, 2, 4
Polypeptides, 72
Polysaccharides, 72, 77, 242–243
Population
  growth, 1
    rate, 312
  pressure, 183
Pore space, 34–35, 94, 105, 138
Pores, 135, 137
Porosity, 35, 55–56, 94, 139, 245
Postharvest losses, 318
Potassium, 53, 80, 84, 136, 206–207, 223, 325
Potato, 206–209, 232, 336–337
Potential
  evaporation, 21, 71
  evapotranspiration, 20, 23, 158, 162, 275–276, 278–279, 283, 335
Poverty, 357
Processes, geomorphological, 187
Psamments, 283
Pseudomonas spp., 230, 233
Pullman clay loam, 167
Pulses, 224
Pythium spp., 215, 218–220, 222, 224–228

R

R. solani, 225
R. solani AG8, 218, 228

Radiant energy, 35–36, 53
Radiation, 336
  balance, 193
Radiocarbon dating, 76
Raindrop
  energy, 32, 47, 50, 60
  impact, 47, 49–50, 56, 94, 105, 124, 169, 254, 257, 265
  splash, 49
Rainfall, 322
  amount, 289, 296–298, 300, 302
  dependability, 281
  distribution, 281, 283, 286, 328–329
    Mali, 314
  intensity, 33, 50, 274, 285, 289–290, 298, 300
  onset, definition, 290–291
  patterns, 21, 322–323
    bimodal, 278, 280, 284
    continental, 10–11, 15, 17–18
    multimodal, 10–11, 15
    summer, 10–11, 15, 17, 266
    unimodal, 278, 280, 285, 303
    winter, 10–11, 15, 18
  probabilities, 158–160
  use efficiency, 304
  variability, 9, 274, 279, 307–308, 319
Range, 313
Ratooning, 339–340
Recreational potential, 178
Reduced tillage, 59, 82–85, 112, 114, 116, 119, 122, 124–125, 138, 176, 228
Relative humidity, 17–18, 35, 223
Reservoir siltation, 178
Residues *see also* Crop residues, 5, 54, 81, 89, 93, 114, 124–125
Resource base, 7
Respiration, 138, 241
Response farming, 156, 307
Rhizoctonia solani, 220–221
Rhizoctonia solani AG8, 224
Rhizoctonia spp., 215, 218
Rhizosphere, 85, 215–216, 222, 230, 232, 244–245, 270
Rice, 29, 75, 144, 312, 316, 320, 325, 340, 353
Ridge
  planting, 29
  till, 354
Risk, 7, 156, 170, 302, 304, 307, 328, 335–337, 348, 353, 356
Rodents, 46, 53
  control, 318
Root
  activity, 134, 137
  density, 218
  development, 168, 254
  elongation, 227
  growth, 69, 79, 92, 96, 135, 341
  infecting pathogens, 215–233
  penetration, 83–85, 96
  rot, 221–225, 228, 231–232
  zone, 180
Rooting
  depth, 20, 165
  pattern, 165
Row
  dams *see also* Tied ridges, 338
  spacing, 145, 147, 153–154, 267, 290, 336
Rubber, 337
Ruminant animals, 7
Runoff, 2, 4–5, 32–35, 37–38, 45, 47, 49, 51–52, 84, 91, 94, 105, 114, 146, 151, 166–167, 176, 179–182, 247, 257, 259, 268, 305, 313, 338–340, 348, 354
  control, 256
  control practices, 341
  curves, 323
  erosivity factor, 179
  prediction, 182
  reducing, 80, 83, 168, 255, 265
Rye, 226

