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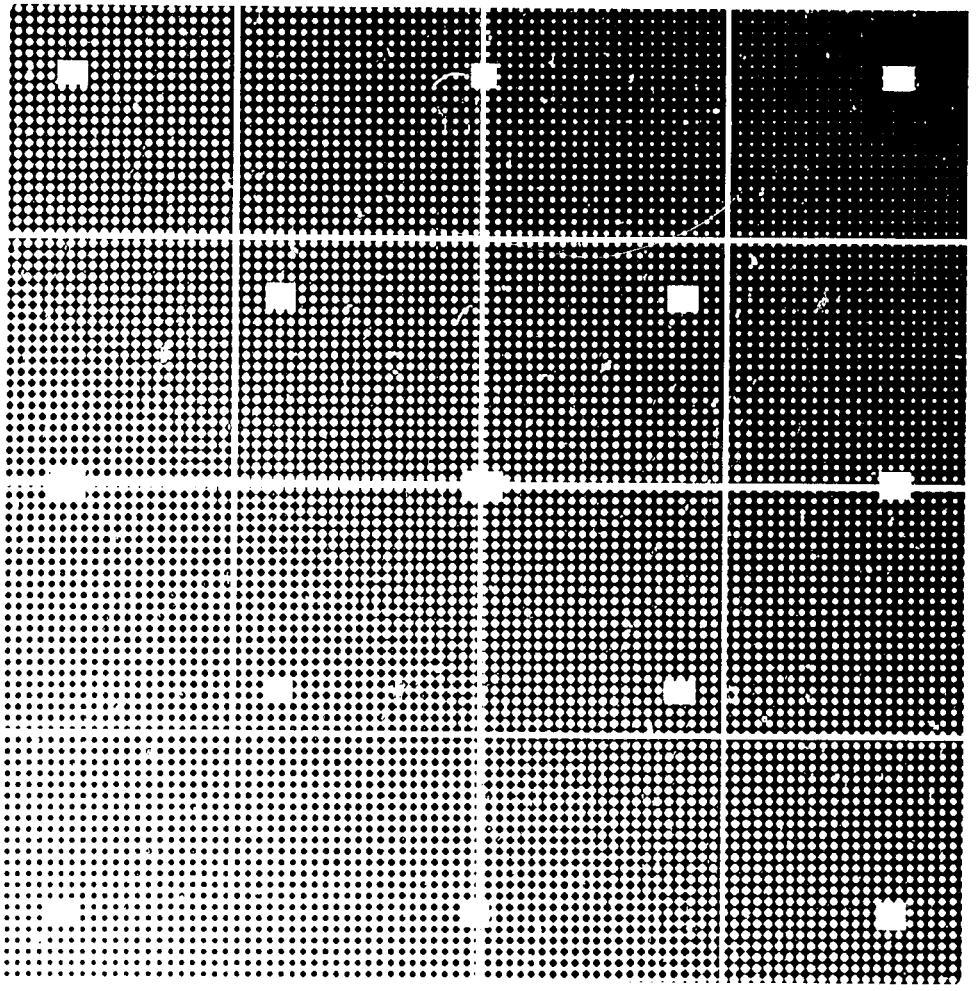

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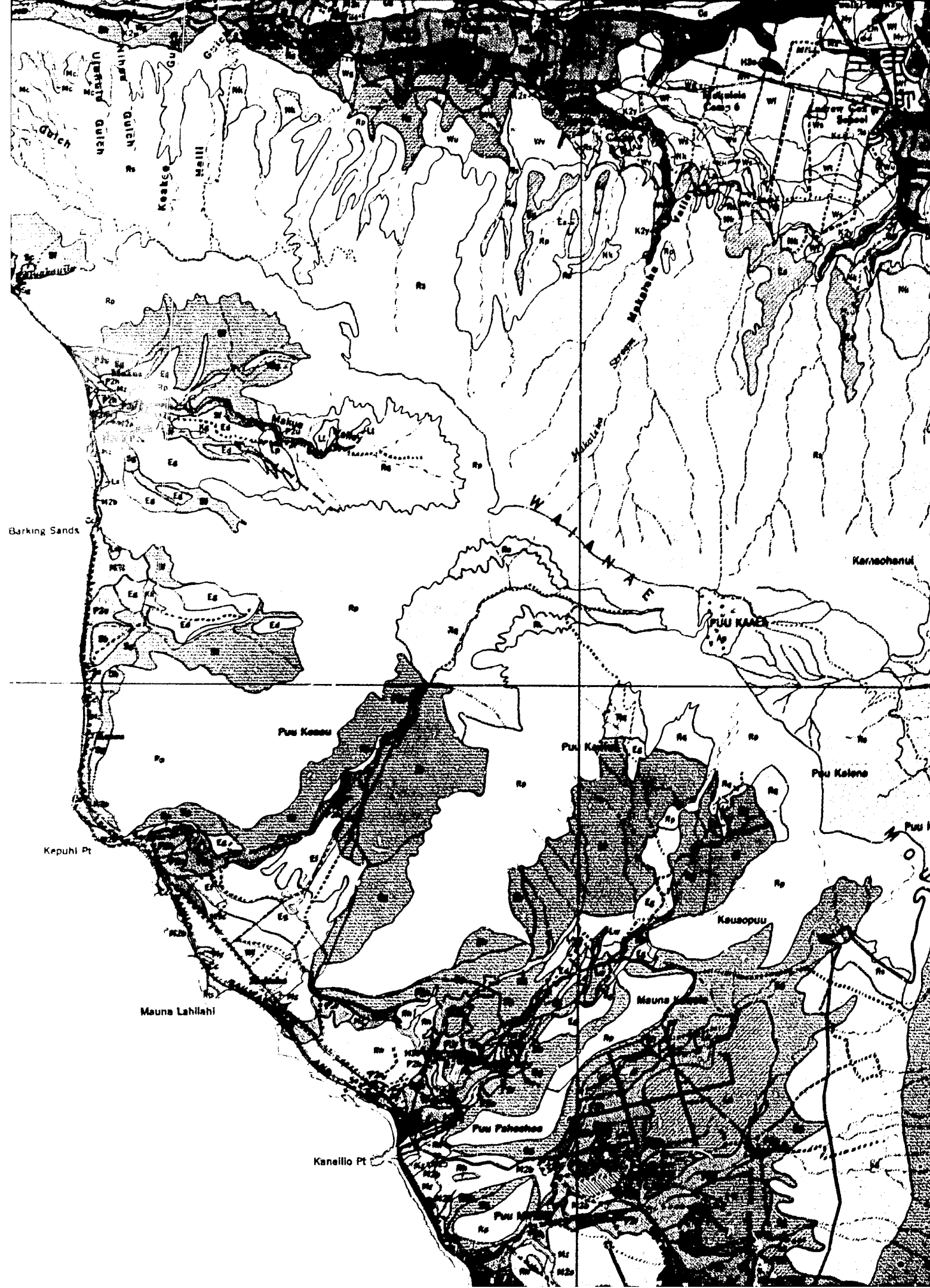
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Experimental Designs for Predicting Crop Productivity with Environmental and Economic Inputs for Agrotechnology Transfer

Edited by James A. Silva

Benchmark Soils Project
UH/AID Contract No. ta-C-1108

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CONTENTS

Page

Preface 5

Section 1: Description of the Benchmark Soils Project 7

Crop Production and Land Capabilities of a Network of Tropical Soil Families--A Description of the UH/UPR/AID Benchmark Soils Research Projects *[illegible]* 9
- Introduction 9
- Specific Objectives 12
- Design of Experiments 12
- Contributions to Institution Building 13
- Dissemination and Application of the Results 14
- Relation to Indigenous and International Institutions 15
- Future Plans 16
- Literature Cited 17

Some Considerations on Soil Classification in General, and "Soil Taxonomy" in Particular *[illegible]* 18
- Introduction 18
- Basic Rationales of Soil Classification 19
- Kinds of Soil Classifications and Their Purposes 20
- Soil Taxonomy 20
- Special Considerations Regarding Soil Taxonomy 22
- Summary 24
- Literature Cited 25

Field Experimentation to Allow Economic Evaluation of Management and Environmental Effects on Soil Productivity *J. A. [illegible]* 26
- Objectives 26
- Site Selection 27
- Crop Selection 27
- Treatment Selection 28
- Experimental Design 30
- Analysis of Imposed Management Factors 34
- Economic Analysis 34
- Soil Factors 35
- Climatic Factors 37
- Management Factors 38
- Plant Factors 38
- Development of Yield Response Equations with All Factors 38
- Literature Cited 39

Section 2: Approaches to Field Experimentation in Developing Countries ... 41

Some Considerations in the Design and Analysis of Fertility Experiments for Developing-Country Use *[illegible]* 43
- The Decision-Making Environment 45
- Analysis of Experience for Decisions 47
- Measurements and Design for Generalized Functions 49
- Literature Cited 54

Concepts of Program Design for Soils Research and Information Transferral in Developing Countries *F. A. [illegible], R. R. [illegible], and [illegible]* 55
- Working Concepts 55
- Economic Considerations of Data Extrapolation 58
- Transfer of Soil Management Practices via Soil Classification 61
- Summary 65
- Literature Cited 66

Some Cornell University Experiences *[illegible]* 67
- Research Priorities 68
- Nitrogen and Phosphorus Experiments in Puerto Rico 68
- Phosphorus Experiments at Brasilia, Brazil 72
- Conclusions 74

Page

Section 3: Experimental Designs Suitable for Soil Fertility Experiments 75

Key Elements in Field Experimentation for Generating Crop Production Technology *R. J. Laird and Antonio Torrent* 77
Introduction---------- 77
Collection of Information on the Area of Study---------- 79
Objectives and Organization of Research---------- 80
Selecting a Treatment Design---------- 81
Summary---------- 103
Literature Cited---------- 105

Some Examples of the Use of Production Functions to Quantify Environmental Influences on Crop Productivity *J. Ph. Oulot* 107
Introduction---------- 107
Wheat Productivity in the Central Valley of Chile---------- 108
Wheat Productivity in the Andes Piedmont of Southern Chile---------- 115
Concluding Comments---------- 120
Literature Cited---------- 121

Design and Analysis of Soil Fertility Experiments in the Tropics *Foster B. Cady* 122
Selection of Experimental Sites---------- 125
Determination of Treatment and Experimental Designs---------- 126
Collection of Plot and Site Data---------- 126
Analysis of Data---------- 126
Evaluation of the Transfer Hypothesis---------- 130
Bibliography---------- 132

A Family of Models and Experimental Designs for Evaluating Response to Fertilizer Nutrients When the True Model Is Not Known *R. L. Anderson and L. A. Nelson* 133
Introduction---------- 133
Use of Quadratic and Square Root Models for Single Nutrient Experiments---------- 134
Development of the Linear-Plateau Family of Single Nutrient Models---------- 137
Fitting Quadratic, Square Root, and Linear-Plateau Models to Multi-Nutrient Data---------- 140
Design of Experiments for Choice of Model and Determination of Optimal Rates of Fertilizer---------- 141
Summary and Conclusions---------- 144
References---------- 144

An Application of a Fractional Factorial Design to a Fertilizer Experiment in Japan *Tadikazu Okono* 146
Introduction---------- 146
Use of Fractional Factorial Design---------- 147
An Example of Fertilizer Experiments---------- 148
Data Analysis---------- 149
Discussion---------- 153
Conclusion---------- 157
References---------- 158

Consideration on Experiment Design and Production Functions *B. G. Capó* 159
Introduction---------- 159
Production Functions---------- 159
Optimum Economic Level of the Yield-Limiting Factors---------- 162
Actual Available Levels of Nutrients in the Soil---------- 162
General Yield-Production Function---------- 165
Additional Considerations---------- 165
References---------- 166

Economic Aspects of Production Functions for Soils *George E. Pringle* 167
Use of Production Functions---------- 168
Desirable Attributes of Production Functions---------- 168
Some Economic Aspects of the Capó Function---------- 169
The Derivation of Yield and Profit Functions for Sugarcane---------- 171
General Considerations---------- 175
Literature Cited---------- 175

Experimental Design for Predicting Crop Productivity w Environmental and Economic Inputs *E. A. Byers, J. B. Cowan, and J. Kirkwood* 176
Purpose---------- 176
Rationale for Experimental Design---------- 176
Assumptions and Restrictions Inherent in the Design---------- 177
Experimental Design---------- 177

PREFACE

The papers compiled here were presented at a Workshop on Experimental Designs for Predicting Crop Productivity with Environmental and Economic Inputs, which was held from May 20 to 24, 1974, at the University of Hawaii. The major objective of the workshop was to develop a reliable experimental methodology for generating data to be used by the Benchmark Soils Project in scientifically determining the transferability of agrotechnology. Participants at the workshop included leading scientists from the United States and abroad in the fields of soil science, agronomy, statistics, agricultural economics, and tropical agricultural research. A list of participants has been given by Silva and Beinroth (1975) and also appears on page 183.

The fact that agrotechnology can be transferred from one geographic area to another has long been generally accepted by scientists; however, there has been no scientific evaluation of the success of such transfer. The basis for transfer has not been well defined, but the development and publication of Soil Taxonomy in 1975 by the Soil Conservation Service of the United States Department of Agriculture and cooperating land-grant universities has provided a basis for the transfer of technology, the soil family. The soil family identifies similar agroenvironments and thus stratifies the world into agroenvironmental niches, thereby providing the possibility of transferring experience between similar agroenvironmental niches throughout the world. The Universities of Hawaii and Puerto Rico, with the support of the United States Agency for International Development, undertook the task of testing the hypothesis that agrotechnology can be transferred among soils of the same family as described in Soil Taxonomy (Soil Survey Staff, 1975).

The papers presented have been organized for publication into three major sections. The first includes papers that describe the Benchmark Soils Project of the two Universities and give the rationale for the Project as well as a preliminary research approach. Papers in the second section describe general approaches to and results from field experimentation in developing countries. The third section includes descriptions and discussions of experimental designs suitable for soil fertility experiments. Several designs are evaluated and models for production functions are described and compared.

The need for reliable and properly designed experiments is very great in many parts of the world, especially in developing countries where much information is needed immediately. The papers presented at this workshop offer alternative approaches to good experimentation and describe the various experimental designs and analytical methods that might be applied. Many of the authors are recognized leaders in their fields, and their years of experience provide insight into the problems of field experimentation in developing countries.

These papers are being printed with no further updating of references; Soil Taxonomy, for instance, was published in 1975, although it is cited in this publication as "in press." It was felt that the material contained in these papers would be useful as guidelines for field experimentation and the design and analysis of soil fertility experiments and should therefore be made available without further delay. The reader may wish to contact the individual authors directly for updated citations.

The workshop laid the basic foundation for the experimental design and approach used by the Benchmark Soils Project for the field experimentation

conducted throughout the three soil family networks (Silva and Beinroth, 1975) to provide reliable data for testing the transferability of agrotechnology. The Project has employed the 5^2 partial factorial design of Escobar described in the paper by Laird and Turrent and the analytical approach described in the paper by Cady. Information about the progress of the Project is available from the addresses on the inside front cover.

The Universities of Hawaii and Puerto Rico acknowledge the assistance of the Research Advisory Committee, which suggested that the workshop be held, and of the United States Agency for International Development, which provided most of the funds for participant travel. Appreciation is also expressed to the University of Hawaii, which hosted the workshop and provided the necessary facilities for the meetings. We are also very grateful to the participants who gave of their time to prepare the papers and attend the workshop where they joined in vigorous and stimulating discussions.

Note: Author listings are from the time of the workshop; several have moved since then, and their current affiliations are indicated here:

Richard L. Anderson, College of Agriculture, University of Kentucky, Lexington, Kentucky
Johnnie B. Collins, Department of Soil Science, Alcorn State University, Lorman, Mississippi
Philippe Culot, Project Manager, FAO, Mar del Plata, Argentina
J. Kirkwood, Director, Agriculture and Allied Programs, Fort Valley State College, Fort Valley, Georgia
Tadakazu Okuno, Department of Mathematics and Engineering, University of Tokyo, Tokyo, Japan
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George E. Pringle, Director, Department of Agricultural Economics, College of Agricultural Sciences, University of Puerto Rico, Mayaguez, Puerto Rico
Leslie D. Swindale, Director, International Crops Research Institute for the Semi-Arid Tropics, Hyderabad, India.

The rest of the authors can be reached at the addresses on their papers.

References:

Silva, J.A., and F.H. Beinroth. 1975. Report of the workshop on experimental designs for predicting crop productivity with environmental and economic inputs. Departmental Paper 26. Hawaii Agricultural Experiment Station, University of Hawaii 50 pp.

Soil Survey Staff, Soil Conservation Service, U.S. Department of Agriculture. 1975. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys. Agriculture Handbook 436. U.S. Government Printing Office, Washington, D.C.

Proceedings of a workshop on experimental designs for predicting crop productivity with environemtnal and economic inputs, May 20-24, 1974, University of Hawaii.
List of participants appears on page 183.

SECTION 1:

Description of the Benchmark Soils Project

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Crop Production and Land Capabilities of a Network of Tropical Soil Families — A Description of the UH/UPR/AID Benchmark Soils Research Projects

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INTRODUCTION

From most authoritative sources in recent years, it has been firmly stated that major emphasis must be given to increasing productivity per unit of land if the world food needs are to be met. Through research and extension, the temperate regions of the world have achieved high productivity in agriculture. The Green Revolutions in wheat and rice in Mexico, India, and Pakistan, and in the rice bowls of Asia give clear indication that such advances are also possible in the tropics. What is most needed is a clear indication of the regions in tropical countries where it is possible to concentrate immediate food production efforts. Throughout tropical Asia, Africa, and Latin America, crop yields on the upland soils that will be the focus of this experiment are very low. Existing national knowledge, therefore, is no guide to the true potential of these soils. Thus, if it can be shown that profitable crop yields can result--yields two or three times greater than are presently thought possible--without consequent soil deterioration, a modern agricultural system can be developed without the necessity of 50 years of experimentation and extension.

The high yields resulting from extensive soil management in Hawaii on tropical soils are based upon current practice in relation to sugar, coffee, sorghum, and fruit, vegetable, and tuber crop production, and upon 70 years of continuous agricultural research by the Hawaii Agricultural Experiment Station and the research stations of the sugarcane and pineapple industries. We need to find ways to transfer these results to other tropical regions. The purposes of these projects are to correlate food crop yields on a network of benchmark tropical soils, and to determine scientifically the transferability of agroproduction technology among tropical countries, particularly from Hawaii and Puerto Rico to tropical developing countries.

The projects are central to the need for improved information on the management of tropical soils and water, a major current interest of the U.S. Agency for International Development (AID). For the most part, temperate

countries have made great progress in developing their soil resources. But the majority of the world's underprivileged people live in the tropics, and the soils of the tropics have so far proved difficult for most people to manage.

The magnitude of the problems of managing tropical soils was documented by the United Nations Conference on the Application of Science and Technology for the Benefit of the Less-Developed Areas (Vol. 3, Chap. 2, Geneva, 1963). More recently, Aubert and Tavernier in Soils of the Humid Tropics (1972), a review undertaken by the National Research Council for AID, concluded: "In equatorial regions...basic agricultural experimental work is lacking for adequately predicting soil behavior."

Only when countries in the tropics have gained an appreciation of the potential of their soils under different levels of management will it be possible for them to plan both (1) to insure basic food and protein supplies and (2) to promote the production of exportable crops. But, at present, in most tropical countries, research efforts related to basic food and protein supplies are aimed at a low level of soil management with consequent high food prices and occasional food shortages. Under these conditions, lacking the information and perspective necessary, it is not possible to create the progressive rural structure and the modern agriculture that Mosher (1969) proposed.

The benchmark soils that are to be the bases of the research network will belong to related soil families as defined by the new U.S. Soil Taxonomy. This Taxonomy, essentially completed in 1971, has as its major purpose the establishment of relationships among soils and between soils and their natural and cultural environments. Through proper use of the classification, predictions can be made about soil behavior from the relations of soils for which we lack experience to soils on which we have conducted research or have experience.

This system of soil taxonomy has been developed over the last 22 years by the Soil Conservation Service of the U.S. Department of Agriculture with active cooperation of the Land-Grant Colleges and soil scientists in foreign countries. It is by far the most comprehensive, most precise, and most nearly logical system of soil classification yet developed.

The fifth level of subdivision in the system is the soil family. Charles E. Kellogg, while Deputy Administrator for Soil Survey of the Soil Conservation Service, described the significance of soil families (Kellogg, 1964). He pointed out that many characteristics that can be related to plant growth and to engineering were related to the soil family subdivisions, and, in consequence, the soil family provides the link between soil classification and land capability groupings. Soils in the same family should have essentially the same management practices. Therefore, it is essential to classify soils in different lands into their common families in order to make reasonably direct transfers of agricultural know-how; conversely, when soils have been classified into their common families, it should be possible to use the maximum production results of one soil as production targets for all soils in the same family.