S
Saccharum officinarum L., 54
Sahara, 1, 7, 10, 188–189, 193, 197, 274, 285, 293, 299, 314
Sahel, 74, 274, 279, 285–287, 295, 305–308, 311–314, 319, 328–329
  carrying capacity, 312
  life expectancy, 311
  per capita income, 311
Saline
  areas, 189
  seeps, 96
  soils, 96, 166
Salinity, 348
Salinization, 5
Sand encroachment, 313
Schizaphis graminum Rondani, 52
Secale cereale, 226
Sediment, 2
Seed germination, 30, 56, 145, 161, 167, 220, 225, 226, 229, 316
Seeding rate, 152, 274
Seedling blight, 226
Semiarid
  areas, 114, 124, 336
  Mediterranean region, 71
  regions, 1, 4, 9, 14–15, 18–20, 23, 70–72, 74, 77–78, 80, 82–85, 120, 187, 192–193, 197, 269, 329, 347
  steppe, 71–72, 74, 77
  tropical regions, 78
  tropical zone, 71
  tropics, 23, 71, 74, 77, 85, 90, 273–308
    agroecological features, 274–275
    climatic classification, 275
    population, 273
    zones, 311
      definition, 71
Semidesert, 275
Senegal, 13, 17, 23, 276, 285, 293–295, 301–302, 311–312
Septoria spp., 215
Sheep, 143, 352
Shelterbelts, 188
Short rains, 278–279
Simmondsia chinensis, 336
Slope steepness factor, 179
Slot plant, 29
Snow
  control, 261
  trapping, 91, 94, 123, 144, 167
Social economics, 170
Socioeconomic factors, 312
Sodic soils, 136
Soil
  biota, 241
  compaction, 232
  degradation, 195, 242–243, 247, 349
  deterioration, 143, 316, 351
  erodibility, 180
  erodibility factor, 179
  fertility, 1, 5, 7, 46, 69, 82–83, 97, 112, 132, 166, 168, 195, 202, 218, 230, 241, 244–245, 247, 268, 274, 325, 354
  freezing, 257
  fumigation, 216–218, 223, 228–230
  loss tolerance, T, 182
  productivity, 1–2, 4–5, 6, 69–72, 80, 82–85, 142–143, 177–178, 182, 195, 242, 246–248, 264, 269, 323, 327–328, 349, 352, 356
    declining, 253
  resource base, 355, 357
  roughness, 48–50, 196
  salinity, 135–136, 146
  sealing, 85, 313
  strength, 94
  structure, 73, 76–77, 82–85, 89, 105, 112, 122, 124, 136, 243, 247–248, 313

temperature, 17, 36, 53–54, 91, 123, 133, 135, 138, 245, 247, 278, 341
variability, 204–207, 210
Soil acidity, 313
Solanum tuberosum, 232, 336
Solar radiation, 13–15, 91, 105, 316, 335, 338
Solute transport, 341
Sorghum, 28, 36–37, 39–41, 43–45, 52, 58, 70, 90–93, 106, 113, 144, 152–154, 157–167, 221–222, 226, 263, 284–285, 302, 304–305, 312–316, 318, 320, 322–325, 336–339
growth stages, 304
Sorghum bicolor, 226, 336
Sorghum bicolor (L.) Moench, 28, 152
Sorghum vulgare, 70, 263
South America, 10–11, 132, 193
South Dakota, 33–34, 91
Soviet Union *see also* USSR, 11
Soybean, 51, 82, 120, 142, 145, 156, 165, 225–226, 232, 284
Spatial variability, 181, 201–212, 278
Spinach, 222
Stalk rot, 52, 221–222, 231
Statistical techniques, 202
Straw barriers, 188
Streptomyces, 244
Strip cropping, 34, 50
Strip tillage, 29, 113–114, 116
Stubble mulch, 29, 37–38, 43, 48, 59, 78, 80, 84, 105, 106, 109, 112, 124, 141, 226, 263, 304
Subhumid regions, 1–112, 120
Subsurface tillage, 29
Subtropic regions, 55
Subtropical areas, 132, 143
Sudan, 17, 307, 348
Sugar cane, 54
Sugarbeet, 92
Sulfur, 53, 70, 72–73, 78, 81, 83–84, 226, 313
Sunflower, 37, 43–44, 166, 335
Superphosphate, 351
Surface roughness, 34–35, 91–92, 94, 105, 112
Surface sealing, 49–50, 60, 257
Surface water contamination, 269
Sustainability, 349, 356
Sustainable agriculture, 2–4, 6, 233, 248
Sustainable production, 241
Sweetclover, 144
Syria, 18