Existing knowledge about the use of the soil family for technology transfer has been established in the continental United States and in Hawaii through cooperative work of the Soil Conservation Service of the USDA and the Hawaii Agricultural Experiment Station. De Ment, et al. (1971), critically examined the family classification system to see how well it has worked within the con-

tinental United States. In the abstract of their report, they state, "In general, crop suitability correlates well within classes at the family level. Yields for short-season crops can be reliably predicted, particularly if soil slope and erosion phases are used. Yield predictions are less reliable for long-season crops that are subjected to moisture stress during parts of the growing season." The authors suggest that some classes of soil moisture stress during the growing season should be used in family criteria.

Experience has shown that agricultural technology developed for temperate zone soils is not directly transferable to the tropics. But evidence has not yet been obtained to determine the extent to which agricultural technology developed under high levels of management in tropical regions can be transferred. Recent progress in soil classification related to questions of transfer of technology and research in Hawaii give considerable hope that this can be done.

For example, for short-season crops--such as head cabbage and lettuce grown on the Kula and Waimea soil series, two soils in the medial isothermic family of Typic Eutrandepts on different islands of the Hawaiian chain--yields and cost of production are very similar. For longer season crops--for example, sugarcane, pineapple, papaya, and pasture production on soils in the same family--yields are listed as being equal by the Soil Conservation Service in their forthcoming reports on the soils of the State of Hawaii.

The success of the Soil Taxonomy system at the family level in many U.S. soils and within the limited testing that has been possible in tropical and subtropical Hawaii suggests that it can be used to transfer agricultural technology between soils in many tropical regions. Thus, the present high level of agricultural technology developed in Hawaii for crops such as sugar (0.53 ton sugar per acre per month--T/A/M), pineapple (3 T/A/M), papaya (2.5 T/A/M), sorghum dry grain (1.0 T/A/M), maize dry grain (1.1 T/A/M), and beef production (83 lb/A/M) can be translated to the less-developed countries.

In making this assertion, it is fully realized that the translation can only be made initially in terms of production targets. Many problems, social and economic as well as technical, will need to be solved before production targets become production realities. But this correspondence of soils will show what soils should be developed first, what comparative advantages exist, and what direction the countries should take in their development plans. It may also determine on what soils in Hawaii and Puerto Rico future research should be concentrated to provide the greatest benefit for the less-developed countries.

Although soil families have not yet been fully classified in tropical Asia, Africa, or America, soil survey and characterization has progressed far enough in the countries indicated as possible participants that the selection of benchmark soils in soil families common with Hawaii and Puerto Rico should not be too difficult. One example of transference of Hawaii soil management practices based on soil classification criteria is the response of sugarcane to soluble silicates on Humic Ferruginous Latosols in Mauritius following the earlier response to silicates on these soils in Hawaii (Plucknett, 1972).

The most likely countries in which the appropriate soils will be found are Ethiopia, Zaire, Tanzania or Kenya in Africa; Sri Lanka, Indonesia, India (Kerala or Mysore), the Philippines (Mindanao), or Vietnam (the Central Highlands in Asia; and Colombia, Peru, Venezuela, or Brazil in Latin America.

Two crops will be grown at each station in the network in a series of linked-parallel experiments. The most probable crops will be a cereal, either corn, upland rice, or sorghum, and a root crop, either cassava or yam. Yields and other output criteria will be correlated among the stations and in relation to land potentials and capabilities in the countries of the network.

The projects will establish by their findings the factors that must be taken into account in order to make the soil family level work in the tropics as it does in the temperate zone and the classification level to be used in the transfer of agricultural knowledge from place to place.

In later phases of the projects and in concert with related AID research contracts and with national and international research institutions, the research network of benchmark soils will be extended to other areas in the above countries and to other countries in the tropical regions of the world. Because the crops used in the experiments will be of local importance--but probably of improved genetic stock--government agencies will be able to use the experiments for demonstration purposes in local development and to prepare for the creation of local village organizational structures to maintain long-term benefits from the work carried out.

SPECIFIC OBJECTIVES

1. University of Hawaii
   a. To correlate crop yields to land potential and capability on a network of upland tropical soils.
   b. To establish by experimentation and demonstration the transferability of agricultural technology between Hawaii and other tropical regions and among those regions.
2. University of Puerto Rico
   a. To correlate crop yields to soil parameters on a network of red upland soils of the tropics.
   b. To establish by experimentation the transferability of agricultural technology among tropical countries.
   c. To demonstrate the agricultural potential of tropical red upland soils in LDCs of Latin America.

DESIGN OF EXPERIMENTS

Selection of Soils

A comparative study of soil and climatic maps at scales around 1:5,000,000 will be used to delineate probable areas of interest. The resources of the Universities' holdings on tropical soils, the AID (211-d) Consortium on Tropical Soils, the World Soil Geography Unit of the USDA, and the FAO/UNESCO Soil Map of the World will be used to provide the information needed.

Detailed soil investigations will need to be conducted in the field to obtain the information necessary to classify soils and to determine if the soil areas meet the criteria that will be used to determine their suitability for linked-parallel experiments on crop production.

Hawaii and Puerto Rico have one family of Tropeptic Eutrorthox and one family of Orthoxic Tropohumults in common. When these families occur in other regions, they will be used; otherwise, other closely related soils will be used which have families in two or more of the locations of the network. In general, it is expected that the work will be concentrated in families of Andepts and Oxisols which are well represented and used for intensive agriculture in Hawaii.

Crop and Soil Management Experiments

The experimental designs to be used will be in part determined by the results of this workshop.

The objectives of the experiments will be:

1. To determine the potential productivity of soils under high management input.
2. To develop optimum management systems for multiple cropping.
3. To determine optimum plant population for various crops under local soil and climatic conditions.

The potential productivity of soils at each location will be determined with an N x P x K experiment to allow correlation with soil parameters and evaluation of transferability of agricultural technology. The aim is to attain maximum or near-maximum production with appropriate levels of these nutrients under optimum management conditions, that is, adequate irrigation, calcium (pH), plant protection (weed, disease, and insect control), and plant population.

Land Capabilities

The soils data, soil characteristics, yield data, and related climatological data will be processed by methods of multivariate analysis to produce the desired land potential, capability, and transferability information. Local yield data and land capability information, where it exists, will probably be included in the data base to increase the chances of making yield predictions at various levels of the soil classification to cover a larger group of soils than will be represented by the benchmark soil network.

Where similar soil indexes of production capabilities are determined by analysis, the information will be directly translated through the soil linkage as a first approximation to production targets for these soils where they occur in other tropical and subtropical lands.

CONTRIBUTIONS TO INSTITUTION BUILDING

The projects are proposing a creative approach to the development of modern agriculture in tropical countries. They will need to work closely with national research institutions to change in part their orientation and targets and retrain some of their staff, depending upon where the stations are established. The projects propose to work through the strengths of national institutions. Included in the proposals are funds enough to provide fellowships for staff members of these institutions to undertake training courses and

graduate degree courses at the two Universities.

The seminars, workshops, and meetings that will be part of these projects will also contribute to training institutional counterparts and national field staff of the project.

The projects will give participating countries a basis for understanding and exploring the potential of their soils for crop production. They should lead to increased soil-based research in national institutions as they seek similar information for soil families not included in the project studies.

The two Universities will be strengthened by the project. Their staffs will gain a greater insight into the problems of tropical countries and will gain in knowledge and understanding through their contacts with other research scientists. Their store of research information will be increased by the experiments conducted.

The authors of Soil Taxonomy of the USDA recognize its probable inadequacies in the classification of tropical soils. Referring to the Oxisols, soils central to the objectives of this project, the Taxonomy states, "The classification of Oxisols...seems to produce satisfactory groupings of the...soils in Hawaii and Puerto Rico. It needs to be tested more widely...and is far from completion." Soil scientists in tropical countries have recognized the value of the Taxonomy by using it to the extent that their limited analytical data will allow. The U.S. Soil Conservation Service and the use of the Soil Taxonomy in tropical countries should benefit substantially from the findings of this project.

DISSEMINATION AND APPLICATION OF THE RESULTS

It is expected that the projects will demonstrate that the transition from traditional to modern intensive agriculture can be made efficiently and with a minimum of error by means of technology transfer from the developed to the less-developed regions of the tropics. It should also show that management systems implemented on one soil in one region can be transferred to the same soil in any other region.

This transferability of existing agricultural knowledge will be demonstrated on an international network of benchmark soils families. Preliminary results will also demonstrate transferability of knowledge for several in-country sites related to the international network.

The land capability schemes developed for the countries of the network should be able to indicate suitabilities of different regions for development under high, medium, or low levels of input and the probabilities for the success of information transfer from the network. This information will be available for incorporation into the 5-year development plans of the cooperating nations, and the project personnel will work to involve national planners in the project from its early stages and include them in the training seminars and workshops.

Either corn, sorghum, upland rice, cassava, or yam will be cultivated continuously for 3 years. Two years of data will be obtained on other crops. Yields from the experimental plots are likely to be two to six times greater than those obtained by farmers cultivating similar soils and using traditional agricultural practices.

Bird and rodent damage, in addition to disease and insect and weed infestation, will seriously limit yields in the control plot. The projects will therefore have strong visual impact and will also supply scientific data related to locally important crops.

Strict management control of the projects will be required in order to obtain highly profitable yields in upland areas. It is hoped that AID Missions and local and national institutions will assist in organizing farmer field days and other local training sessions that will be associated with the project. Governmental willingness to support farmers who have been psychologically prepared to make the change will be necessary in order to ensure basic food supplies.

Fellowships will be offered to students from host countries with leadership potential. They will receive academic training at the Universities and field experience on the experimental site in their home country. Those students working on thesis research in their home countries can help local farmers incorporate the newer methods into their social and cultural framework.

Training seminars for the project staff will be held in years 1, 2, 4, and 5. These will provide training on soil families and classification, experimental design and crop management, and on interpretation of the project results by the staff. Project workshops will also be held to acquaint appropriate officials of cooperating countries and AID staff members with the purposes and benefits of the project and with the meaning of the results as they are obtained. These workshops will also be used to obtain important input into the project from individuals and to maintain their involvement to a high degree.

RELATION TO INDIGENOUS AND INTERNATIONAL INSTITUTIONS

When the stations of the network have been decided upon, arrangements will be made with indigenous institutions to assist and advise the projects. The willingness of such institutions to play such a role will be an important criterion in determining where stations will be.

The projects will draw directly on past and current research on crop and soil management by the Hawaii and Puerto Rico Agricultural Experiment Stations. They should be able to draw also on the expertise of the AID/University (211-d) Consortium on Tropical Soils, which includes Cornell University, North Carolina State University, Prairie View Agricultural and Mechanical University, and the Universities of Hawaii and Puerto Rico.

For suitable crop varieties, the project will cooperate with IITA, WARDA, CIMMYT, IFAT, and other research institutions that can provide the required information. For assistance in soil selection the project will cooperate with national soil survey institutions, the Soil Conservation Service of the USDA, ORSTOM, INEAC, and FAO.

Cooperative arrangements with other AID-sponsored projects working in similar regions or similar fields are expected to be achieved through AID. We are hopeful that the AID-sponsored research by Cornell and North Carolina State, which deals with soil fertility assessments and crop production in Latin America, will help us with advice and information, and perhaps set up cooperative experiments on suitable benchmark soils in their regions of work.

The work in Africa will be closely coordinated with IITA, which has on its staff several individuals who have worked in the Hawaii Agricultural Experiment Station and obtained graduate training in the College of Tropical Agriculture of the University of Hawaii. The soil management program and orientation of IITA can be extended to other areas of Africa through such coordination.

Belgian scientists at INEAC and the Universities of Louvvain and Ghent, who have had considerable experience with soils of the type to be included in this project, are also being consulted and included as cooperators when suitable arrangements can be made.

It is to be expected that the work in Asia will be coordinated with the new crop management extension program of the International Rice Research Institute (IRRI). A proposal has recently been developed and has been approved in principle to conduct a major seminar on the relevance of modern soil and land classifications to the development of tropical soils with joint sponsorship by the Hawaii project and ICRISAT. The seminar would be held at ICRISAT in December 1975.

The work in Latin America will be coordinated with CIAT, CIMMYT, and IITA through the University of Puerto Rico.

FUTURE PLANS

Data for additional crops will be obtained at the stations of the research network. New stations on additional soil families will be established in the countries of the network to extend the usefulness of the results and test the validity of the land capability schemes more adequately.

First priority for extension of the projects to new locations will be given to regions with high agricultural potential in which a breakdown of the traditional agricultural system appears imminent. The transfer of technology will be linked to a strong farmer-training program. The host country, in turn, must give assurance that a permanent support program giving farmers access to fertilizer, chemicals, and seeds will be established. Transfer of agrotechnology is only a necessary first step in agricultural development.

Second priority should be given to sparsely populated regions with high potential for development. Between the humid and arid regions there is a large segment of the tropics in which continuous cropping is restricted by low rainfall during 3 to 6 months of the year. Introduction of agrotechnology to these areas will give government planners the information needed to plan for water resource development and proper use of the soil resources.

Third, the transferability of technology should be tested in regions of medium to low potential, where shifting agriculture will continue to be practiced for many more generations. Introduction of agrotechnology to these areas will serve as a means to prepare the people for exposure to the outside world.

The projects, therefore, should have both visual impact in and technical value to the participating countries.

The experience and knowledge gained from this project will:

1. Remain in the host country to create a progressive rural structure, and

2. Be extended to other tropical regions with immediate and future growth potential.

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Some Considerations on Soil Classification in General, and "Soil Taxonomy" in Particular

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INTRODUCTION

The recognition of soils as independent natural bodies possessing various kinds and degrees of internal organization expressed in the soil profile provided the first model for the scientific study of soils proper. Moreover, this theory, developed about 100 years ago in Russia under the leadership of V. V. Dokuchaev, marks the most fundamental change in the concept of soil and subsequently led to the establishment of soil science as a separate discipline. As with most scientific models, the Russian concept has undergone considerable change with time in reflection of advances in soil geomorphology, soil chemistry, soil physics, soil mineralogy, and soil biology. A further significant change has occurred in the quantitative aspects of the model. As a consequence, the present concept is more nearly a quantitative representation of our knowledge since most soil properties can now be characterized in terms that have quantitative meaning at some level of precision (Cline, 1961).

This has had a great impact on the development of soil science. For as Lord Kelvin pointed out, "...when you cannot measure what you are speaking about, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; ...scarcely advanced to the stage of science...."

Since soils, then, are objects whose inherent properties can be quantified in terms of defined criteria, they may also be classified on the basis of these characteristics, and many systems of soil classification have been proposed in recent years. Yet, all such systems are subject to criticism because they are circumscribed by the current understanding of soils. As this knowledge is still incomplete, most systems of soil classification contain a certain amount of speculative logic. Consequently, soils as they occur in nature may not in all instances conform to the theories and schemes propounded by pedologists. As Bertrand Russell put it, "nature herself cannot err, because she makes no statements. It is men who may fall into error when they formulate propositions."

The purpose of this paper is to examine some of the underlying rationales of soil classification and to discuss some aspects of the official U.S. Soil Taxonomy system.

BASIC RATIONALES OF SOIL CLASSIFICATION

In most existing systems of soil classification there is the basic assumption that there are individual soils, just as there are individual animals and plants. The aggregate of an almost infinite number of these individuals constitutes the soils of the world. Whereas former concepts regard the pedosphere not as a universe of individuals but as a kind of continuum varying from place to place in reflection of changing soil-forming conditions, the present view considers soil as a "collection of bodies" (Soil Survey Staff, 1960). Cline (1961) pointed out that "the perspective in which we view our model has changed from one in which the whole is emphasized and its parts are loosely defined and indistinct to one in which the parts are sharply in focus and the whole is an organized collection of parts." This implies that there are small, discrete units that can be treated as a population.

Although the individual is the smallest entity one may call "a soil," it would be impractical to deal with all of these units in any system of soil classification. These individual pedons, however, are the sampling units used to define the lowest category of most soil classification systems, that is, the soil series. Thus, soil pedons are the only existing substances that can be measured and analyzed, whereas the categories of soil classification systems are conceptual abstractions of these particulars made at different levels of generalization.

Parenthetically it may be noted that this kind of reasoning conforms to the theories of Realism, originally postulated by Plato and later moderated by Aristotle, according to which universals exist and are implicit in particular instances. On the rationale that categories of soil classification may not exist independently of our mental constructions, Robinson (1949) prefers to regard these categories as "constructed universals" following the philosophy of the Representationists.

It is of interest in this context to consider Kant's (1781) ideas about knowledge and experience as advanced in his Critique of Pure Reason. On the assumption that experience is necessary but not sufficient for knowledge, he set out to explain experience in terms of concepts rather than vice versa. Knowledge that in principle is independent of experience is termed "a priori," and whatever derives from experience is described as "a posteriori." Both of these concepts have been used in developing systems of soil classification (Manil, 1959).

In a priori, or descending, systems, the higher categories are conceived in consideration of hypotheses and principles of generally pedogenetic nature and more detailed categories are added as observation proceeds. Many of the soil classification systems developed in Europe are examples of the a priori kind of system, and although they are the only possible ones when no large amounts of accurate data are available, they have the inherent defect of all pre-established schemes used to accommodate factual knowledge. Bridgeman (1927) pointed out that the scientist "recognizes no a priori principles which determine or limit the possibilities of new experience." The second method of elaboration is a posteriori, or ascending, in which reasoning moves from facts to concepts. This approach requires, of course, a great amount of data about recognizable bodies of soil, especially those identified as soil series. The U.S. Soil Taxonomy is essentially of the a posteriori type. It should be stressed, however, that the organization of categories and classes are direct consequences of the theory in our current model (Cline, 1961).

KINDS OF SOIL CLASSIFICATIONS AND THEIR PURPOSES

Cline (1949) stated that "the purpose of any classification is so to organize our knowledge that the properties of objects may be remembered and their relationships may be understood most easily for a specific objective." It is implicit in this statement that there are as many systems of soil classification conceivable as there are objectives for grouping soils. Each of these systems may be the "best" for the particular purpose for which it was designed. Yet, since the things important for one objective are seldom important for another, a single system will rarely serve two objectives equally well (Cline, 1949). For example, a system developed for classifying soils on the basis of their suitability as bauxite ore will not be very useful for determining the site-index for loblolly pine. Such systems, which may be constructed for a great variety of technical purposes or soil uses, have been classified "technical" by Mill (1925).

"Technical" systems limited by the special bias dictated by their purpose are in opposition to "natural" or "taxonomic" classifications in which the objective is to show relationships in the greatest number and most important properties without reference to a specific practical purpose (Cline, 1949). A taxonomic classification recognizes that soils have many properties, some of which are associated in an apparently causal relationship; then the population attributes with the greatest number of covariant or accessory characteristics are selected to define and separate the various classes and categories (Mill, 1925). To quote Cline (1949) again, "the natural classification, therefore, performs the extremely important function of organizing, naming, and defining the classes that are the basic units used (a) to identify the sample individuals that are the objects of research, (b) to organize the data of research for discovering relationships within the populations, (c) to formulate generalizations about the population from these relationships, and (d) to apply these generalizations to specific cases that have not been studied directly."

The U.S. Soil Taxonomy is an attempt at a comprehensive natural classification of soils. As will be shown, however, there is a clear tendency to give more weight to properties of agricultural relevance, particularly at lower categoric levels.

SOIL TAXONOMY

The U.S. system of soil classification, the U.S. Soil Taxonomy, represents the most advanced effort yet to tackle the three main problems encountered in contriving a taxonomic system. These are (1) the selection of differentiating criteria, (2) the definition of classes and their grouping in categories, and (3) the nomenclature of taxa.

In recognition of the real need for an entirely new system, Soil Taxonomy has been developed over the past 20 years in the Soil Conservation Service of the U.S. Department of Agriculture under the leadership of G. D. Smith, with the cooperation of soil scientists of U.S. universities and certain pedologists from other countries. The system went through a series of approximations, and the 7th Approximation was published in 1960 (Soil Survey Staff, 1960). After substantial revisions it is now in press, and will be available in the near future as a book entitled Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys.

In developing the basic rationales of the system, the book's authors were influenced by Bridgeman's Logic of Modern Physics (Bridgeman, 1927). They also drew on Western European experience, particularly on the definitions of concepts basic to the French classification (Smith, 1965). More than 70 years of soil survey provided the detailed information, without which the development of the system would not have been possible.

Like most taxonomic systems, Soil Taxonomy is a multi-categoric system. Each category is an aggregate of taxa, defined at about the same level of abstraction, with the smallest number of classes in the highest category and the largest number in the lowest category. In order of decreasing rank, these categories are order, suborder, great group, subgroup, family, and series.

By applying concepts of pedogenic processes, orders, suborders, and great groups are differentiated on the basis of the presence or absence of a variety of combinations of diagnostic horizons and soil properties. Three levels of such sets are employed in the three highest categories, each set of properties marking pedogenic processes that operate within the sets characterizing the higher category or categories. Examples of differentiae used at the order level are diagnostic horizons, such as the oxic and spodic horizons or the mollic epipedon. Soil moisture regime and extreme chemical or mineralogical properties, such as the presence of large amounts of allophane, are examples of criteria for differentiating suborders. Properties that appear to be superimposed on the diagnostic features of the orders and suborders, such as various kinds of pans or the presence of plinthite, are used to differentiate great groups.