T

Take-all disease, 53, 223–225, 228–230, 233
Tanzania, 277–278
Temperate regions, 131–132, 136, 143
Temporal variation, 181, 278
Termites, 245, 254, 257
Terraces, 34, 93
bench, 175
Terracing, 5, 50
Texas, 11–13, 18–19, 37–38, 43–44, 59, 94, 103, 109, 154, 158–161, 166, 167, 189–190, 227, 334, 337–340
The Netherlands, 341
Thelaviopsis spp., 218
Thorn savanna, 275
Tied ridges, 34, 37, 94, 114, 117, 168, 318, 324–329, 338, 354
Tigres River, 348
Tillage, 5, 341, 356
Tilth, 5, 69, 82–83, 247, 268
Togo, 285
Topsoil removal, 143, 177
Torrertic Paleustoll, 167
Toxicants, 5
Toxicities, mineral, 165
Trace elements, 53, 72
Transpiration, 35, 38, 151–152, 155, 163–164, 223, 254, 264, 341

Transpirational demand, 222
Transpirational stream, 221
Triticum aestivum, 139, 218, 254, 336, 351
Triticum aestivum L., 28, 152
Triticum vulgare, 70
Troll's climatic classes, 275
Tropic regions, 55
Tropical areas, 143, 336
Tropical rainforest, 275
Tunisia, 16, 82

U
Ultisols, 313
United Kingdom, 59, 101, 104, 118, 341
United States, 2–3, 28–29, 35, 38, 42, 46, 48, 52, 54, 58, 78, 91, 93, 95–96, 100, 105, 114, 120, 123, 144, 155, 157, 161, 164, 167–168, 176–178, 180, 182–183, 188–189, 195, 197, 225–226, 255–257, 261–267, 347–350, 352, 355, 357
Urea, 79, 146
Urease, 243
USSR *see also* Soviet Union, 189, 195
Ustalfs, 284
Usterts, 284

V
Vapor pressure, 36
Vapor pressure deficit, 17–18, 161, 168, 254
Vegetables, 320, 325–326
Vegetative barriers, 144
Verticillium spp., 215, 221
Verticillium dahliae, 218
Vertisols, 71, 155, 167, 284–285

W
Washington, 75, 217–218, 223–224, 227–228, 230, 258–260, 264, 268
Water balance, 181
  model, 328
Water conservation, 5, 32, 37–40, 45–46, 59–60, 77, 80, 82, 85, 89, 92, 95–96, 98, 105, 114, 123, 141–144, 147, 166, 168, 246, 254–255, 263, 268, 304, 318, 320, 327, 336, 354, 356
  measures, 322
  options, 320
  practices, 323, 339
Water erosion, 2
Water harvesting, 304–305, 354
Water holding capacity, 2, 20, 35, 57, 71–72, 85, 94, 175, 177, 195, 284, 292–293, 304–305, 313, 320–321, 328, 335, 339
Water management,
  options, 319, 325
  practices, 307–308, 328
  strategies, 312, 324, 326
  systems, 285
  techniques, 305
Water potential, 223, 232
Water quality, 176–179, 183, 193, 269
Water use efficiency, 40–41, 44, 46, 151–170, 353
  definition, 152
Waterlogging, 5, 169
Watermelon, 222
Weed control, 30–32, 38–41, 43, 45, 58–59, 82, 83, 90, 95–97, 99–100, 112–114, 118, 120, 122, 124, 133, 166, 263, 266, 268, 304, 316, 318, 354, 356
Weeds, 24, 30, 32, 89, 98–99, 143–144, 169, 224, 264, 268, 270
  grassy, 229

West Indies, 193
Wheat, 28, 36–38, 41–42, 44–45, 51–54, 58, 59, 70, 75, 77, 81–83, 90–93, 106, 112, 139, 141–142, 144–145, 152, 164–166, 168, 195, 216–231, 233, 254, 262, 266–268, 336, 349, 350–351, 353
  cattle grazing, 164
  freeze damage, 262
Wilts, 223–224, 232
Wind barriers, 19, 195–197
Wind erosion, *see* Wind speed, 36, 48, 60, 91–92
Wind tunnel, 196
Woodlots, 313
Wool, 351
  production, 352
Wyoming, 141

Z

Zea mays, 225, 354
Zea mays L., 28, 165
Zero-tillage *see also* No-tillage, 277–278
Zinc, 223