Subgroups are subdivisions of great groups representing either the central concept of the category, intergrades to other groups, or extragrades which have additional aberrant properties. Families and series are distinguished on the basis of properties selected to create taxa that are successively more homogeneous for practical uses of soils. Thus, families attempt to provide classes having relative homogeneity in properties important to the growth of plants, and series are subdivisions of families intended to give the greatest homogeneity of properties within the genetic soil or the rooting zone, consistent with the occurrence of mappable areas at scales of detailed soil surveys.

On the rationale that the same processes operate in most soils, though at widely differing rates and intensities, the classification of tropical soils in Soil Taxonomy is consistent with that of other orders. Soils of tropical areas are differentiated by their soil temperature regime, and importance is given to the degree of continuity of biologic activity. Soils of the humid tropics are distinguished at high categoric levels by order, suborder, or great group. With few exceptions (for example, Torrox and Torrerts), soils of arid and semiarid tropical regions are differentiated at the family level because seasonal lack of soil moisture is not unique to the tropics (Smith, 1965).

Evidently, the classes of Soil Taxonomy have been formed in consideration of concepts of pedogenic processes. As these causes are not suitable as diagnostic criteria, however, some of their more prominent effects were selected as differentiae. Insofar as possible, properties that are the result of soil genesis were chosen as differentiae because such properties carry the maximum number of accessory properties and also have geographic implications of susceptibility to mapping. As a basic principle, these differentiae are recognizable soil properties and there are defined operations to identify them (Smith, 1965). The Soil Survey Manual and the Soil Survey Laboratory Methods

(Soil Survey Staff, 1951 and 1967) provide the definitions and procedures essential for these operations.

The nomenclature of Soil Taxonomy marks a complete departure from past practice. It was conceived not to mystify the outsider as some may think, but because the old names were ambiguous, of diverse linguistic provenance, difficult to redefine, and generally unsuited for use in systematic taxonomy. Therefore, new names were coined, largely from Greek and Latin roots, that fit any modern European language without translation. The name of each taxon clearly indicates the place of the taxon in the system and connotes some of its most important properties.

Soil Taxonomy is the official system of the National Cooperative Soil Survey of the U.S., but it is also used in some other countries, particularly those in South America (Costa de Lemos, 1971). Of the numerous classifications used in tropical areas, Soil Taxonomy is among the most important (Aubert and Tavernier, 1972). Although it has not met with unanimous acceptance outside the U.S., it is likely to be adopted as a system of reference for international communication, especially in technical papers.

SPECIAL CONSIDERATIONS REGARDING SOIL TAXONOMY

Dependence on the State of Knowledge

Soil Taxonomy is not a "zero-defect system." It is an organized abstract of current knowledge of soils and of concepts derived from this knowledge and can, therefore, be no better than the state of that knowledge. Our knowledge of soils is still sketchy, and this is especially true for many tropical soils, particularly Oxisols. As a result, the classification of Oxisols has been based on a limited amount of factual data; hence, it has lagged behind that of other orders of mineral soils and is certain to have many shortcomings (Soil Survey Staff, 1973). However, the Soil Conservation Service is now beginning to direct efforts toward more meaningful methods of assessing organic soil materials and toward characterization of relevant properties of tropical soils (Flach, 1973). In all probability, this will lead to additional differentiae for classifying Oxisols and will entail future changes in the present system.

Genetic Bias and Its Implications

The definition of criteria, classes, and categories of Soil Taxonomy is factual and leaves no scope for subjective speculation. The guiding rationales underlying the development of the framework of Soil Taxonomy, however, are provided by concepts of soil genesis, which is reflected in the choice of differentiae and class limits. As many pedogenetically significant processes take place in the subsoil, criteria relating to subsoil properties tend to be used more frequently as differentiae than those relating to surface soil properties.

Even a casual analysis of the Key to Soil Taxonomy reveals that diagnostic subsoil properties commonly take precedence over surface soil criteria. This controls the kind and amount of information a taxon contains by virtue of its definition. With few exceptions, more quantitative statements can be made about the subsoil than the surface soil; however, because the criteria of Soil Taxonomy have many covariant properties and accessory characteristics,

qualitative inferences of reasonable accuracy can be made about the surface soil.

There are, of course, compelling reasons to place comparatively more weight on subsoil properties in a taxonomic system: in cultivated soils, for instance, the surface is also the main management zone and as such is affected by frequent changes in physical and chemical properties. If these properties were selected as differentiae, the classification of cultivated soils would also be subject to change with equal frequency.

Aspects Related to Crop Production

Since a considerable portion of the root zone of annual crops coincides with the surface soil zone, the greater importance assigned to subsoil properties signals certain limitations of Soil Taxonomy as regards its validity for agricultural interpretations. Although, at the family level, the system provides for criteria explicitly selected to reflect conditions important to plant growth--texture, mineralogy, and temperature--these differentiae are also applied to the subsoil. The control section for the determination of both the particle-size and mineralogy classes starts below the A-horizon, and soil temperature regimes are usually measured at 50-cm depth. This would constitute a serious defect in Soil Taxonomy if it applied to a technical system for crop production; since it is a natural classification, however, it merely points out an inherent limitation of any taxonomic system when used for a specific purpose.

Recently a technical system of soil classification was developed by Buol, et al. (1974) which was designed for the express purpose of grouping soils on the basis of similar fertility properties. This system recognizes the need to place greater emphasis on the nature of the plow layer. The criteria used are to a considerable degree identical to differentiae employed in Soil Taxonomy, but some are new. Buol, et al.'s system, therefore, with some justification, may be considered a derivative of Soil Taxonomy, interpreted and restructured for the specific purpose of fertility evaluation. The system, although incomplete at this time, represents a promising approach, and the testing it is now undergoing may well demonstrate its value.

Applicability in the Process of Transfer of Agrotechnology in the Tropics

In reflection of growing government interest in natural resources, many tropical countries are engaged in active soil surveys. Soil classification has an important function in these programs because it provides the framework for a systematic land resources appraisal based on soil surveys. An equally important function of soil classification should be to facilitate the transfer of experience gained with a given kind of soil in one place to a similar kind of soil in another place.

This transfer of experience clearly has a technical purpose, and thus an argument could be made in favor of using some kind of technical system for this process. While this may be a reasonable statement of principle, however, it appears that the transfer has to be made on the basis of the existing soil maps and the classification systems employed in their construction. The systems most widely used in tropical areas are the FAO/UNESCO Legend (Dudal, 1968; FAO, 1970), the French Soil Classification (Aubert, 1965; Commission de Pedologie, 1967), the Classification of Brazilian Soils (Bennema, 1966), and the U.S. Soil Taxonomy (Soil Survey Staff, 1973). Taxa of these systems can

be correlated at various categoric levels and, in most cases, with some degree of accuracy (Beinroth, 1974; Beinroth, et al., 1974).

All the mentioned systems are, in principle, taxonomic classifications. Their application in soil surveys alludes to the rationale that soil surveys, although practical in purpose, must also have reasonable scientific standards to be useful. In particular, a soil survey should not become obsolete with changing agricultural technology and it should further facilitate the interpretation for a variety of uses, some of which might not have been anticipated at the time when it was made. It is evident that these requirements can only be met if a taxonomic system is used (Smith, 1965).

With respect to transfer of agrotechnology, Smith (1965) further contended that, in order to be useful, a classification "should be a multi-categoric system with a large number of taxa in the lower categories... (These) must be as specific as possible about a great many soil properties... Higher categories are essential for comparisons of the soils of larger areas, but are of limited value for the transfer of experience."

Because classes of Soil Taxonomy are defined in terms of soil properties, and because soil behavior correlates with soil properties, taxa of the system should reflect behavioral patterns. As soil families within a given subgroup are differentiated primarily on the basis of soil properties important to plant growth and indicative of soil-water-root relationships, taxa of this category should have the greatest prediction value. Soils classified into the same soil families should, therefore, have nearly the same management requirements and similar potentials for crop production. This assumption was recently substantiated in a study of soils of the southern United States (De Ment, et al., 1971). The study further showed that only general kinds of soil behavior can be predicted within classes of the broader defined higher categories.

The bulk of the world's research on soil management has been carried out in temperate regions, but the transfer of this experience into the tropics has met with varying success. Therefore, the transfer process should be primarily within tropical regions; to date, however, the methodology for transferring existing experience among tropical countries has not been developed. Thus, the Universities of Hawaii and Puerto Rico will jointly initiate research along these lines, and it is hoped that this research will either demonstrate the validity of Soil Taxonomy for purposes of agrotechnology transfer or establish the modifications necessary to make it viable.

SUMMARY

The objective of taxonomic soil classification is to provide a conceptual framework to accommodate the current knowledge of soils, and the concepts derived from this knowledge, in an organized manner. Soil classification systems allow for comparisons of soils, both for similarities and differences, and should also facilitate the transfer of agricultural technology. If the experiences of the U.S., the U.S.S.R., and other countries are to be a guide, it is clear that taxonomic systems of soil classification with a large number of precisely defined taxa in the lower categories are required. Technical systems derived from taxonomic soil classifications may also provide a useful methodology for expediting management experience of relevant crop production.

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Field Experimentation to Allow Economic Evaluation of Management and Environmental Effects on Soil Productivity

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This project is being undertaken to correlate food crop yields on a network of benchmark tropical soils and to determine scientifically the transferability of agroproduction technology among tropical countries. Crop production experiments will be carried out on selected soils belonging to related soil families in several countries and the hypothesis tested that agrotechnology developed on a particular soil family in one location will produce comparable yields on the same soil family in another location. These soils will belong to soil families of related subgroups as defined by the new U.S. Soil Taxonomy since the family level in this classification is the level at which transference of agrotechnology is proving possible in the temperate zones and within Hawaii. Results of these experiments will have maximum usefulness if production functions are developed to relate crop yield to management, soil, climatic, and plant factors that permit economic evaluation. These production equations will also allow yield prediction in other areas with similar soils. This paper presents a preliminary proposal of methodology to attain the objectives of this project.

OBJECTIVES

The major objectives of the project are to:

1. Test the hypothesis that agrotechnology developed for a soil family in Hawaii will produce comparable yields on the same soil family elsewhere, that is, Africa, Asia, and Puerto Rico.
2. Develop yield response equations for each site and determine the important management, soil, climatic, and plant variables.
3. Develop yield response equations for the same soil family at all sites combined to determine which factors are required to allow a single equation to adequately describe yield response for various members of a soil family.
4. Develop, if possible, a universal yield equation that will adequately describe the yield response for any soil, given the appropriate variables.
5. Determine economically feasible inputs for the different production functions at various levels of national resources.

In order to attain these objectives, a series of experiments will be installed at each of the major sites so that the response to the major nutrients, N, P, and K, as well as other management variables, can be measured. These experiments must be relatively uniform at all sites of the same soil family so that proper evaluation can be made. In addition, the experiments should be comparable over all soil families if comparisons between soil families are also to be made.

SITE SELECTION

The soils studied will be limited to upland tropical soils of the Oxisol and Andept great groups. Families that occur in Hawaii will be sought in one country in Africa and two countries in Asia. It is anticipated that the exact soil family may not always occur in a suitable location in every country; therefore, it may become necessary to utilize closely related soil families that differ only in relatively minor characteristics and which are, for all practical purposes, the same as the family occurring in Hawaii. Among the criteria considered in selecting a site for the experiments, the most important will be the presence of the appropriate soil family. The existence of a research institute in the country (government research station or university) interested in cooperating on the experiment, the attitude of the local government to the project, and the presence of an AID mission in the country are other considerations that must be met before a site is selected. The location of the site to a nearby population center with adequate facilities, such as electricity, telephones, and water, will also be desirable. The ability to irrigate the experiment is considered an important requirement of the site since variations in rainfall can cause reduced yields or complete failure of crops--with loss of information. It is not considered necessary that there be a large, continuous water source on the site proper, but a source from which water can be hauled should be within reasonable distance. It is planned to use drip irrigation, which has relatively low water requirements; however, it may be found in the field that this requirement is impractical, and it may have to be discarded, but it will be a goal to seek.

CROP SELECTION

At least one crop must be grown at all sites in order to make appropriate yield comparisons. The crop selected should be an important food crop in the countries concerned, responsive to fertility differentials, and reasonably simple to manage. Maize, or corn, is being considered since it generally meets the criteria mentioned above. Cassava is another possible crop of worldwide importance, although it has the reputation of being rather unresponsive to fertilizers. In some studies, cassava has shown fairly large yield increases from fertilizer applications, so it may be suitable. Upland rice is also being considered because it is of worldwide importance and meets the aforementioned criteria. Sorghum has been suggested as an indicator crop, but there is concern that its susceptibility to bird damage may make it impractical to use with confidence that reliable grain yields could be obtained. It does have appeal because of its drought resistance and ability to ratoon, but its vulnerability to birds, especially in small plantings, makes its usefulness to the small farmer questionable. Pigeon peas have also been suggested because of its versatility as a food for man as well as animals. However, recent information from Puerto Rico indicates that it is not an important food crop in

many South American countries. Soybeans are being considered, but their sensitivity to photoperiod is of concern.

It may be difficult, if not impossible, to find a single variety of a crop that will produce well at all sites. Although it is necessary to have at least one crop grown on all sites, several other crops of interest to the host country can also be grown so that information of particular interest to them can be obtained. Because varieties of the same crop can differ in their yield potential, it is necessary that the same variety of the indicator crop be grown at all sites. This may cause problems due to lack of adaptability to the environment, insects, and diseases at all sites in question. It is proposed, however, that two varieties reasonably well adapted to the major locations be grown at all sites so that information will be obtained not only on the same variety at all sites, but also on the best-adapted variety at each site. This has an added advantage in that it allows evaluation of the management parameter, variety.

TREATMENT SELECTION

The treatments selected must allow evaluation of crop response to major nutrients, as well as evaluation of interactions between major nutrients and other variables, controlled and uncontrolled, and also allow development of production functions from which economic interpretations can be made. Productivity, or yield, which is a function of management, soil, climate, and plant factors, may be expressed by the equation

$$y = f(x_m, y_s, z_c, w_p) \qquad \ldots(1)$$

where y is yield, x_m are management variables, y_s are soil variables, z_c are climatic variables, and w_p are plant variables. Soil and climatic variables are characteristic of the sites and generally not subject to human control. These variables, however, can have marked effects on the productivity of an area and thus must be measured if possible. This will be discussed in more detail later, but the controllable variables will be considered in the present section as they can be manipulated to provide a series of treatments that allow evaluation of soil productivity.

Management variables include fertilization (amount and timing), irrigation, pH, plant population, weed, disease, and insect control, time of planting, crop, variety, and so on. Of these, fertilization (quantity of fertilizer) is one of the most important in controlling productivity of a soil. Therefore, levels of N, P, and K will be employed to give a range of yields to allow evaluation of site productivity. Other nutrients may also be considered, but it is felt that these three major nutrients generally are the most limiting in tropical soils and measureable improvement in yield should be obtained with increasing quantities of these elements. Possible deficiencies of other nutrients may be discovered from soil or plant analysis and can be incorporated into the experiment, if considered necessary.

Nitrogen is usually the most limiting element in tropical soils, so three or more levels of nitrogen, ranging from zero to an amount considered more than adequate for the crop, will be used at each site in combination with amounts of P and K. Soil analysis will be used to evaluate the status of P and K at each site, and levels of each nutrient will be established on the basis of this analysis. Soil P will be evaluated by the P sorption isotherm

method of Fox and Kamprath (1970) and soil levels will be adjusted to provide comparable ranges of P in solution with a maximum of about 0.20 ppm P in solution. Therefore, the P differential in a particular experiment will depend on the soil P level and the crop. Similarly, soil K will be assessed with N NH_4OAc, pH 7.0, and the range of K applications will be adjusted accordingly. Since it is desired to develop a production function including these nutrients, three or more levels of each nutrient will be included if any of them is found to be inadequate. Where P and K are adequate, only two levels of the element will be required for verifying the soil analysis. A control plot that receives no fertilizer will be included to allow evaluation of the natural fertility of the soil. A blanket application of micronutrients, including B, Cu, Mg, Mn, Mo, Zn, and possibly others considered essential for the soils and crops used will also be applied to all fertilized plots to prevent yield reductions from inadequate levels of these nutrients. A preliminary assessment of micronutrient deficiencies will be obtained from selected plots that receive near-optimum amounts of N, P, and K, but are not given the blanket application of micronutrients.

Irrigation is another management factor that can have marked effect on yields, especially when normal rains do not occur or when a crop is to be grown during the normally dry season of the year. Productivity of a soil can be greatly influenced by the presence or absence of adequate irrigation. Therefore, it is essential to include an irrigation differential to evaluate soil productivity properly. If soil productivity with irrigation is high enough, it may be a sufficient incentive for a government to develop facilities to irrigate the area and thus increase productivity in the country. Furthermore, there are large areas of arable land in the tropics that are idle during the normal dry season when sunlight energy is at its highest and could be used by plants for production of food for man and his livestock. A supply of irrigation water during this period would increase and would help to stabilize food production in a country. Therefore, it is proposed that at least two irrigation levels, with and without irrigation, be included as treatments in each experiment and possibly several levels of irrigation be included where supplies of irrigation water are readily available. Experience with drip irrigation in Hawaii suggests that its reduced water requirements would make it suitable for these experiments. Where several levels of irrigation are to be included, a differential consisting of three intervals, zero irrigation, medium frequency, and high frequency may be used, or moisture sensing equipment such as Bouyoucos blocks or tensiometers could be employed to establish an irrigation differential.

Adjustment of soil pH or application of lime is a management factor that can produce large yield increases in tropical soils not only because it increases availability of nutrients, but also because it reduces Al toxicity and supplies Ca. It is proposed that at least three pH levels, which would range from the original soil pH to a pH considered adequate for crop production, be included in the experiment. There are several opinions regarding the definition of an adequate pH level: Kamprath (1970) recommends liming to neutralize KCl extractable Al and Puerto Rico recommends liming to 75% of base saturation, but results in Hawaii have suggested that a pH of 5.5 to 6.0 is adequate. A decision will have to be made on which criterion should be used, and then a series of treatments can be established.

Plant population, or stand, is a management variable that affects productivity of a crop and can be included in the experiments. In the original project proposal, however, a series of plant population experiments was planned independently of the main fertility experiment. In light of the number of variables being considered, it might be wise to use only one plant population--

that considered best in Hawaii, or in the country where the experiment is located--in the main fertility experiment. More detailed evaluation of stand can be obtained in a separate study at the site.

The crop and variety (also management variables) can be kept constant at all sites, but, as was mentioned earlier, there is the possibility that one variety will not be adaptable to all sites and the evaluation of soil productivity would be biased by a poorly adapted variety. Therefore, it is proposed that two varieties that are adaptable to several sites be grown at all sites so that soil productivity at each site can be evaluated by an adapted variety and yet variety continuity throughout the sites be maintained. An alternative procedure is to have one standard variety at all sites and a second variety that is well adapted to each individual site. Thus, there may be as many as four or five different varieties in all sites combined, but only two varieties at any one site.

EXPERIMENTAL DESIGN

The design selected should be one that provides sufficient levels to allow development of production functions, permit evaluation of interactions, and result in an experiment of manageable size. Because several factors are being considered, and interactions are desired, the two general classes of designs that should be considered, according to Justesen (1971), are the classical factorial and the central composite designs. If the experiment involves two factors each at three equidistant levels, the two types coincide.

In the present experiment the factors to be tested are applied N, P, K, and pH, and variety and irrigation with a minimum of three levels of the first four variables required to allow development of production functions. A complete factorial combination of these four factors at 3^4, 4^4, or 5^4 would have 81, 256, or 625 treatment combinations, respectively. This does not include the four irrigation-x-variety-treatment combinations, which would increase these values fourfold, making the experiments too large for proper management.

The size of the experiment can be reduced by taking a fraction of the fertility combinations and imposing upon them the four irrigation-x-variety treatments. Such a design for 1/3 replicate of a 3^4 factorial is given by Cochran and Cox (1957) (see Table 1) and would reduce the total number of treatment combinations to 27 for the fertility variables. The treatments are in blocks of nine, and the defining contrast is ABCD. Three additional treatment combinations were added to the original design for the purposes of this experiment (Table 1). A 0000 plot was added to blocks II and III to provide estimates of indigenous soil fertility for each block, and a 2222 plot without micronutrients was added to block I for a preliminary assessment of micronutrient deficiencies. This gives a total of 30 treatment combinations, and combining them with the four irrigation-x-variety treatments brings the total number of plots to 120. There are, however, only three levels of each fertility variable to permit linear and quadratic surfaces to be developed for determining optimum nutrient levels.

Irrigation treatments generally require relatively large plots; therefore, it is proposed that the plot arrangement be such that irrigation treatments are set up in two large blocks, one with adequate irrigation and the other without. The fertility treatment combinations would be allocated at random throughout an irrigation block, and each fertility plot would be split into two subplots on which the two varieties would be assigned at random.

Table 1. Coded fertility treatments for an extended 1/3 replicate of a 3^4 factorial with 30 units in incomplete blocks of 10 units each[a]

Block I				Block II				Block III			
N X_1	P X_2	K X_3	pH X_4[a]	N X_1	P X_2	K X_3	pH X_4	N X_1	P X_2	K X_3	pH X_4
0	0	0	0	0	0	2	1	0	0	1	2
0	1	2	2	0	1	1	0	0	1	0	1
0	2	1	1	0	2	0	2	0	2	2	0
1	0	2	2	1	0	1	0	1	0	0	1
1	1	1	1	1	1	0	2	1	1	2	0
1	2	0	0	1	2	2	1	1	2	1	2
2	0	1	1	2	0	0	2	2	0	2	0
2	1	0	0	2	1	2	1	2	1	1	2
2	2	2	2	2	2	1	0	2	2	0	1
2	2	2	2-Micro nutr.[b]	0	0	0	0[b]	0	0	0	0[b]

[a]Combinations from Cochran and Cox, 1957.

[b]Added treatments.

Defining contrasts: 2 d.f. from $X_1X_2X_3X_4$, equivalent to putting $X = X_1X_2X_3(Y)$.

Analysis of variance (added plots deleted)

1.

Effects	d.f.
Block	2
Main	8
2-factor	16
Total	26

2.

Effects	d.f.
Block	2
Main	8
X_1X_2, X_1X_3, X_2X_3	12
Error (X_4 interactions)	4
Total	26

If all interactions of X_4 are negligible.

Colwell (1971) proposed a fractional factorial design with 4N x 4P x 2K x 3S variables with 48 plots, which was considered suitable for soils likely to give little or no response to K. This design has some merit for the present experiment, especially in situations where P or K are considered adequate. However, when the four irrigation-x-variety treatment combinations are included in this design, the total number of treatment combinations is 192.

The second degree composite designs proposed by Box and Wilson (1951) offer additional possibilities for obtaining sufficient precision in a manageable experiment. Justesen (1971) lists three advantages of the central composite designs over the factorial designs when there are three or more variables: (a) regression coefficients can be tested directly for their importance because of orthogonality; (b) fewer observational points are required and degrees of freedom for testing the fitness of the model are still ade-

quate; and (c) the number of levels is increased by two for each factor to provide for a better test of the lack of fit.

Baird and Fitts (1957) described a central composite design that consisted of five rates each of N, P_2O_5, and K_2O selected to furnish maximum information on main effects and interactions. The total number of plots was 18, and increments of all nutrients were equally spaced. Hurst and Mason (1957) presented a graphical display of the 17 treatment combinations originating from the central composite design and explained that the remaining three treatments were included to provide supplemental information for calibration of soil tests. Voss, et al. (1970) used a one and one-half cube with star points replicated design with 25 treatment combinations to study the yield response to N, P, and K.

The four fertility variables in the present experiment may be arranged in a central composite design and then combined with the four irrigation-x-variety treatments. A central composite rotatable second order design for four x-variables with N = 31 is presented by Cochran and Cox (1957). It is basically a 2^4 factorial + star design + 7 points in the center. When the four irrigation-x-variety treatments are combined with these 31 treatments, the total number of plots is 124. However, variation within the 31 fertility plots could be quite large, and it would be advantageous to break these treatments into smaller blocks with less intra-block variation. Therefore, a central composite second order design in incomplete blocks presented by Cochran and Cox (1957) was investigated. With four x-variables, N = 30, there were three incomplete blocks of 10 plots each. The treatment combinations are shown in Table 2. As described in the section on treatments, a measure of productivity of the soil without fertilizer is desired; to assess this, an unfertilized plot, -2-2-2-2, was therefore added to each incomplete block. In order to maintain balance in the design, as suggested by Tramel (1957), an offsetting treatment combination of 2222 was added to one block. This treatment completes one diagonal of the design and is also of agronomic interest in that it has the highest rates of all four variables. Theoretically, it should then have the highest yield, barring excessive rates. Also, an assessment of possible deficiencies of micronutrients is desired, so additional 0000 and 1111 plots were added, which would not receive the micronutrient applications. These plots bring the total number of plots per block to 12 and the total number of plots for the fertility variables to 36. Combination with the four irrigation-x-variety treatments brings the total number of plots in the experiment to 144. This is a fairly large experiment, but in light of the variables being evaluated and the type of response curves to be developed, it does not appear likely that very great reduction in total number of plots is possible without sacrificing information on certain variables. There are five levels for each fertility variable, which allows development of fairly precise yield response curves for determination of optimum rates for each variable and for tests for lack of fit.

Nalimov, et al. (1970) presented two designs for four variables which have the property of D-optimality. Both had three levels of each variable. One of them had 24 treatment combinations and the other--which was basically Kono's (1962) design modified to satisfy the condition of nonsingularity for Hartley's (1959) second-order designs--had 18 treatment combinations. These designs would reduce the total number of plots to 96 and 72, respectively, but offer only three levels of each variable, which would provide (1) rather low precision for estimates of optimum rates and (2) tests for lack of fit.

Table 2. Fertility treatments for a central composite second order design in incomplete blocks of 12 units[a]

Block I				Block II				Block III			
N X_1	P X_2	K X_3	pH X_4	N X_1	P X_2	K X_3	pH X_4	N X_1	P X_2	K X_3	pH X_4
-1	-1	-1	-1	-1	-1	-1	1	-2	0	0	0
1	-1	-1	1	1	-1	-1	-1	2	0	0	0
-1	1	-1	1	-1	1	-1	-1	0	-2	0	0
1	1	-1	-1	1	1	-1	1	0	2	0	0
-1	-1	1	1	-1	-1	1	-1	0	0	-2	0
1	-1	1	-1	1	-1	1	1	0	0	2	0
-1	1	1	-1	-1	1	1	1	0	0	0	-2
1	1	1	1	1	1	1	-1	0	0	0	2
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
-2	-2	-2	-2[b]	-2	-2	-2	-2[b]	-2	-2	-2	-2[b]
1	1	1	1-Micro nutr.[b]	0	0	0	0-Micro nutr.[b]	2	2	2	2[b]

[a]N = 30 original treatment combinations + 6 added treatment combinations.
[b]Added treatments.

Treatment levels (kg/ha)

Code	N	P	K	pH	
	X_1	X_2	X_3	X_4	
-2	0	0	0	0	
-1	50	150	50	+ .5	pH unit
0	100	300	100	+1.0	"
1	150	450	150	+1.5	"
2	200	600	200	+2.0	"

ANALYSIS OF IMPOSED MANAGEMENT FACTORS

Data obtained from the series of treatments described above will allow calculation of relationships between yield and the six management factors studied. The selected quadratic equation for which 26 parameters must be estimated is given below.

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + b_6X_6 + b_7X_1X_2 + b_8X_1X_3 + b_9X_1X_4 + b_{10}X_1X_5 + b_{11}X_1X_6 + b_{12}X_2X_3 + b_{13}X_2X_4 + b_{14}X_2X_5 + b_{15}X_2X_6 + b_{16}X_3X_4 + b_{17}X_3X_5 + b_{18}X_3X_6 + b_{19}X_4X_5 + b_{20}X_4X_6 + b_{21}X_5X_6 + b_{22}X_1^2 + b_{23}X_2^2 + b_{24}X_3^2 + b_{25}X_4^2 \quad \ldots(2)$$

where X_1 = applied N, X_2 = applied P, X_3 = applied K, X_4 = applied time (pH), X_5 = irrigation, and X_6 = variety.

An alternative approach is to calculate a yield equation for each variety under each of the two irrigation conditions giving a total of four equations for each site. The quadratic equation is given below for one variety at one irrigation level.

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_1X_2 + b_6X_1X_3 + b_7X_1X_4 + b_8X_2X_3 + b_9X_2X_4 + b_{10}X_3X_4 + b_{11}X_1^2 + b_{12}X_2^2 + b_{13}X_3^2 + b_{14}X_4^2 \quad \ldots(3)$$

where the symbols are the same as described above. This approach appears somewhat more logical as there would be interest in the performance of each variety separately and also under the two irrigation conditions.

The production surface equation selected here is the quadratic, which is generally considered adequate for describing fertility responses. However, Heady, et al. (1971) compared four production surface equations--specifically, the Cobb-Douglas, square root, 1.5 power, and quadratic, or square, equations--and found the square root equation to be the most efficient in predicting the corn production surface. The experiment was an N x P experiment with nine levels of each element in an incomplete factorial design. Therefore, it would be wise to evaluate several possible production models in this study to find the most efficient one.

Several regression procedures are available for developing regression equations with a computer. Laird and Cady (1969) evaluated three of these: stepwise, backward elimination, and agronomic. They found that, based on residual sum of squares, the backward elimination model was slightly better than the stepwise, which, in turn, was better than the agronomic. However, if the criterion used was the ability of the equation to predict yields for new sets of data, measured by the predictive mean squares, the agronomic and stepwise models were best. Since the aim of the present study is to predict yields on similar soil families in other areas, it would be wise to use predictive mean squares as the criterion for selecting the best regression model.

ECONOMIC ANALYSIS

The production functions estimated by the regression analysis will be what economists refer to as production frontiers (frontier functions as op-

posed to production functions inasmuch as the equations represent the yields determined under well-controlled situations and will generally be greater than a producer would be expected to obtain under the same conditions). These production surfaces can be solved to determine derived demand equations for each of the agronomic variables. Derived demand equations will determine the optimal input combinations for any specified market conditions. The set of derived demand equations combined with the production frontier determine a profit frontier (function) allowing determination of the potential profitability of the crop for a given region and a specified set of market conditions.

Other possible economic applications could be the determination of the social rate of return on such production-related investments as irrigation or the subsidization of fertility inputs. It is also possible to estimate the potential internal rate of return to the economic factor of investments in irrigation facilities or in inputs that improve the long run (more than one growing season) fertility of the soil.[1]

SOIL FACTORS

One of the objectives of this project is to develop yield response equations for the same soil family over all sites where it occurs so that appropriate inputs of fertilizers, for example, can be made to obtain economically optimum yields. It is realized, however, that local soil and climatic conditions existing at each site, even of the same soil family, can have measurable effects on productivity of the soil. Therefore, it is imperative that appropriate soil and climatic parameters be included in the yield equations to allow adjustment for local variation. Soil properties can be divided into three broad categories: chemical, physical, and mineralogical. Within each category, a range of parameters exists that may be measured. The task is to identify those parameters that are likely to be important in plant growth and productivity. Several workers have investigated this problem and arrived at various conclusions. Voss, et al. (1970) considered soil N, P, K, pH, subsoil N, P, K, pH, and soil yield potential based on soil type, slope, and erosion. Soil N and P had the greatest effects on yield response. Elgabaly (1971) suggested the physical properties including texture, structure, bulk density, and available water range (1/3 atm to 15 atm); the chemical properties including pH, $CaCO_3$, organic matter, C:N, total N, P, K, available N, P, K, CEC, Exch Al, Mn, and Ca; mineralogical information on the semiquantitative estimation of clay minerals; morphological information on depth of solum, depth of humus horizon, and depth of carbonate horizon; and slope characteristics including aspect, degree, and length. He also suggested collecting soil samples at 25-cm intervals to a depth of 100 cm. Okuno (1972) investigated the variables to be included to predict crop yields for the main crops grown in Bulgaria, and included soil, climatic, and management factors. He considered the soil factors, content of physical clay, content of humus, and pH in water all at two depths (0-30 and 30-50 cm), texture coefficient, and thickness of humus horizon. Three of these variables appeared in the final yield equation. They were pH in subsoil, texture coefficient, and humus in top soil. Sopher and McCracken (1973) studied the correlations between soil properties, management practices, and corn grain yields on selected North Carolina Coastal Plain soils and considered the following soil variables: 1/3-bar moisture, 15-bar moisture, and

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[1]This economic analysis was provided by P. Garrod, Department of Agricultural Economics, University of Hawaii.

1/3-bar to 15-bar moisture (%); sand, silt, and clay (%); pH in water and pH in N KCl; total exchange acidity (me/100 g), exchangeable Al (me/100 g), acid extractable P and K (kg/ha), organic matter (%), and exchangeable Ca, Mg, K, and Na (me/100 g); and CEC, base saturation (%), and CEC/clay + organic matter (me/100 g). They found the soil factors that affected yields most were soil moisture-holding capacity, certain combinations of clay and sand, extractable P, percentage of base saturation and properties that control soil acidity, and the amount of charge on the cation-exchange complex.

Buol, et al. (1974) developed a somewhat different approach using a technical soil classification system for grouping soils with similar fertility limitations. Soils were grouped at the highest level according to topsoil and substrate textures, and the 13 modifiers were selected to evaluate specific fertility-related parameters. These modifiers included low CEC, Al toxic, acid, Fe-P fixation, x-ray amorphous, Vertisol, K deficient, carbonate, saline, sodic and cat clay indices, as well as two climatic parameters designated as gley (saturated with water for more than 60 days per year) and dry (dry for more than 60 consecutive days per year). They found a considerable improvement in fertilizer rate recommendations when the fertility-capability groupings as well as soil test results were used.

Based on the above literature and experience in Hawaii and Puerto Rico, it is proposed that the soil parameters listed below be measured at each site in the surface and subsoil.

Chemical parameters

1. CEC
2. Lime requirement
3. pH H_2O
4. pH N KCl
5. Δ pH
6. Exchange cations--Ca, K, Mg, Mn, Na
7. Base saturation
8. Al saturation
9. P sorption
10. Extractable P (0.5 M $NaHCO_3$)
11. Total N
12. Total organic C
13. C:N ratio
14. Micronutrients--Cu, Zn, Fe, Mo, S
15. Iron (Free iron/clay)
16. Free $CaCO_3$
17. K in silt fraction
18. Electrical conductivity

Physical parameters

1. Particle size (texture)
2. Structure
3. Bulk density
4. 1/10-bar moisture
5. 1/3-bar moisture
6. 15-bar moisture
7. Moisture release curve
8. COLE value (Coefficient of Linear Extensibility) swell-shrink
9. Atterberg limits
10. Aggregate stability

11. Horizon depth
12. Mottling
13. Slope

Mineralogical parameters

1. Relative mineral composition

These parameters include criteria used in the soil family classification as well as others closely related to soil fertility. Thus, it should be possible to identify important parameters affecting soil productivity for each family.

CLIMATIC FACTORS

Several researchers have studied the relationships between climatic factors and yield of various crops. Laird and Cady (1969) included excess moisture, drought, and hail in their equation for corn yield. Voss, et al. (1970) considered relative photosynthesis based on daily precipitation, evapotranspiration, and available soil moisture to a depth of 150 cm at 15-cm increments at the beginning of the growing season. This variable was highly correlated with corn yield. Elgabaly (1971) suggested pre-sowing rain, temperature units during the growing season, moisture balance (total precipitation + moisture supply - evapotranspiration) and rainfall during a given critical period of growth, for yields in Bulgaria. Trashliev, et al. (1971) suggested some of the same variables in their studies of yields of wheat and maize in Bulgaria, as did Okuno (1972), who also included number of days above 5°C in winter. Oldeman (1971), working with sugarcane in Hawaii, considered rainfall in the summer, in the winter at month of harvest, and at one month before harvest; pan evaporation per month; radiation per month; and maximum and minimum temperature and diurnal temperature difference at harvest. Buol, et al. (1974) included two climatic parameters in their condition modifiers for the fertility-capability classification system they developed. These were gley (saturated with water for more than 60 days in most years) and dry (dry for more than 60 consecutive days per year within a 20- to 60-cm depth).

The climatic parameters listed below have been selected in discussions with Paul Ekern, University of Hawaii, and are being proposed for the present experiment.

1. Rainfall--quantity and intensity (hourly recording)
2. Air temperature--maximum, minimum, and average (continuous recording)
3. Solar radiation (hourly recording)
4. Relative humidity (continuous recording)
5. Wind--velocity and direction (continuous recording)
6. Daylength (from sunlight record or latitude)
7. Pan evaporation (daily)
8. Soil moisture (periodically)
9. Soil temperature 3- to 6-inch depth--maximum and minimum (daily)

Parameters 7, 8, and 9 are considered to be optional if facilities are not available to obtain them. A measure of soil moisture, however, especially at the beginning of a crop, would be helpful in assessing crop growth. Also, pan evaporation measurements would be useful in determining the rate of moisture loss from the area and would assist in scheduling irrigation and assessing moisture balance.

MANAGEMENT FACTORS

In addition to management variables being intentionally varied as treatments in these experiments, there are others that can vary from site to site or crop to crop and have pronounced effects on yield levels. Laird and Cady (1969) considered three of them (specifically, previous crop, leaf blight, and weeds), and all were included in the agronomic model that was found to have the highest predictive ability of the equations developed. Voss, et al. (1970) included past cropping, planting date, weeds, and plant population in their regression equation and found a considerable improvement in R^2. Elgabaly (1971) suggested date of sowing, land preparation, plant population, pest control, weed control, crop rotation, moisture level, and genotype as the important management variables to be included in production equations. Oldeman (1971) included month of harvest, age, crop cycle, irrigation water per month, applied N, P_2O_5, and K_2O, and days after last irrigation. Sopher and McCracken (1973) considered the management variables plant population and planting date.

In the present experiment it is proposed that the management parameters listed below be recorded in addition to the imposed management variables.

1. Plant population
2. Crop rotation
3. Insect damage
4. Disease severity
5. Weed population
6. Planting date
7. Harvest date
8. Tillage

PLANT FACTORS

The ability of plants to take up nutrients is not always directly proportional to the levels of those nutrients in the soil because of conditions, chemical or physical, which may restrict absorption of certain nutrients. This has been shown in Hawaii by Thiagalingam (1971) and Khalid (1974). Therefore, it is suggested that appropriate tissue samples be taken from each plot at the appropriate time and analyzed for moisture, N, P, K, Ca, Mg, Mn, Al, and possibly micronutrients. This will provide information on the content of these nutrients in the plant and allow better understanding of nutrient interactions and effects on yield. Other plant parameters may also be required for various crops, for example, barrenness in corn, tillering in rice or sorghum, and so on.

DEVELOPMENT OF YIELD RESPONSE EQUATIONS WITH ALL FACTORS

The yield response equations developed for the imposed variables in the experiment should be expanded to include the various management, soil, climatic, and plant factors in order to identify factors of importance in predicting yields for other soil and climatic conditions. The yield function is given by the formula

$$Y = F(X_1, X_2, \ldots X_m; Y_1; Y_2, \ldots Y_s; Z_1; Z_2, \ldots Z_c; W_1; W_2, \ldots W_p) \quad \ldots(4)$$

where Y = yield of crop; $X_1, X_2, \ldots X_m$ = management factors; $Y_1, Y_2, \ldots Y_s$ = soil factors; $Z_1, Z_2, \ldots Z_c$ = climatic factors; and $W_1, W_2, \ldots W_p$ = plant factors.

These factors will be included in a regression equation, which will be of the general model given below.

$$Y = \beta_o + \beta_1 X_1 + \ldots + \beta_m X_m + \gamma_1 Y_1 + \ldots + \gamma_s Y_s + \sigma_1 Z_1 + \ldots$$
$$+ \sigma_c Z_c + \eta_1 W_1 + \ldots + \eta_p W_p + \Sigma \qquad \ldots(5)$$

This is a linear function of the unknown parameters $\beta_o, \beta_1 \ldots \beta_m$, $\gamma_1 \ldots \gamma_s$, $\sigma_1 \ldots \sigma_c$, and $\eta_1 \ldots \eta_p$ where the independent variables $(X_i;\ i=1,\ldots m)$, $(Y_j;\ j=1,\ldots s)$, $(Z_k;\ k=1,\ldots c)$, and $(W_u;\ u=1,\ldots p)$ can be the original measurements and variables derived from them, such as squares, products, square roots, and logarithms. Regression equations will be developed for each site to determine the important management, soil, climatic, and plant factors. Then, data from soils of the same family at different sites will be included in a regression analysis to produce a single equation containing the important parameters, which will allow prediction of yields on the same family in different locations. Finally, an attempt will be made to include data from all sites in the study and to develop a generalized, or universal, yield response equation that will adequately describe the yield response for any soil family, given the appropriate variables.

Economic evaluation of the derived demand equations for combined data should prove informative since effects of uncontrolled variables on yield levels will modify the economically optimum rates of fertilizer use. Also, P. Garrod suggested that if it were possible to approximate the probability distribution associated with climatic variables, then it would be possible to determine the production frontier, derived demand equation, social rate of return, and internal rate of return subject to risk criteria, that is, when the economic factor can be 95% sure of occurring. Information derived from these analyses will be extended to the local governments, as described earlier.

One test of the hypothesis of transferability of agrotechnology can be made by testing the response equations developed for two sites of the same soil family to determine if the response surfaces described are actually similar. This testing procedure is described by Pesek and Heady (1961). Analysis of variance of the combined data with a test of site effects would provide another evaluation of this hypothesis. Laird and Cady (1969) describe such a procedure, which may have to be modified somewhat, depending on the experimental design finally adopted.

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SECTION 2:

Approaches to Field Experimentation in Developing Countries

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Some Considerations in the Design and Analysis of Fertility Experiments for Developing-Country Use

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This workshop represents one of the more formal steps in initiating and implementing an important project--Soil Classification, Fertilizer Response, and Crop Production in the Tropics. Initiated with appropriate design, relevant analysis, and use of data as the pilot relative to soil fertility research objectives for less-developed countries, it can make an important contribution to agricultural development and improved human welfare. Designed, analyzed, and used in a manner to have generalizeable research over a range of LDC's, it can also make an extremely important contribution of biological science to economic development. Further, it can similarly have important general contributions to science if it produces a set of country experiments with results that are generalizable in prediction of the response of yield to manageable inputs and the agro-climatic environmental variables of other soils in other countries. It can accomplish these goals, however, only if the appropriate ultimate use of the data in guiding farmers of developing countries dominates the intellectual planning of (a) the analysis of data to best aid these decision processes for farmers who operate under a wide range of economic conditions, and (b) the design of experiments that will generate data allowing this analysis. In other words, I turn first to the decision and economic environment under which farmers of LDC's function; second, to the analysis of data (its nature and form) most useful in this decision environment; and third, to the design of experiments that will best generate data for analysis geared to the decision environment. The framework for the research needs to be thought through for these three steps, in the order enumerated, if the project is to be most productive in promoting greater food supplies and improved incomes in countries where nutrition and welfare are too restrained. I will return to these points later.

My link with this project is indirect and somewhat "back door." I am here not as a direct participant in the project or as the bearer of any recipe indicating what the design and framework of the analysis should be. Clearly, these responsibilities are those of the people who will implement the project. Instead, I come more as a representative of the Research and Advisory Committee of AID, which reviews this agency's research grants and recommends approval or not. In recommending eventual approval of this potentially important project for LDC's, the Committee emphasized that the proposers of the project, before they went to the field, should systematically think through and specify the methodology to be used in the analysis and design steps. It was expected that the past year would be fairly well devoted to the outlining and specifying pro-

cess on an interdisciplinary basis by the relevant subject matter specialists (for example, agronomists, agricultural economists, and statisticians) involved. It was recommended that the staffs of the proposing institutions should go so far as to develop a prospectus of:

1. The soil situations and countries where the experiments could be best conducted;
2. The designs and extent of experiments appropriate for the large number of managed input variables (nitrogen, phosphorus, potassium, stand, irrigation, variety and timing, and method of application) suggested relative to soil and climatic variables;
3. The specification of the variables and statistical and economic models to be used in analyzing and applying the resulting data.

Then, after this step was completed for the main candidate designs, methods, or models for each, the staffs of the proposing institutions were recommended to come together in a small workshop for final evaluation of the proposed methods--the participants being mainly the staffs of the proposing institutions but with a few "outside" experts for "straining," evaluation, and recommendation of the methods proposed. This, rather than a general conference on designs for and analysis of crop yield functions, was envisaged.

There is an important reason for this recommendation. Too many projects have "gone to the field" in LDC's, with the purpose and justifications of promoting development, without these "thinking through" steps. An experiment of yield response to irrigation has been put out on a soil type of "this" country, an experiment of response to fertilizer on a soil type of "that" country--with no prior thought of how the results are to be linked or used. Not infrequently, the soil or water specialist has gone ahead on his own. Then, when the time arrives to link the data into a useful system and make it applicable to a range of conditions, he turns to the crop specialist, climatologist, statistician, or economist and says "now you do that"--or vice versa. Unfortunately, the experiments have not been designed or located, or the appropriate data have not been collected, to allow generalizeable predictions to other locations and countries or to appropriate economic analysis and application. If costly experiments are to have generalizeable results and contribute most to economic decisions and economic development, the several involved disciplines must come together at the stage of decisions on analysis and design models--not ex poste to data collection.

If this project were financed and had only the objectives of basic science, it should not be conducted in or justified for LDC's. It would be better conducted in the U.S. or in developed countries where trained scientific staffs, skilled field technicians, and more sophisticated equipment are available. If its main objective were largely to illustrate that experimental data generated for one soil category at one location, with appropriate quantification of climatic variables and those representing prior differences in management, can provide efficient predictions for a quantitatively equivalent soil category in a different or distant location, it would be better and more cheaply accomplished at two or more points in the U.S.--or at points in the U.S. and Western Europe. If the major objective were to determine that a particular experimental design is optimal for prediction, a particular one of several algebraic response models, it would be best accomplished under controlled conditions of the U.S.--perhaps even in greenhouse experiments. If the major objective were to prove that one algebraic form of response equation is generally dominant for yield response to nutrient levels over a range of crop, soil, and climatic variables, it could be most efficiently and economically accomplished at home. If the objective were to develop efficient methods of statistical estimation

for response functions based on a multitude of control variables such as nitrogen, phosphorus, potassium, plant population, crop variety, and irrigation against variation in many soil and climatic variables, travel to far countries is hardly justifiable, and it again could be best accomplished near home facilities of field technologists, statisticians, computers, and so on.

The stated objectives of this project relate to developing countries and the proposition that fertilizer experiments can be conducted to have general value in aiding decisions of farmers and promoting development in LDC's. Hence, it is important that we come back to the three "thinking through" steps: (1) the decision or economic environment of the proposed farmers who will use the results in decisions; (2) the analysis that best provides data for these decisions; and (3) the experimental designs that will best generate the appropriate data.

THE DECISION-MAKING ENVIRONMENT

There can be numerous models of farmer decision environments ranging from (a) complete allocative models with investment alternatives on the farm which compete for scarce resources and thus suggest how scarce capital should be distributed among fertilizer outlay, new seeds, water systems, and so on, to (b) extreme micro-analyses that assume each farmer has unlimited capital and perfect knowledge and can drive the marginal value productivity of fertilizer investment down to its per-unit cost. The first situation best characterizes the mass of low-income farmers in developing countries; the second, if fully applicable anywhere, best characterizes large plantation set-ups owned by foreigners or agri-business firms. To make relevant and highly refined fertilizer recommendations in the first situation we would need "complete" (continuous) mathematical models of the entire farm--as well as of the fertilizer response surface in its relation to the soils and environmental variables of the particular farm. A more reasonable and manageable "short cut" to a "complete" mathematical model is a programming model that still relates fertilizer investment to competing alternatives in the use of capital throughout the farm. Even though farms have precisely the same quality of management, fertilizer response surface and soils, and climate, the optimum use of fertilizer will vary according to the farms' capital position or restraint. To recognize this difference in fertilizer recommendation, however, the agronomist or economist would need to solve a programming model for each farm. This not being possible, we need fertilizer response data in a farm that will allow "rule of thumb" approximations of this fertilization level. Therefore, the design of experiments needs to be such that it provides response predictions over the range of the surface to which different "rules of thumb" might apply. We could examine some of the "rule of thumb" (i.e., economic decision environments) situations for which data need to be available. Supposing we know the fertilizer response function as in (1)

$$y = f(x, s, z, w) \qquad \ldots(1)$$

where x, s, z, and w are, respectively, vectors of management (here considered fertilizer nutrients), soil, climate, and plant variables where we suppose the elements of the last three are fixed. Then, with $x = (x_1, \ldots x_j, \ldots x_m)$ the "rule of thumb" optimum fertilizer use by the farmer with unlimited capital and perfect knowledge is prescribed by (2)

$$\frac{\partial y}{\partial x_1} p/c_1 = 1.0$$

$$\frac{\partial y}{\partial x_j} p/c_j = 1.0$$

$$\frac{\partial y}{\partial x_m} p/c_m = 1.0 \qquad \ldots(2)$$

where the variables, c, are subscripted to indicate nutrient prices and p is crop price. Solving the equation set, if possible, for the x_j, we have the optimum fertilizer use for farmers with unlimited capital and knowledge under given soil, climatic, and plant conditions. If, however, the farmer has capital limited to K to spend on fertilizer and he wishes to allocate it among different crops and nutrients to maximize return from K, then we can determine the optimum level of each nutrient to each crop by solving the set of equations in (3) where y is subscripted to indicate crop, the first subscript of x indicates the nutrient and the second crop, while p is now subscripted by crops. The value, r, determined in solving the equations, is the rate of return to be obtained for investment

$$\frac{\partial y_1}{\partial x_{11}} p_1/c_1 =$$

$$\frac{\partial y_i}{\partial x_{ij}} p_i/c_j = r$$

$$\frac{\partial y_n}{\partial x_{mn}} p_n/c_m = r$$

$$\sum_i \sum_j c_j x_{ij} = K \qquad \ldots(3)$$

in each nutrient on each crop with total investment restrained to K as in the last equation of the set. (Other procedures such as La Grange multipliers could be used similarly for solution.) While the procedure just illustrated is the correct principle in fertilizer use for farmers with limited capital, it is too complex and cumbersome, perhaps, for most situations. For the majority of small, low-income farmers in LDC's, however, it is generally more relevant and not much more complicated than specifications such as those relating to equation set (2), or even the fertilizer levels that maximize yield per acre (i.e., the partial derivatives of x_j in equation 1 set at zero). But we may need to turn to less complicated "rules of thumb." For example, some literature suggests that LDC farmers are generally willing to invest in new technologies if they have prospects of a marginal return of, say, 200 percent.[1] Too, recommendations on nutrient mix of fertilizers is generally going to be given to farmers (although the production or response function serves as the basis for this determination and the optimum mix will change with level of crop yield except for algebraic functions such as Cobb-Douglas). Hence, in equation (4), supposing f is the level of a fertilizer mix, c_f is its price, p_y is the crop price, and y is the yield, we would solve for the value of f which

$$\frac{\partial y}{\partial f} p_y/c_f = 3.00 \qquad \ldots(4)$$

gives a marginal return of 200 percent. (Actually, we might solve for various levels of marginal return that could be communicated to farmers.) Hence,

[1]Note that a level of fertilizer application that gives a marginal return of 200 percent on the last unit will give a considerably higher return over all units of fertilizer applied.

whereas farmers might hesitate to invest in fertilizer if only a zero-one alternative or recommendation were given them, in the form of yield/acre or profit/acre maximum, they are more likely to invest in a more modest application rate--which is much better than none and represents progress in development--if it is one that gives a high return and justifies some risk and uncertainty. Since response surfaces generally have very low production elasticities in the neighborhood of yield/acre and profit/acre optima, it is possible to "back down" the function and greatly lessen fertilizer investment, yet reduce only slightly the yield and return per acre. In some situations I have examined, backing down from the yield/acre or profit/acre maximum to a level still giving 100 percent marginal return gives around 25 percent fewer fertilizer applications and costs for only a 5-7 percent reduction in yield and income. (The general quantities need to be more widely established.) Since the elasticity of the function, in our own experience, is high at low levels and small at high levels of the surface, the design could emphasize treatments of the upper reaches of the surface if (a) we were concerned only with "developed farmers" trying to attain per-acre profit or yield maximum, and (b) the surface maximum and thus its negatively sloped portion needed prediction. Since these may not be appropriate quantities for the mass of farmers in LDC's, a different configuration of treatments in the design is posed, so that portions of the response surface with higher elasticities are better predicted.

I have reviewed (incompletely) this "thinking through" step in farmer decision and economic environment to emphasize that data needed for the analysis will cover the major portion of the positively sloped sides of the response surface reflecting its slope and elasticities. Designs need to be organized accordingly. One fertility expert proposes that the response curve is simply composed of two linear segments--one with high and another with zero slope. Were this true, the "corner" at the intersection of these two curves would be "the only level" of fertilization, whether the farmer were maximizing profit per acre or attaining a level of return on capital, and designs need to allow testing of this proposition against the one more widely held of curvilinear surfaces. The difference in possibilities has great importance in fertility research in LDC's. To adequately resolve this important difference in concept, designs must extend to nutrient treatments beyond levels conforming with the potential maximum y dimension of the surface and allow estimation of slopes on its "backside."

ANALYSIS OF EXPERIENCES FOR DECISIONS

We have estimated a range of fertilizer response surfaces for a range of soil conditions in Iowa. These experiments, however, were simple relative to the vast array of management, crop, soils, and climate variables posed for this tropical soils project which is to have inter-country predictive ability. The greatest number of our experiments have involved 3 to 4 variables, such as yield, nitrogen, phosphorus, potassium, or stand, under fixed conditions of other variables. We used a range of designs for them, usually on a "judgment basis" of those that would allow us to predict and compare different algebraic forms of surfaces.

These have ranged from an incomplete factorial, as in Table 1, where each x refers to a plot of a treatment, to central composite designs--and numerous variations between. While the design in Table 1 may have represented an "overkill," it was one of our first experiments to estimate response surfaces, and we were interested in all algebraic and subject matter details of the surface and examination of alternative algebraic forms. Few would want to go to the cost and detail of this design for a large-scale project over many locations. Aside from economy of experiments, I doubt that our experience would yet indi-

Table 1. Incomplete factorial design[a]

Lb. P_2O_5 per acre	Lb. nitrogen per acre								
	0	40	80	120	160	200	240	280	320
0	xx	xx	xx	xx	xx	xx	xx	xx	xx
40	xx	xx			xx	xx			xx
80	xx		xx		xx		xx		xx
120	xx			xx	xx			xx	xx
160	xx	xx	xx	xx	xx	xx	xx	xx	xx
200	xx	xx			xx	xx			xx
240	xx		xx		xx		xx		xx
280	xx			xx	xx			xx	xx
320	xx	xx	xx	xx	xx	xx	xx	xx	xx

[a]From experiment reported in Heady et al., 1955.

cate any outstanding statistical efficiency of one design over another under field conditions--if each includes enough treatments to give a sufficient number and range of the treatment variables over input space. While there are designs that can be proved most efficient for a particular algebraic form, one is not certain that this form is going to prevail for every response under each particular set of environmental conditions of variables. We have found each of several polynomial forms to "fit best" for the unique conditions of particular experiments, locations, years, and weather conditions. For the majority of cases, however, the best function seems to be a conventional quadratic with linear and squared terms and first-order interactions for the fertilizer variables. Under a wide range of locations and conditions, we generally have found a "peak" for the response surface and declining marginal products or partial derivatives for variables such as nitrogen, potassium, population, temperature, and water in corn and similar Midwest crops. We have never found an important case of increasing returns to fertilizer variables. I would expect that these same conditions prevail widely over the world--at least in developed countries where management is rather high. They may even dominate in less-developed agricultures. Presence of increasing returns (a possibility posed in one paper of this set) and a response surface characterized by a peak imply the need for more treatments of "closer spacing" than when these conditions are absent.

I am not certain that we yet have sufficiently wide and basic knowledge to proclaim with certainty that crop production surfaces conform to one specific algebraic form. Each form imposes certain strict mathematical restraints on the relationships that can be derived from and characterize it. For example, a Cobb-Douglas, Mitscherlich or quadratic form supposes the "fixed" conditions of marginal productivities (first derivatives) between yield, y, and fertilizer input, f, respectively in equations (5), (6), and (7)

$$\left(\frac{dy}{df}\frac{f}{y}\right)_j = \left(\frac{dy}{df}\frac{f}{y}\right)_{j-1} \qquad \ldots(5)$$

$$\left(\frac{dy}{df}\right)_j = r\left(\frac{dy}{df}\right)_{j-1} \quad (r < 1.0) \qquad \ldots(6)$$

$$\left(\frac{dy}{df}\right)_j = \left(\frac{dy}{df}\right)_{j-1} - k \qquad \ldots(7)$$

where the subscript refers to the jth input level of the variable. I have not yet seen an established biological basis for imposing one of these fixed conditions over others on the response function--except that (5) and (6) could never prevail for surfaces with negative slopes. Our own quantitative experience has been restricted to relatively few control or management variables (usually three or four) with fixed crop, soils, and climatic variables. This study for tropical soils poses the use of a good many more management variables. If appropriate functions and interactions are to be estimated for these variables, the response surfaces are to be appropriate to the decision-making environment of LDC farmers with a range of capital restraints, and if results are to be transferable among locations, soil categories, and countries, large and complicated experiments are posed. Perhaps before any recognized or formal attempt is made to develop universal or generalized functions to be used over soil groups and countries, two prior steps or sets of research are necessary: (a) one set of studies that experiments only with designs and predictions for a rather large number of control or decision variables where environmental variables are fixed (i.e., a given site), and (b) another set of studies that determines which environmental variables of crops and soils best relate to the height and slope of yield surfaces and how to measure and aggregate them for later use in broader statistical estimates and geographical stratification of experimental sites. Perhaps this project should be considered to serve these purposes and the promised or posed generation of response functions that have transfer value for prediction and economic applications in other countries should be considered to be the more formal and realistic objective of a second project. I rather doubt that, within the budgeted time period, this project with its two components can go further than the first alternative suggested.

MEASUREMENTS AND DESIGN FOR GENERALIZED FUNCTIONS

If the response to the management variables at experimental sites is to have predictive value over extended space as represented by other soil and climatic regimes, the experiments (a) need to be implemented at locations with a wide range of values in the environmental and crop variables, and (b) the soil, climatic, and crop variables need to be specified carefully as those with a direct or measurable influence on crop yield and be measured a priori to or during, as is most applicable, the execution of the experiments at individual sites. In execution of the project, the environmental variables should be built, as near as possible, directly in the design, at least to the extent of locating site experiments over a wide range in values of those variables. The strategy of how experiments are to be located in LDC's thus becomes an important aspect of the project pre-planning activities. A "course of least resistance" would be that of simply executing experiments at a given site of experimental facilities in each of several countries. A preferable strategy undoubtedly would be to have fewer countries, if necessary, and experiments extended over a wider range of environmental variables. An example of site location by this stratification is the Iowa study by Voss, Hanway, and Fuller (1970) where two-thirds of the sites were spread rather widely over Marshall and Monona silt loam soils to attain a considerable range of a set of nonexperimental variables, including past cropping, planting date, weeds, plant population, soil N, soil P, soil K, subsoil N, subsoil P, subsoil K, subsoil pH, relative photosynthesis, and plant barrenness. The experimental variables were N, P, and K applied to corn under a central composite design. A generalized function was then fitted for prediction to both Marshall and Monona soil types (Table 2). The generalized regression equation with estimated coefficients for 29 variable terms, including nonlinear and interaction expressions, accounted for

Table 2. The 1½-cube design for the Marshall-Monona fertility-environment experiments

	Actual rates (kg/ha)																						
K	0	0	134	128	6	6	128	100	34	34	100	67	67	67	67	67	67	67	67	134	134	34	67
P	0	67	0	64	3	64	3	51	17	51	17	34	14	34	34	67	67	0	0	34	34	34	34
N	0	224	224	214	214	10	10	168	168	56	56	224	224	0	0	112	112	112	112	112	112	112	112
	Coded values																						
K	-2	-2	+2	+1.9	-1.9	-1.9	+1.9	+1	-1	-1	+1	0	0	0	0	0	0	0	0	+2	+2	-2	0
P	-2	+2	-2	+1.9	-1.9	+1.9	-1.9	+1	-1	+1	-1	0	0	0	0	+2	+2	-2	-2	0	0	0	0
N	-2	+2	+2	+1.9	+1.9	-1.9	-1.9	+1	+1	-1	-1	+2	+2	-2	-2	0	0	0	0	0	0	0	0

80 percent of the variance in corn yield and served relatively efficiently in predicting for a given set of environmental or nonexperimental variable levels on either soil.

The method of measuring or aggregating a number of the environmental variables will usually present a problem--especially for variables relating to climate but possibly also for soils and crops. While not initially designed for these purposes, a large amount of experimental data exists that could be analyzed to provide intelligent "first leads" for environmental variables of relevance in predicting yields and for methods of aggregating them. An illustration is the study by Pesek, Heady, and Venezian (1967) where a generalized yield response function was fitted to a time-series experiment of corn-oats-meadow-rotation applied P and K over Clyde, Cresco, calcareous Webster, and acid soils in Iowa. The generalized production function, with R^2 values ranging up to .90 for corn, .92 for oats, and .93 for hay, were fitted to 5 years of data at each location. The environmental variables included soil N, soil P, soil K, temperature, and rainfall plus dummy variables for location or soil types. The temperature variable was measured as deviations below and above a range considered from prior research to be optimal for crop yield in specific periods of crop growth. This measurement of the temperature variable proved statistically superior to other measurements tried. The rainfall variable was measured as negative deviations from the mean of the 5-year period for a particular period of growth for each crop--with greater weight given to extended periods of negative deviations. While the measurements of both variables were somewhat arbitrary, those used were superior to others tried.

I mention these types of findings to emphasize (a) the possibility that numerous leads on measurement might initially be forthcoming from an analytical scanning of existing data, (b) that project experiments at scattered world locations could best be initiated with economy and momentum if existing data were fully exploited before initiation of new projects, and (c) the need to arrange initiation of relevant measures of environmental variables with the experiments. These steps are particularly important in a project with objectives revolving around a very large number of experimental and environmental variables that propose results for generalized use over a range of soils and in the less-developed countries.

As a final illustration and an expression of hope in estimating generalized crop functions, I would like to mention one measuring response to irrigation and fertilizer in relation to selected soil and climatic variables. Also, this research further emphasizes the need to integrate the soil fertility and water management projects funded by AID for tropical soils. This project, sponsored by the Bureau of Reclamation, was initially designed to measure crop yield response to water for various crop and environmental conditions. Since water response interacts greatly with fertilizer, however, the experiments generally were designed to predict crop yield response to applied fertilizer and irrigation water. The project was conducted in states west of the Missouri River, generally wherever we could obtain cooperators. Fifty experiments were conducted in six states over a 3-year period with wheat, corn, cotton, sugar beets, alfalfa, and potatoes. We would have preferred experiments only with corn but had to accept the crops of current interest to research workers in the various states. Since little was known about yield response to water in interaction with fertilizer (the nutrient mix generally recommended for the crop and location--although we would have preferred a standard mix), the random incom-

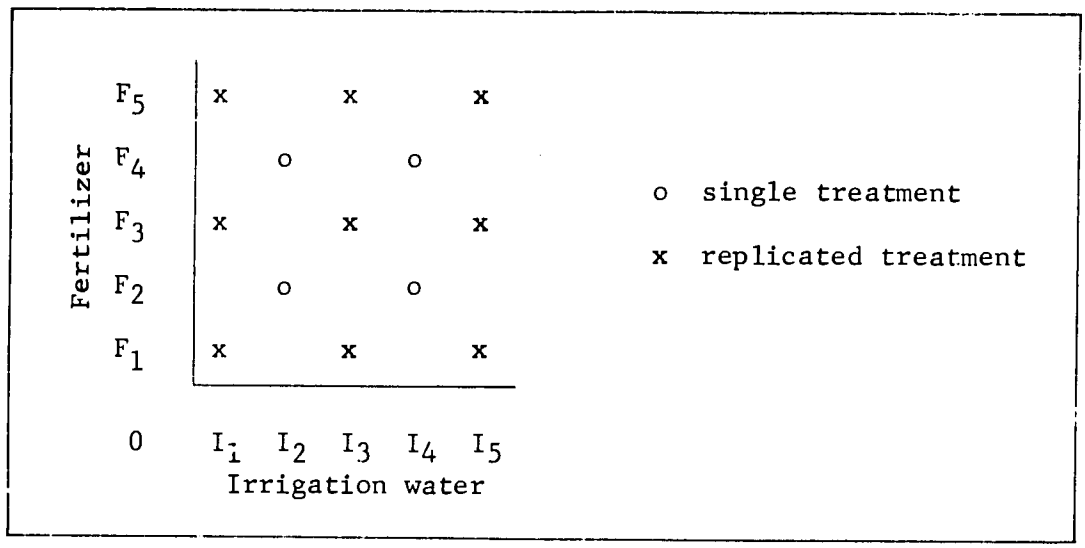

Figure 1. Incomplete block design with factorials for irrigation-fertilizer experiments

plete block design with factorials in Figure 1 was used (where the x's denote replicated treatments and the circles represent single treatments) because of limited research resources. Response surfaces were fitted for each crop at each location, and results were generally good. (In a few cases for corn, stand was included in the design.)

Special interest revolved around relating water response to soil and climate variables. We would have preferred to be able to "stratify" our "sample of experiments" over space to give a range of values for the climatic and soils variables, which are quantifiable and generally associated with yield. In contrast to the procedure preferred and which might best be used for this project dealing with tropical soils, we simply had to accept experiments at sites conforming with interested research workers and their established research facilities; however, we did have measurements of potentially relevant environmental variables made at and prior to initiation of the experiments. Then, after fitting the site or location functions, we estimated "generalized" functions on an individual commodity basis over the several sites and years for each crop. The results are included in equation (8) for corn and equation (9) for cotton wherein the variables are defined.[2]

$$
\begin{aligned}
Y = {} & \underset{(16.607)}{11392.5064^{***}} + \underset{(16.819)}{1407.2765^{***}W} + \underset{(6.239)}{32.3869^{***}N} - \underset{(-16.842)}{472.3484^{***}W^{1.25}} \\
& - \underset{(-5.044)}{6.2424^{***}N^{1.25}} + \underset{(2.874)}{.1645^{***}WN} + \underset{(10.583)}{10610.2525^{***}pH} + \underset{(1.045)}{120.0265EC} \\
& + \underset{(12.104)}{746.0988^{***}AWC} - \underset{(-18.816)}{5908.4357^{***}PE2} - \underset{(-4.276)}{9.9884^{***}N \times pH} \\
& R^2 = .731 \quad F = 112.31 \quad n = 424
\end{aligned}
\qquad \ldots(8)
$$

[2]Value of "t" statistics are given in parentheses. ***Estimated coefficient is statistically significant at the 1 percent level. *Estimated coefficient is statistically significant at the 5 percent level. The seven sites

where Y = 161 lb/acre of corn (grain) at 15.5 percent moisture; W = water applied in acre inches plus total rainfall exceeding 0.25 inch at any occurrence during the growing season; N = lb/acre of nitrogen applied; pH = $(pH - 7)^2$, where the 7 represents the normal or standard value; EC = electrical conductivity measured in micromhos/cm at 25°C; AWC = available water-holding capacity of the soil in acre inches of soil moisture in the top 4 feet of soil; and PE2 = sum of daily pan-evaporation over a 10-day silking period defined as the "critical period" of growth affecting final yield.

$$
\begin{aligned}
Y = & \underset{(-6.368)}{-626.1732^{***}} + \underset{(8.265)}{96.8446^{***}W} + \underset{(2.625)}{1.6855^{***}N} - \underset{(-9.152)}{30.9322^{***}W^{1.25}} - \underset{(-3.036)}{.4780^{***}N^{1.25}} \\
& + \underset{(3.859)}{.0196^{***}WN} - \underset{(-2.794)}{70.4192^{***}pH} - \underset{(-1.705)}{8.9182^{*}EC} + \underset{(13.614)}{71.6196^{***}AWC} + \underset{(5.278)}{.1732^{***}WxPE1} \\
& R^2 = .802 \quad F = 95.79^{***} \quad n = 223 \qquad \ldots(9)
\end{aligned}
$$

where Y = lb/acre of cotton (lint) and PE1 = sum of daily pan evaporation data from planting up to first harvest reflecting climatic conditions and length of growing season.

We believe these modest results for a design that was relatively efficient for the individual sites but suboptimal for the "generalized" estimates, do allow optimism in the belief that crop response functions for fertilizer and similar management or decision variables can be estimated in relation to environmental variables, and these functions can allow communication of fertilizer and water management knowledge over a wider extent of space as it relates to and has application under a wide range of soil and climatic variables. Certainly this needs to be the hope and objectives of this large project with its major purpose of guiding a more rapid and efficient development of agriculture in LDC's. The design of the experiments will serve as the basis for this generation and communication of knowledge. Optimally, then, the design and spatial pattern (the selection of countries and the geographic distribution of experiments therein) of research should incorporate the relevant soil and climatic variables. Further, the specific design of the experiments will need to relate to the existing knowledge of researchers (for example, whether or not some knowledge already exists on treatments approaching maximum yield/ha, algebraic form of response, limitational inputs, extent and rate of diminishing productivity for management variables, the presence of increasing returns, and so on), the range of economic conditions for farmers destined to use the results, and the amount of funds allocated to each major phase of the project. In the latter respect, this project should be brought into active interface with those emphasizing water management in LDC's. The latter are moving toward incorporation of fertilizer treatments, since this input set has high interaction with water. The personnel of the current fertility project suggest some rather modest steps in inclusion of irrigation treatments because of interaction with fertilizer and other management and environmental variables. Each set of projects could benefit from integration with the other, and more complete interaction effects could be measured. The potential economies of scale are so great that the opportunity should not be foregone.

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for corn were 1968, Ft. Collins, Colorado; 1970, Davis, California; 1970, Mesa, Arizona; 1970, Yuma Mesa, Arizona; 1970, Yuma Valley, Arizona; 1970, High Plains, Texas; and 1971, Colby, Kansas. The six sites for cotton were 1967, Shafter, California; 1969, West Side, California; 1971, Safford, Arizona; 1971, Tempe, Arizona; 1971, Yuma Mesa, Arizona; and 1971, Yuma Valley, Arizona.

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Concepts of Program Design for Soils Research and Information Transferral in Developing Countries

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The purpose of this paper is to describe the approach used by the Soil Science Department at North Carolina State University in designing and conducting a research program aimed at increasing food production in developing countries. This approach is based on the Department's overseas experience gained during the past 19 years, initially through the N. C. State Agricultural Mission to Peru and later through the International Soil Fertility Evaluation and Improvement Program. More recently, the activities supported by a tropical soils research contract and a 211(d) grant have brought these concepts into sharper focus.

The authors felt that the most appropriate way of presenting this information for the purposes of this conference was to limit ourselves to three aspects of the program. The first section describes the general principles of structuring and operating the program. The specific research topics and their results are not presented. These can be obtained from our annual reports. The second and third sections describe our approach for extrapolating data in economic and agronomic terms.

WORKING CONCEPTS

The first strategy consideration is to define the long-term objectives of a land grant university department in international work. Two goals of this Department were emphasized in the University's long range plans set forth in 1971: (1) to contribute in a measurable way to alleviating the world food production problem through the application of practical soil fertility and management practices in the tropics, and (2) to strengthen the Department as one of the main centers of expertise in tropical soils.

Land grant universities are not permitted to use Hatch Act or state legislature funds for work outside their state boundaries. Recognition by the University administration that experience outside these boundaries makes better teachers, researchers, and extension workers permitted the Department to seek other sources of financial support for this purpose. Our long-term goals clearly match those of the U.S. Agency for International Development, and we have been fortunate to obtain support for training, research, and technical assistance from AID over the years.

Our research planning is based on the following concepts:

1. Field problems are solved best by on-site activity rather than by remote control. Consequently, our emphasis has been to place competent staff in actual field conditions where the problems can be viewed in their totality.

2. Field researchers need substantial backstopping from campus-based personnel. This primarily involves cooperative greenhouse and laboratory work plus interactions and discussions with experienced faculty. Campus-based faculty need some exposure to the field, and, likewise, field personnel need the contact with the campus. Thus, a two-way movement of scientists occurs between Raleigh and the field stations as often as needed. In this way, campus-based scientists gain first-hand knowledge and are able to support the field researchers better. Last year, 23 campus-based soil scientists and economists participated in 55 short-term visits to 14 countries, with a total time spent overseas equivalent to 1.9 man-years.

3. The broad research objectives have to be precisely defined. This is easier said than done. For example, our AID-supported research contract has one objective: "To develop methodology for an economically sound system of making fertilizer recommendations based on soil analysis and crop response data, primarily for Latin America, for developing countries in the tropical region, and to obtain basic soil fertility and chemistry data needed to support the above objective."

The process of reducing these generalities into specific objectives that could be accomplished with present resources consisted of several steps. An extensive review of the literature of soils work in the region was conducted by several staff members and later published. Several senior staff members travelled to Mexico, Central America, Colombia, Peru, and Brazil to discuss with Latin administrators and scientists how our program could contribute to the overall efforts and how it would fit with the present activities of several national and international institutions.

The literature review and the visits provided two conclusions: (1) Significant knowledge has been achieved by a variety of institutions in the highly populated coastal and inland valley areas of Mexico, the Andean Highlands, and Southern Brazil. The major limitation is not research knowledge but its utilization. (2) There was a need for more knowledge in the savannas and jungles of the South American interior and in the densely populated Central American highlands. The key issues were determined to be those of how to manage the highly acid infertile Oxisols of the savannas, how to modify the present shifting cultivation system in the jungle Ultisols, and how to intensify food production in Central America in soils developed from volcanic ash. Specific projects were then developed jointly with the counterpart institutions. In order to bring all the research together, region-wide studies in soil characterization, economic interpretation, and means for extrapolating data were also conducted.

4. U.S. scientists, in order to be truly effective, have to work in close cooperation with scientists of the host countries and within national institutions. Foreign enclaves surrounded by high fences and enclosing transplanted ivory towers have serious operational limitations. Likewise, operating out of the U.S. Embassy or AID Mission offices creates an unnecessary political atmosphere that clouds the scientist's view of the in-situ problems.

5. The specific research projects have to meet a dual purpose. Projects have to be high-priority issues for both the regional research contract and the

country's specific problems. Serious national support cannot be expected unless our presence helps solve the problems of the host country.

6. A large proportion of the project leader's time has to be devoted to intensive and frequent contacts with the cooperating national research institutions. Most of the problems in making agreements and following them up are not solved by letters but by frequent on-site visits supplemented by telephone calls. In order to have true cooperative work, research personnel must know each other well at the personal level, understand each other's institutional policies, procedures, and constraints, and adjust to the frequent reorganizations that take place. For example, in 1973, each institution we cooperated with in Costa Rica, Peru, and Brazil went through massive reorganization. Although they seldom affect the actual experimental work directly, these reorganizations often require rather subtle or even substantial changes in direction, reporting system, and other operational aspects. An understanding of all the bureaucracies involved is essential. There are some instances in which these administrative problems become insurmountable. In such cases, it is best to get out with a clean break.

7. Top-level U.S. scientists are seldom the most effective personnel to conduct overseas research. Competence in soil science or economics per se is not the only criterion, although an indispensable one, for success in international soil-related research. In addition, scientists located in the field should have competence in the local language, an appreciation for and adaptability to working in a different cultural and administrative system, and sufficient energy to conduct field work under adverse physical conditions. Our policy is to send young soil scientists (in their 20s and 30s) who are competent in the scientific aspects and are both willing and capable of mastering the language and cultural aspects. They are eager to work hard and to establish a professional reputation. They need to have a deep interest and a personal commitment to a career in international agriculture. We also find that their age more closely approximates that of their counterparts in the field and that this is a distinct advantage.

8. To the maximum extent possible, we use carefully selected graduate students instead of Ph.D. degree holders to conduct on-site research. There are several good reasons for this approach. The main one is that graduate students do not have sufficient status in the eyes of the national institutions to be requested to attend planning sessions, advise the Ministers, and get involved in a web of what is best termed "research politics." Consequently, they can devote their full time to research that is essential to the contract and also to fulfilling the requirements for the advanced degree. If properly backstopped by frequent visits of their faculty advisors and constant communications, they can produce a first-class dissertation. The long-term involvement of the faculty advisors provides continuity of the work. The overall project is constantly improved by the new ideas these students bring up in the course of their research. The fact that their research is carried out under actual tropical conditions, with all its advantages and limitations, gives them the kind and depth of training that no university campus can provide. Their education is complemented by taking the conventional coursework on campus, and, when appropriate, they conduct additional laboratory and greenhouse research back home.

9. In programs where there is considerable daily contact with local administrators or when the information is ready to go into a utilization phase, Ph.D. faculty level personnel are needed. It is unfair to expose graduate students to too much administrative pressure. When research is ready to be utilized, the prestige of title, position, and experience is needed in working with

the local institutions. Also, pending changes and long-range planning cannot be allowed to unduly interfere with the on-going research work.

10. We do not consider the training, research, and utilization components of such a program as precisely defined compartments. These aspects are in fact a continuum in which a shift is made from one to the other as the opportunity arises. The best way to train tropical soils scientists--regardless of nationality--is through research programs of this kind. We do not have to wait until the research results are all complete and published before beginning to utilize them. Nor should we expect that our job is finished when we present a formal research report to the local institutions and say, here it is, you give it to the farmers to apply. If the field research is of good quality and the on-site researcher of adequate motivation, nearby farmers and local government authorities will be attracted. Some will ask to put a demonstration plot at other locations. Before a formal extension program takes shape, significant advances can be made in that direction. Our job is not complete when a scientific paper is published or a Ph.D. degree awarded. Our real goals are attained when farmers adapt new practices that significantly increase food production and when we have produced a competent senior research scientist knowledgeable of not only the soil related problems but also the associated social, political, and economic aspects of tropical agriculture.

ECONOMIC CONSIDERATIONS OF DATA EXTRAPOLATION

A major focus of interest in our project is the general topic under discussion at this conference--predicting crop response to fertilizer, given some information about soil on which the crop is to be produced. With respect to this focus, our objective is to develop analytical techniques and soil classification schemes that will allow us to make recommendations to farmers, which will consistently lead to high economic returns to fertilizer or other management practices. The term "high economic returns" is, of course, a relative one. Some approaches will lead to consistently higher returns than will others, and we view it as our task to devise new analytical techniques and classification schemes and to test their economic value (in the above sense) against alternative approaches.

In predicting the effects of various factors on crop yields, it is useful to group them into three categories: (1) those factors that can be directly controlled (such as applied nutrients); (2) those that can be observed ahead of time but cannot be controlled (such as soil characteristics); and (3) those that can neither be controlled nor observed ahead of time (such as weather). Our statistical problem then becomes the following: having obtained some experimental data, we wish to make some inferences about crop response to fertilizer on areas remote from our experimental plots.

Presumably we, or the farmer, can control the level of fertilizer applied. But, clearly, the farmer cannot control the type of soil he has (though we may be able to observe the characteristics of the soil), and just as clearly the population of farmers who will receive our recommendations will have soils whose characteristics differ from our experimental plots. One issue that emerges is the homogeneity of the population of soils about which we wish to make inferences. We can classify soils rather narrowly--and thereby limit the extent to which the characteristics of the population of inference differ from the experimental plots. Or, we can classify soils very broadly and attempt to make recommendations that apply to a wider range of farm situations. We refer to this grouping problem as the aggregation issue.

Furthermore, we will always be making recommendations for situations in which uncontrolled, unpredictable factors, such as weather and plagues, will differ from the experimental conditions. If the experimental data being analyzed contain sufficient variability in these factors, their yield effect may be estimated.

The Role of Experimental Design

Given this overview of the problem before us, we can now address the question of the role of experimental design in a research program directed at this problem. In its most common usage, the term experimental design refers to the choice of treatments to be applied and the manner in which these treatments are to be assigned to the experimental units. In other words, it refers to the choice of directly controllable factors affecting yield. We have come to the position that experimental design in this sense is no longer a significant issue, even though it is important. We think that the three professions (statistics, agronomy, and economics) have arrived at a consensus that central composite and fractional factorial designs, assigned by some type of randomized blocks, are appropriate for both agronomic and economic interpretation, provided a sufficient range of levels of each nutrient is included. For economic interpretation, a minimum of four levels of each nutrient should be included.

With respect to "uncontrollable" factors such as soil type and soil characteristics, we have no option at all of assigning "treatments" to experimental units, and the best we can do with respect to the choice of "treatments" is to attempt to place experiments on as wide a variety of soil conditions as possible. Unfortunately, this is expensive. But in any case, sampling theory would be of more help in determining the optimal number and distribution of experimental sites than is experimental design theory. With respect to such uncontrollable factors as weather and diseases, neither design theory nor sampling theory will be of much help in the selection of the "treatments." In all these cases, however, we have adopted the principle in our project that uncontrollable factors, such as weather, should be monitored and recorded for later analysis. Soil characteristics should be recorded and later aggregated within quasi-homogeneous limits for interpretation of results.

The two most challenging issues involved in the problem before us are the aggregation issue and the selection of a response model that can most effectively incorporate soil (and meteorological) variables into our recommendation procedures. If the theory of experimental design can offer us no help in the solution of these problems, what can? We have adopted two criteria to guide us: statistical tests and an economic criterion of profit predictability. The following paragraphs will indicate how we have made use of these and the results we have obtained to date.

Response Model Selection

The issue of response model selection has been long and often vigorously debated. Among the well-known candidates for selection are the Mitscherlich, Spillman, quadratic, and square root models. Advances in statistical theory and computational technology have admitted more complicated nonlinear models to the set of contenders, but even without these, the number of models that have been proposed is staggering. Unfortunately, statistical theory does not provide us with any very satisfactory tests for discriminating among these models. The most generally adopted criterion is R^2, but statisticians caution us against its use. For well-defined sets of experiments, a "goodness-of-fit" test is

made possible by assuming a common experimental error estimate for all experiments, and attributing the remaining unexplained yield variation to the goodness-of-fit of the algebraic model. It has been our experience that such statistical criteria are inconclusive. R^2's usually do not differ from model to model, and there is really no way to test whether R^2 differences or differences in goodness-of-fit are significant.

Therefore, we have adopted an economic criterion that we call "profit predictability" to compare alternative models, which works as follows. Model A and model B can both be used to derive fertilizer recommendations, given a set of experimental data to be evaluated. Both models can be utilized to predict the profitability of each treatment in a new set of experiments, and, in fact, each model can be used to predict which of the treatments will be most profitable. Given a sufficient number of new experiments, say 10 or more, the profitability of the treatments selected by the two models can be compared, and we can statistically test the hypothesis that the recommendations from model A result in higher profits than from model B. We are just beginning to make use of this tool in analyzing a large amount of data previously collected in experiments conducted throughout Latin America. We have compared two radically different response models--a generalized quadratic model and a simple Leibig-type linear-response-and-plateau model. When applied to a set of 60 corn-response experiments in Brazil, we found that there was no significant difference in the profitability of the treatments recommended by the two models. Perhaps the response model does not really make much difference. We shall have to wait for further applications before we can generalize.

Economics of Soil Aggregation

The aggregation issue has seldom been considered in fertilizer response research. There has been no theoretical debate and little empirical analysis because the issue has not been generally recognized. With respect to the choice of soils aggregation level (or classification scheme), we have somewhat the same situation as the response model choice. Many persons have a priori reasons for selecting a particular classification scheme, but there exist no fertility management criteria for choosing among alternative schemes. For fertilizer response purposes, we have adopted the profit-predictability criterion. If classification system A allows us to make recommendations that result in significantly higher profits than does system B, then A is preferable. To date, we have applied the criterion only to the abovementioned set of corn-response experiments, and have considered only two rather simple classification schemes. The first scheme was to classify soils by soil test phosphorus level: soils above 10 ppm were classified as high, the rest as low. The second scheme was to classify soils by geographic area: soils in the western part of the state of Minas Gerais were classified versus soils in the eastern part. These two classification schemes are, of course, about as crude as one can get. It may be of mild interest that both of them were failures. Complete aggregation of the data, that is, pooling of all the experiments regardless of soil test and regardless of geographical location, resulted in recommendations with significantly higher profits than those based on grouping soils by either of the classification schemes. Farmers will be better off, we predict, if we just forget about the two aforementioned schemes. We are anxiously awaiting the results of the Buol classification scheme and the more traditional classification schemes to test these Brazilian data.

A more promising classification scheme is the fertility-capability soil classification system, described by Buol, et al. (1977). We have used this scheme to aggregate 73 potato fertilization experiments conducted in the Sierra

of Peru during a 3-year period. The experimental sites were aggregated in five groups, which was further reduced to three groups as shown in Figure 1. When fertilizer recommendations were made separately for each group, the average predicted net returns were $150/ha higher than when recommendations were made from a single model for all sites. When fertilizer recommendations were based both on soil test results and on fertility-capability classes, the returns to fertilizer applications further increased to $195/ha (Buol, et al., 1977). These preliminary results show that such an aggregation system is complementary with soil tests.

To sum up this section, it is currently our position that the problem of experimental design is not a particularly difficult one to resolve. The more challenging issues are the choice of response models and the level and system of soil classification to be used in the analysis of the data once they are generated. A great deal of debate has left the former issue unresolved, and we hope that our use of the profit-predictability criterion with a very large set of tropical America data will help to resolve it. The latter issue has been seldom addressed in the literature and could benefit from considerably more statistical and agronomic theorizing. Meanwhile, we hope that the profit-predictability criterion will assist here, also, in providing some empirical evidence on the economic value of alternative soil classification schemes.

TRANSFER OF SOIL MANAGEMENT PRACTICES VIA SOIL CLASSIFICATION

When considering the problem of extrapolating experimental results, one encounters numerous considerations. These could generally be grouped under social, political, economic, and physical categories. Although they are of overriding importance many times, the interactions of the social, political, and economic considerations are usually rather transient. The agronomist, while being aware of these considerations, should seek to quantify the physical problems in a form that can incorporate them with the social, political, and economic considerations.

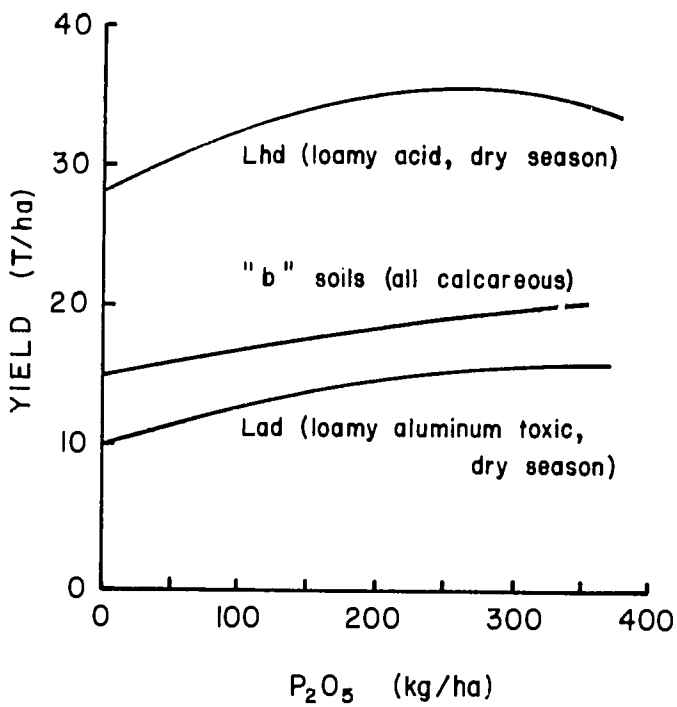

Figure 1. Aggregation of yields from potato fertilization experiments into soil groups.

Although an extensive list of the physical considerations in management could be made, including crop type and variety as well as soil and climatic variables, it has been our premise that soil conditions afford the firmest basis for extrapolation rather than other physical considerations.

It probably serves no purpose here to review the factors and processes by which soils acquire their properties. The rather recent concept, however, that temperature and moisture status of soils are considered to be soil properties bears mention. Previous concepts viewed these parameters as climatic. Although these parameters are closely related to climate, their inclusion, as measured in the soil, has tended to greatly increase the usefulness of soil taxonomy for soil management problems.

Two basic concepts of quantifying soil properties for use in management decisions are generally accepted. Both concepts have their proponents among soil scientists and both have attained some degree of success. We are speaking, of course, of soil testing and soil survey. The remainder of this portion of the paper will address itself to attempting the integration of these two approaches.

The fundamental thesis of soil testing is that an empirical extraction of nutrients can be made from a soil sample that reflects the ability of that soil to satisfy the plant requirements. After the correct relationships between the analysis of the extractions and plant growth are determined, a high degree of success is attained in using this approach as a basis of managing the fertility aspects of crop production. This approach seems to suffer, however, when one attempts to apply the relationships developed in one kind of soil to areas where the soil properties are highly contrasting. Alternate methods of extraction partially overcome this problem as do alternate interpretations of the soil test value.

Soil classification and survey have demonstrated their usefulness by broadly delimiting soils of contrasting pH, organic matter, mineralogy, and so on. The total taxonomic system limits its usefulness to crop production management by attempting to incorporate all soil properties that can be measured and are of significance to any soil use. In short, the soil taxonomic systems are massive and cumbersome for specific uses. Also, in most soil taxonomic systems there is an emphasis on grouping soils into taxonomic classes on the basis of properties not easily altered by management practices. For example, the U.S. Soil Taxonomy (Soil Survey Staff, 1973) states:

> Changes produced by a single, or repeated plowing that mixes the surface soil to a depth of 18 to 25 cm (7 to 10 in), for example, should have the least possible effect on the placement of a soil in the taxonomy. Truncation by erosion should not produce changes in the placement of a soil in the taxonomy until horizons important to the use or identification of the soil have been lost. Consequently, insofar as possible, the diagnostic horizons and features should be below these depths (p. 10).

The same publication goes on to state:

> It is commonly necessary to subdivide taxa and regroup those subdivisions into new classes of another classification for the greatest number and most precise interpretations possible. This taxonomy is designed to facilitate interpretations, but the interpretations themselves require at least one additional step of reasoning (Cline, 1963) (p. 12).

The Soil Taxonomy (Soil Survey Staff, 1973) goes on to point out some of the possible phases and then states:

> A different classification is needed for each use for which we make interpretations (p. 12).

In view of the foregoing considerations, we believe there is a need to group soils more precisely for use in making interpretations of soil test results and other soil-fertility-management problems.

The parameters by which the soils are grouped should reflect the soil conditions in the plow layer more precisely than is the case in the soil taxonomic system. Also, by selecting conditions in the soil surface layer as criteria, there can be an additive effect created by interfacing with soil testing procedures that rely on samples from that layer.

The justification for concentrating emphasis in the Ap horizon, that is, surface horizon, comes in large part from the rationale that that horizon is where most of the crop plants concentrate their roots and also where additions of fertilizer are made. A quantitative example of the importance of Ap horizon conditions is illustrated in Table 1 where Sopher et al. (1974) found that the R^2 values for Ap horizon properties equaled .48 in a regression analysis of corn yield in Ultisols. Note that this is higher than R^2 values for properties of lower horizons. The system for grouping soils that we have designed in an attempt to create groups with similar problems associated with and response to managed fertilizer practices is outlined in Table 2 (Buol, 1972; Buol et al., 1977). This system is still somewhat in the conceptual state; however, some testing has been done and is continuing. From the test grouping previously reported (Buol et al., 1977), the system seems to produce a reasonable number of groups about which the fertility aspects of crop production can be extrapolated. Trial groupings indicate that all the soils in the world separate into about 150 groups. This is in contrast to approximately 4,000 taxonomic soil families and 13,000 soil series presently used in the United States and Puerto Rico (Soil Survey Staff, 1973). A test of the economic value of some of these groups has been presented earlier in this paper.

Although the proposed criteria tend largely to combine taxonomic families, there are several conditions in which they also separate taxonomic families. Most of these separations result from the variability in surface horizon texture, which is usually not considered in taxonomic groupings. The separations are perhaps most noticeable in those soils with argillic horizons (primarily the Ultisols and Alfisols). A brief examination of what such separations may mean with respect to fertilizer and lime management is found in work by Shelton (1960) on an eroded and uneroded Typic Hapludult clayey kaolinitic thermic soil. The eroded site would classify as Ch and the uneroded site as LCh in the fertility-capability system. Equal applications at two levels of 700 and 1400 lb/A P_2O_5 caused the LCh site to attain and retain for 2 years a soil test value double the level retained in the Ch site. Total yields differed little after the P level in the soil was raised to a satisfactory level. The point is, however, that it took approximately twice as much P_2O_5 fertilizer to attain the yield in the Ch soil as it did in the LCh soil.

A review of the literature will verify that complete soil information is usually not obtained or reported in fertility studies. Detailed classification is necessary to apply the results by taxonomic families. Maps and pictures at various scales as well as detailed maps are necessary to show soil variations on a field-to-field basis. Identifying individual test sites from general soil maps often leads to erroneous soil identification. The fertility-capability

Table 1. R^2 values for selected regressions of corn yield on soil characteristics

Factors in model	No. of variables	R^2 values
Soils--All horizons	57	.655
Soils--Ap horizon	19	.480
Soils--2nd horizon		.291
Soils--3rd horizon		.365

Source: Sopher, et al. (1974).

Table 2. Fertility-capability classification[1]

TYPE: Texture is average of plowed layer or 20 cm (8") depth, whichever is shallower.

S = Sandy topsoil: loamy sands and sands (USDA)
L = Loamy topsoil: < 35% clay but not loamy sand or sand.
C = Clayey topsoil: > 35% clay.
O = Organic soil: < 30% O.M. to a depth of 50 cm or more.

SUBSTRATA TYPE: Used if textural change or hard root-restricting layer is encountered within 50 cm (20").

S = Sandy subsoil: texture as in Type S.
L = Loamy subsoil: texture as in Type L.
C = Clayey subsoil: texture as in Type C.
R = Rock or other hard root-restricting layer.

CONDITION MODIFIERS: In plowed layer or 20 cm (8"), whichever is shallower, unless otherwise specified (*).

*g = (Gley): Mottles $\leq$ 2 chroma within 60 cm of surface and below all A horizons or saturated with H_2O for > 60 days in most years.

*d = (Dry): Ustic or xeric environment; dry > 60 consecutive days per year within 20-60 cm depth.

e - (Low CEC): < 4 meq/100 soil by Σ bases + unbuffered Al.
< 7 meq/100 soil by Σ cations at pH 7.
< 10 meq/100 soil by Σ cations + Al + H at pH 8.2.

*a = (Al toxic): < 60% Al saturation of CEC by (Σ bases and unbuffered Al) within 50 cm.
> 67% Al saturation of CEC by (Σ cations at pH 7) within 50 cm.
> 86% Al saturation of CEC by (Σ cations at pH 8.2) within 50 cm.
<u>or</u> Ph < 5.0 in 1:1 H_2O except in organic soils.

[1]Proposed Feb. 1974.

--Continued

Table 2 (continued)

*h = (Acid):	10-60% Al saturation of CEC by (Σ bases and unbuffered Al) within 50 cm. <u>or</u> pH in 1:1 H_2O between 5.0 and 6.0.
i = (Fe-P fixation):	% free FE_2O_3/% clay > 0.2 <u>or</u> hues redder than 5 YR and granular structure.
x = (X-ray amorphous):	pH > 10 in 1 N NaF <u>or</u> positive to field NaF test <u>or</u> other indirect evidences of allophane dominance in clay fraction.
v = (Vertisol):	Very sticky plastic clay > 35% clay and > 50% of 2:1 expanding clays; COLE > 0.09. Severe topsoil shrinking and swelling.
*k = (K deficient):	< 10% weatherable minerals in silt and sand fraction within 50 cm <u>or</u> exch. K < 0.20 meq/100 g <u>or</u> K < 2% of Σ of bases, if Σ of bases < 10 meq/100 g.
*b = (Basic reaction):	Free $CaCO_3$ within 50 cm (fizzing with HCℓ) or pH > 7.3.
*s = (Salinity):	> 4 mmhos/cm of saturated extract at 25°C within 1 meter.
*n = (Natric):	>15% Na saturation of CEC within 50 cm.
*c = (Cat clay):	pH in 1:1 H_2O is < 3.5 after drying; Jarosite mottles with hues 2.5Y or yellower and chromas 6 or more within 60 cm.

system requires less extensive observation and, perhaps, because of its simplicity, will encourage fertility researchers to attempt grouping of their results. This is especially needed in order to make maximum extrapolation of results in areas where detailed soil survey and classification are not available.

SUMMARY

We feel that soil characteristics provide the best common denominator for use in the extrapolation of production research findings. A project to determine the limits in extrapolation of fertility-related research by categories of soils is needed. Taxonomic families of the U.S. taxonomy can certainly provide a basis for such groupings. They probably need to be augmented with respect to soil fertility-crop production interaction studies by providing greater attention to the characteristics of the plow layer that are important to soil test interpretations. Also, they are probably too detailed to provide a workable basis for the transfer of fertility-related management practices.

The technical fertility-capability classification system does not replace the taxonomic family grouping but does supplement it, hopefully to create fewer working groups and with greater precision of grouping with respect to soil fertility interactions. Therefore, we would like to see the results obtained in future soil fertility studies organized according to the proposed criteria of the fertility-capability system in addition to any other taxonomic criteria that may be tested.

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Some Cornell University Experiences

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The purpose of this paper is to describe briefly the approach and methodology used in meeting the objectives of the Cornell University soil fertility research project (AID/csd 2490), to highlight some of the problems involved in implementation, and to summarize some of the results and conclusions.

The main objective of the research is to determine the soil and water management and associated practices required to help realize the high food crop production potential on the well-drained acid soils of the humid and subhumid tropics. According to the best available estimates, there are about 600 million hectares of these soils in the tropics (mostly Oxisols and Ultisols) which are potentially arable yet are mostly uncultivated. Those that are cultivated generally have low crop production. These soils commonly have favorable topography and good physical properties. The main limiting factors are their low nutrient status and their soil moisture deficiency at critical growth periods even during the rainy season. Previous research by many investigators on these kinds of soils indicates that they can be very productive with appropriate management practices.

The project was designed so that the results would have application to extensive areas in Latin America, Africa, and Asia. The field research was initiated in Puerto Rico in the spring of 1970 in cooperation with the Agricultural Experiment Station of the University of Puerto Rico and the U.S. Department of Agriculture. Puerto Rico was selected as the initial base for the research because it is easily accessible and has a wide range of acid soils broadly representative of extensive areas of the humid tropics. Important considerations were the interest of the officials of the Puerto Rico Agricultural Experiment Station in collaborating in the research, access to excellent field, laboratory, and library facilities, and availability for consultation of well-qualified Puerto Rican scientists in plant pathology, entomology, statistics, and other complementary disciplines.

Subsequently, field experiments supplemented by greenhouse and laboratory studies were initiated in the fall of 1972 at the Agricultural Experiment Station near Brasilia, Brazil, in cooperation with the Brazilian Ministry of Agriculture and in collaboration with North Carolina State University. This site is located in the Central Plateau of Brazil, and the soils in the experiments are representative of extensive areas of the Central Plateau (Campo Cerrado). Although these acid soils are similar in many characteristics to those in the studies in Puerto Rico, there are some important differences, and the long dry season provides a different climatic environment. However, as in the case of the experimental sites in Puerto Rico, the low nutrient status of the soils and moisture deficiency during critical growth periods

were considered to be the most important factors limiting crop production. Consequently, the same general experimental procedures were used in the two locations.

RESEARCH PRIORITIES

From the work reported in the literature and from conferences with soil scientists working on soil fertility problems in the tropics, it appeared that the initial priorities for the soil fertility research on the acid soils should be on nitrogen and phosphorus supply, lime requirement, and management of soil water. Consequently, the major effort in the research was directed to these problems. For the purpose of this paper, only the experiments with nitrogen and phosphorus will be discussed.

NITROGEN AND PHOSPHORUS EXPERIMENTS IN PUERTO RICO

Selection of Experimental Sites

It was felt that a careful selection of experimental sites was crucial to the studies. Therefore, considerable time and effort were spent over a period of several months in locating suitable sites which would be reasonably representative of extensive areas of infertile Oxisols and Ultisols of the humid tropics and at the same time would meet other important criteria, such as minimum soil microvariability and convenient access. In Puerto Rico, assistance in site selection was given by several soil scientists of the Agricultural Experiment Station and the U.S. Department of Agriculture who were knowledgeable about the soils of Puerto Rico. A Tropical Soils Workshop held in Puerto Rico in August 1969 sponsored by the USDA Soil Conservation Service provided an opportunity to discuss possible site selections with soil scientists familiar with the soils of Puerto Rico.

After a number of possible sites were identified, tentative selections were made based on the morphological, physical, and chemical characteristics of the soils. Final selection of the experimental plots was based on chemical analyses of a large number of soil samples collected from each of the sites. Despite the considerable time and effort expended, it was difficult to find areas of about one hectare sufficiently uniform to accommodate the separate nitrogen, phosphorus, and lime experiments in one place and at the same time satisfy the criteria for the kinds of soils to be studied.

Because of the high rainfall and highly acid character of the soils at many potential sites, it was assumed that crops would be highly responsive to applied nitrogen and lime. In the case of phosphorus, however, it was difficult to find soils with a sufficiently low soil phosphorus level to expect much response to applied phosphorus, primarily because most of the arable soil in Puerto Rico had been under cultivation for many years and phosphate was commonly applied to the crops. Consequently, only two sites were found to be suitable for the phosphorus experiments and the nitrogen and lime trials.

One unavoidable variable in site selection was the past history of the use of the soil. Two of the sites had been in improved fertilized pasture for several years. Another had been under continuous cultivation for at least 30 years with crops such as taniers, yams, plantains, and tobacco. One site had been a pineapple research field but had been fallow for 2 years.

It was apparent that in the selection of sites for the field experiments all the necessary conditions could not be fully satisfied and compromises were

inevitable. It was a matter of judgment as to what extent the various factors involved could be accommodated without unduly jeopardizing the main objectives of the experiments.

The soils at the sites finally selected for most of the field experiments have been classified in the new U.S. Soil Taxonomy as follows:

Series	Family
Humatas	Typic Tropohumult; clayey, mixed, isohyperthermic
Torres	Orthoxic Tropudult; clayey, mixed, isohyperthermic
Catalina	Tropeptic Haplorthox; clayey, kaolinitic, isohyperthermic
Piña	Typic Haplorthox; psammentic, oxidic, isohyperthermic
Coto	Tropeptic Eutrorthox; clayey, kaolinitic, isohyperthermic

In short, the soils at the experimental sites consist of two clayey Oxisols, two clayey Ultisols, and one sandy Oxisol. Two of the sites were on Experiment Station land and two were on private farms. One had been a research site but not at an Experiment Station.

Three of the soils--Humatas, Torres, and Catalina--are in the interior uplands of Puerto Rico at elevations of 220 to 580 meters above sea level. The other two soils--Piña and Coto--are on the northern coastal plain at elevations of 50 to 130 meters above sea level. The average summer maximum and minimum temperatures are approximately 29° and 21°C at the interior sites and 32° and 22°C at the coastal sites. The average winter maximum and minimum temperatures are approximately 3°C lower than in the summer at all sites. Average yearly precipitation for all sites is between 1650 and 2000 mm with only two months (February and March) receiving, on the average, less than 100 mm per month. The evaporation from a class A pan in the summer is approximately 6 mm per day in the coastal plain sites and 5 mm per day in the interior sites. This drops to 4 and 3 mm per day during the winter for the coastal and interior sites, respectively. Solar radiation ranges from an average of 300 langleys per day in the winter to 500 langleys per day in the summer.

Nitrogen Experiments

Objectives. The objectives of the nitrogen experiments were to (1) devise procedures for applying nitrogen to non-leguminous row crops to insure a reasonable recovery of fertilizer nitrogen and attain the yield potential of the crop; (2) measure (a) the efficiency of utilization by crops of added nitrogen through soil and plant analyses and (b) the relative importance of leaching and denitrification in nitrogen loss and conditions under which the two mechanisms are of most significance; and (3) estimate the amount of nitrogen released to the crop during the growing season through mineralization of soil organic matter and crop residues.

Crop and variety. As maize is one of the most important food crops in the tropics, it was decided to use it for the test crop in the initial experiments. Maize is not commonly grown in Puerto Rico, so there was no information available on a potentially high-yielding, locally adapted variety. Consequently, extensive inquiry was made of people knowledgeable about maize varieties for the humid tropics. It appeared that Pioneer X-306, a hybrid maize developed in Jamaica, offered the best possibility, and this variety was used for most of the experiments. The yield potential of this variety,

according to the distributor, was 6300 kg/ha. Recently, another variety, G/95W, was used in a zinc experiment at one of the experimental sites and the grain yield averaged 40 percent higher. This variety is now being used in the nitrogen experiments for comparison with Pioneer X-306.

Experimental design. In planning the nitrogen experiments, as well as the other experiments, it was decided that a relatively simple design would accomplish the objectives. One objective was to compare preplant and postplant applications of nitrogen fertilizer at different levels with respect to yield responses and to the efficiency of utilization of the applied nitrogen by the crop. Another objective was to determine the effectiveness of sulfur-coated urea in comparison with ordinary urea when applied preplant. Thus, there were eight treatments: no nitrogen applied; 34, 67, and 134 kg/ha of nitrogen as urea applied either as a preplant broadcast or as a sidedress when the plants were four to five weeks old; and 67 kg/ha of N applied preplant as sulfur-coated urea. There were five replications of the eight treatments in a randomized block design. The same treatments were maintained throughout the five consecutive cropping seasons of summer and winter crops.

Blanket applications of lime, phosphorus, potassium, and zinc were applied at levels that were considered adequate according to the best available information. Soil insecticides were incorporated with the broadcast fertilizer. Fall army worms were controlled by weekly applications of DDT for the first crop and Sevin for subsequent crops. Beginning in the fall of 1971, Parathion was applied over the row 1 week after planting to control lesser corn stalk borers. Dithane was applied at weekly intervals to inhibit northern leaf blight after symptoms appeared in the winter maize crop. Weeds were controlled in the first two crops by hand weeding, in the third and fourth crops by Simazine, and in the 1972 crops by Dacthal with supplemental hand weeding.

Results and conclusions.[1] The yield potential of 6300 kg/ha of the Pioneer X-306 maize variety was obtained in only 4 of the 14 maize crops grown over five cropping seasons. The grain yield of five crops was reduced by drought, and three maize crops planted in the fall of 1971 were adversely affected by a relatively little known disease, tar spot (*Phyllachora maydis*). The drought occurred during the silking stage in three of the crops and in the early growth stage of the other two crops. At one site there was less than 60 mm/month of rainfall in June and July 1971 and May and June 1972. Normal rainfall for these months is 120 to 150 mm/month; the evaporation for these months is about 150 mm/month.

In the sandy Oxisol site, a traffic pan restricted root growth to the surface 20 cm of soil and severely aggravated the rainfall shortage at this site. The traffic pan was destroyed by deep chiseling in the early spring of 1971 but had reformed by the middle of the following crop.

Surprisingly, at two of the sites maize crops gave little or no response to applied nitrogen and yet grain yields approached the potential for the variety. Although the organic matter content of the soils was not unusually

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[1]This section is extracted from an article on the nitrogen experiments in Puerto Rico by R. H. Fox, H. Talleyrand, and D. R. Bouldin, which will be published in the Agronomy Journal entitled, "Nitrogen Fertilization of Corn and Sorghum in Oxisols and Ultisols in Puerto Rico."

high, apparently there was enough mineralization of the organic matter to provide an adequate supply of nitrogen. This directed efforts to develop a simple chemical test for determining the nitrogen-supplying capacity of the soils in order to estimate the amount of applied fertilizer nitrogen necessary to attain a desired grain yield. Such a test was developed and is now being evaluated by correlation with crop responses to applied nitrogen in field experiments in different tropical areas.

Other results of the experiments were:

1. Confirmation of the general observation that preplant applications of nitrogen are much less efficient in increasing crop yields than are postplant applications. There seems to be no reason to consider preplant applications of nitrogen in the humid tropics except in the case of soils very deficient in nitrogen where a relatively small amount of fertilizer nitrogen is needed at planting;
2. When there were no limiting factors of climate or disease and where the nitrogen-supplying capacity of the soil was low, the utilization efficiency of postplant-applied nitrogen was comparable to that observed in temperate areas;
3. Preplant-applied sulfur-coated urea was no more effective than preplant-applied urea in increasing yields or nitrogen recovery;
4. There was very little residual effect of applied fertilizer nitrogen from one cropping season to the next;
5. There does not appear to be any basic difference between the fate of applied fertilizer nitrogen to Oxisols or Ultisols except that, with the high amount of exchangeable aluminum in the Ultisol subsoils, any nitrogen leached below the plow layer is not available to aluminum-sensitive crops such as sorghum.

Phosphorus Experiments

Objectives. Field experiments with maize and sorghum were designed to (1) define the response curves for applied phosphorus fertilizers on representative Ultisols; (2) measure the relative efficiency of banded versus broadcast fertilizer phosphorus; and (3) estimate the residual effects of the applied phosphorus.

Materials and methods. Of the five experimental sites, only two appeared likely to be phosphorus-deficient on the basis of soil chemical tests and greenhouse assay with beans. Based on soil properties, it had been anticipated that most Oxisols and Ultisols under cultivation would require applied phosphorus for good crop production. Apparently, enough phosphorus has been applied through the years on most of the cultivable soils in Puerto Rico so that the residual phosphorus in the soil was sufficient for good crop production.

Phosphorus experiments were first conducted on the Humatas soil site (Typic Tropohumult), which tested quite low in phosphorus. The first crop was sorghum followed by maize. Four levels of phosphorus were applied broadcast (90, 180, 360, 1120 kg/ha), and four levels were banded (22, 45, 90, 180 kg/ha). There was one control treatment and one that included a low level of both broadcast and banded. The 10 treatments were replicated five times in a randomized block design.

Results. Sorghum was the initial crop tested followed by maize; neither crop showed a response to any of the phosphorus treatments. Subsequently,

plantains were planted in the experimental plots and the treatments were modified to include both nitrogen and phosphorus levels. It had been reported that plantains were especially responsive to applied phosphorus on this soil. The first crop of plantains, however, with a very high average yield of about 27 tons/ha, showed very little response to either applied phosphorus or nitrogen. The very high yields, several times the average in Puerto Rico, resulted from close planting and the use of a new nematocide, Dasanit.

In fall 1971, another phosphorus experiment with maize was initiated on the site of the Torres soil (Orthoxic Tropudult). The treatments were the same as those in the previous experiment.

During the early months of growth, there was a large response to applied phosphorus and the banded applications were considerably more effective than the broadcast applications. Near-maximum growth was obtained with 90 kg/ha of banded phosphorus, whereas 360 kg/ha of broadcast phosphorus was necessary for near-maximum growth. Unfortunately, a little-known disease, Phyllachora maydis (tar spot), attacked the maize and caused premature leaf death, grain yield reduction, and large variability. Nevertheless, there was a substantial yield response to applied phosphorus with the maximum grain yield obtained with 180 kg/ha of applied phosphorus.

A second crop was planted on this site in May 1972, and differences in the early growth were observed with the different phosphorus treatments. By the time the grain matured, however, there were no significant grain yield differences between treatments and the yields were all close to the yield potential of the variety. Chemical analysis showed that the soil in the zero phosphorus plots contained only 0.0027 ppm of phosphorus in solution, which is far below the level considered adequate for near-maximum yields, and yet the yields were as high as those in the treated plots.

One obvious explanation is that there was enough mineralization of organic phosphorus to supply the needs of the crop once the root system had become extensive enough to utilize the immobile, mineralized phosphorus. This hypothesis is supported by the fact that at least 250 kg/ha of nitrogen was mineralized in adjacent experimental plots.

It should be noted that the first crop of maize grown in the winter months showed a significant response to applied phosphorus, whereas, in contrast, the second crop grown in the summer did not respond. This suggests that the warmer summer temperatures resulted in greater mineralization of organic matter than the cooler winter months with a consequent release of larger amounts of phosphorus available to the crop.

PHOSPHORUS EXPERIMENTS AT BRASILIA, BRAZIL[2]

Objectives. The objectives of the phosphorus experiments at Brasilia were essentially the same as in Puerto Rico: (1) to define the response curves for applied phosphorus; (2) to measure the relative efficiency of banded versus broadcast fertilizer phosphorus; and (3) to estimate the residual effects of applied phosphorus.

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[2]These studies are collaborative with North Carolina State University personnel.

Experimental site. In contrast to the difficulty in selecting suitable experimental sites in Puerto Rico, the Agricultural Experiment Station near Brasilia is located on acid soils representative of extensive areas of the Central Plateau of Brazil with many physical and chemical properties common to extensive areas of acid soils in other regions of the tropics. Most of the 2000-hectare Experiment Station land is in native grass and uncultivated. It was relatively easy to select uniform sites with a minimum of soil micro-variability of sufficient size to accommodate a number of experiments. Even in this area, however, it was found that there was enough variability so that crop response to certain comparable treatments in experiments 100 meters apart showed enough differences to affect the interpretation of the results.

The soils in the two experimental sites have been classified in the Brasilian system as follows:

Series	Family
Dark Red Latosol	dystrophic, clayey, cerradão phase
Red Yellow Latosol	dystrophic, loamy, cerradão phase

In the new U.S. Soil Taxonomy these soils would probably be classified as follows:

Typic Haplustox, clayey, kaolinitic, isohyperthermic
Typic Haplustox, loamy, kaolinitic, isohyperthermic

The phosphorus experiment discussed below is on the Dark Red Latosol site. The area had not been cultivated and earlier experiments on a similar soil at the Experiment Station had shown that the soil was severely phosphorus deficient.

Crop and variety. Maize was selected as the test crop for the initial experiments even though there was some question of its suitability for intensive cultivation in the area. The very low nutrient content of the soil, high acidity, periods of moisture stress even during the rainy season, and problems of disease and insect control would entail higher production costs than other areas with higher natural fertility. It was felt, however, that with proper management of these various factors maize would be a good indicator of potential food crop production on this kind of soil, which is so extensive not only in the Central Plateau of Brazil but also in other regions of the tropics.

The best available hybrid maize variety produced and widely grown in Brazil is Cargill 111. This variety was used in the experiments and has an apparent yield potential on the order of 8000 to 9000 kg/ha.

Experimental design. The design was a simple one with 10 treatments and five replications in randomized blocks. The treatments were four levels of P_2O_5 (40, 80, 160, 320 kg/ha) banded and four levels (160, 320, 640, 1280 kg/ha) broadcast and incorporated to about 20-cm depth only at the initiation of the experiment; one treatment of 80 kg/ha of P_2O_5 banded and 80 kg/ha broadcast; and one treatment of 80 kg/ha banded and 320 kg/ha broadcast. The source of phosphorus was simple superphosphate.

The plot size was 4.8 x 12 meters with six rows 80 cm apart. The plants were 20 cm apart in the row, giving about 62,500 plants/ha. The position of the rows within the plots was changed with each crop.

Two consecutive crops were grown. Even though one crop was grown during the rainy season, it was necessary to irrigate once during a severe drought just prior to the tasseling stage. The second crop was irrigated adequately based on information from tensiometers randomly installed in various plots. Irrigation was done about every 4 days on the average.

Blanket applications of nitrogen, potassium, lime, magnesium, zinc, boron, and molybdenum were applied in accordance with the best information available as to methods of application, sources of materials, and amounts.

Results and conclusions. The grain yields of the best treatments for both the rainy season crop and the dry season crop approached the yield potential of the variety. This confirmed the high production potential of corn on these soils. In the first crop, the highest yield of almost 8000 kg/ha of grain at 15.5 percent moisture content was obtained with 1280 kg/ha of P_2O_5 broadcast. In the second crop, the highest yield of about 9500 kg/ha was obtained with 1920 kg/ha of P_2O_5 broadcast. It was obvious that extremely high applications of phosphorus were necessary to obtain maximum yields with the methods used. Data from subsequent crops will be necessary to determine the magnitude of the residual effects of the high levels of phosphorus applied. Also, an important problem will be to devise methods and procedures to effect a more efficient use of the applied phosphorus.

Contrary to expectations and the results in the Puerto Rico experiments, the broadcast applications of comparable amounts of phosphorus were much more effective than the banded applications in the first crop. However, in the second crop (irrigated) a comparison between treatments in which similar amounts of phosphorus were applied in a single broadcast application or in two banded applications shows that the banded treatments had higher grain yields. Data from subsequent crops are needed to determine the relative efficiency of these methods of application over a period of several cropping seasons in order to have a sounder basis for recommendations to farmers.

CONCLUSIONS

The results of the experiments reported here, as well as others of the Cornell soil fertility research project, have demonstrated conclusively the high production potential of the well-drained acid soils in the tropics as represented by the experimental sites. This potential can only be achieved provided a complete set of appropriate management practices are used. While the individual components of the set may vary in detail, certain inputs are essential. These will vary in amounts and methods of application depending not only on the kind of the soil but also on the specific environmental conditions, kind and variety of the crop, previous cropping history, and other important variables.

As demonstrated by the work in Puerto Rico, the uncontrolled variables, such as drought and disease, had a pronounced influence on the crop responses to the controlled management variables. These uncontrolled variables could not be quantitatively evaluated with the experimental designs which were used. The following section presents a general approach to experimental designs which would be useful in relating crop response to both the controlled and uncontrolled variables. This should provide a more reliable basis for making soil management recommendations to farmers.

SECTION 3:

Experimental Designs Suitable for Soil Fertility Experiments

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Key Elements in Field Experimentation for Generating Crop Production Technology

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INTRODUCTION

Crop yield is a function of climate, soil, genotype, management, and time. Each of the first four of these is a multiple factor. Climate, for example, includes intensity and distribution components of rainfall, temperature, winds, and hail. Several variables are usually needed to adequately represent the effect of either of these factors mathematically. Turrent (19), for example, in a study of the effects of environmental factors on maize yield, used six variables to express the influence of rainfall.

The soil factor is equally complex, combining a multitude of properties that determine physical support and nutrition of the plants. These properties include the available levels of the essential mineral nutrients and the physical properties of a sequence of soil horizons that determine the retention of soil moisture, root development, and nutrient uptake. In addition, chemical substances, such as exchangeable sodium and soluble salts, at times reach concentrations sufficiently high to adversely affect plant growth.

Most of the factors that influence plant growth cannot be assigned mathematical values that accurately represent their quantitative importance. Moreover, little is known about the importance of the interactions among variables, except for a few well-studied exceptions, such as nitrogen x phosphorus, nitrogen x soil moisture, nitrogen x plant density, and genotype x planting date.

Because of the extreme complexity of the relationship between plant growth and the factors of production, most attempts to arrive at general equations, useful for predicting yield and input requirements from production factors, have been disappointing. Even when great care is taken to measure the uncontrollable factors of production, general yield equations have usually had R^2 values[1] of 0.80 or less. As investigators, we tend to conclude that we have done quite well when we attain an R^2 of 0.80. However, when we compare the

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[1] R^2 is the coefficient of determination and is an estimate of the proportion of the total variability in yield accounted for by the factors included as independent variables in the regression analysis.

predicted yield values with the experimental ones, we are generally appalled at how poorly we do in scientific situations.

But, in expressing our success in terms of R^2, we are almost certainly greatly overestimating the adequacy of our prediction equation. To correctly evaluate our progress, it is necessary to use the general yield equation to predict outcomes for new producing conditions and compare the results with what actually occurs (7). Although this step has seldom, if ever, been taken, it seems reasonable that success in predicting for new conditions will be much less than success in predicting for the conditions that were used in estimating the parameters for the general equation.

The usual situation, then, is that the researcher with the responsibility for generating recommendations on crop production practices has a multitude of pieces of information, many of which are potentially useful to him in achieving his goal. In addition, he can readily collect complementary information specific for his area, such as data on climate, soil types, available nutrient levels, planting dates, and so on. With all this information, however, the best he can do is to make an educated guess about the quantitative levels of the technological inputs that farmers should use.

It is our experience that this educated guess by an experienced researcher will usually be quite accurate, perhaps acceptably so, for irrigated agriculture and very favorable rainfed conditions. For regions where moisture deficiencies represent a major limitation to crop production, however, the educated guess will be much less reliable.

The reason for this difference is the paramount importance of soil moisture, and the physical properties of soils that affect the retention and availability of moisture to plants, in determining the yield potential of a producing system.[2] These effects are relatively minor under irrigated and favorable rainfed conditions; they become increasingly important as the rainfall becomes more limiting.

It appears, then, that the only reliable way for the researcher to generate improved technology for limiting rainfall conditions is to test his hypotheses about production practices under the producing conditions of his clients; that is, for an estimated 75 percent of the cultivated land in developing countries, we must resort to field experimentation and use the data from carefully conducted field trials to complement existing information and arrive at new recommendations that are more useful to the farmers, in terms of higher yields and net incomes, than their traditional technology.

Unfortunately, due in part to poor methodology, much of the field experimentation that has been conducted over the years to produce recommendations for rainfed agriculture has yielded results that have been next to worthless. This has been particularly true for field experimentation in rainfed areas of subsistence farmers using traditional methods.

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[2]A producing system is defined as a part of a production universe in which the uncontrollable production factors for a crop are reasonably constant. Uncontrollable factors include soil morphology, geomorphology, climate, previous crop, and, at times, planting date.

This situation has changed in recent years. Researchers have begun to realize that generating improved production technology for the small, subsistence farmer in rainfed areas requires a methodology different in many ways from that which has proved quite satisfactory for commercial agriculture. This is an encouraging development and hopefully will lead to significant improvements in methodological procedures in the coming years.

We will comment briefly on a few aspects of field experimentation that have an important bearing on the value of data generated for use in designing technologies for the small, subsistence farmer in rainfed areas. Our remarks are based primarily on experiences in Mexico and other Latin America countries over a period of years. We are very much aware that the science of crop production is presently at a very elementary level in evolving a research methodology for determining production technologies for rainfed agriculture.

COLLECTION OF INFORMATION ON THE AREA OF STUDY

It is our experience that few researchers give adequate importance to the collection and evaluation of information about an area before proceeding to define hypotheses and plan experiments. Time after time, the results of planning with inadequate information are evident. The researcher justifies the failure of an experiment to produce useful data in terms such as "the elevation of the experimental site was a little too high for the maize-bean association," "we planted a little too late and the maize didn't produce very well," or "we had never worked with horse beans before, and the plants were badly damaged by aphids before we realized it."

There are several sources of information available to a researcher when he initiates work in an unfamiliar area: (a) published and unpublished reports, (b) field staff of service agencies that work in the area, (c) the farmers, and (d) the area itself. All too often, the tendency is to underestimate the value of information from these sources and assume that by traveling through the area for a couple of days, talking with three or four farmers, and looking at data on rainfall and temperature averages, one has gained access to most of the useful data.

The first step in bringing together existing information on an area is to get copies of relevant data and writings. These will usually include published and unpublished reports of soil surveys, agronomic research, historical weather records, agricultural and population censuses, the operations of service institutions, and so on. The staff of the service agencies should be interviewed to get their impression about the factors limiting crop production and the conditions that limit their capacity to provide services to the farmers.

The best time to collect information on the area itself is when the crops are observable. Information on the area and from the farmers can be collected at the same time. The researcher, after carefully studying existing information, should travel leisurely over the network of roads connecting the villages in the area. If possible, he should be accompanied by a local farmer or an agriculturist knowledgeable about the region. Something like 0.05 percent of the local farmers should be interviewed. If the area consists of 150,000 ha and 50,000 farm families, for example, the study might take a week to 10 days and include interviews with some 25 farmers. These interviews should be distributed throughout the area and should sample, as well as possible, the major ecological conditions and the different categories of farmers in terms of income and production technology.

The interviews should be kept informal, yet follow a questionnaire, and the information should be recorded during or immediately after the interview. The questionnaire should be structured to obtain information on such factors as cropping systems, technology used with each system, crop yields, area dedicated to each system, use of credit, marketing of produce, price stability, and factors limiting crop production.

The soils should be studied in road cuts and auger samples and information recorded on slope, texture, color, depth of horizons, presence of layers that restrict water percolation and root penetration, and so on. If soil maps are available, they should be used as a guide in making field observations. Soil samples should be collected from the principal kinds of soils in the region and then analyzed for organic matter, pH, and available phosphorus and potassium.

OBJECTIVES AND ORGANIZATION OF RESEARCH

Conventional research on crop production is usually conducted on a pure population of a given crop. Breeding research is carried out to develop those genotypes that perform best in a pure stand. Research on production practices is designed to generate packages of practices for the crop grown alone.

This method of focusing crop production research is too restrictive for subsistence agriculture, much of which consists of mixed plantings/associations, crops planted in relay, or other combinations. The variety that is best for a pure stand may not be the best for an association. A case in point is the maize hybrid developed for the Rionegro region of Antioquia, Colombia, using the conventional approach. The farmers have not accepted the hybrid because they grow their maize in association with pole beans; under these conditions, the hybrid lodges much worse than the native variety. Also, the optimal package of practices may not be the same for a pure stand as for a mixed stand. The recommendation for maize when grown alone on deep soils of Popocatepetl, Puebla, Mexico is, for example, 130 kg/ha of nitrogen, 40 kg/ha of P_2O_5, and 50,000 plants per hectare; when grown in association with pole beans, the recommendation for the same producing system is 150 kg/ha of nitrogen, 40 kg/ha of P_2O_5, and 40,000 plants per hectare (2). For subsistence agriculture, the rational approach to crop production research is to study the cropping systems used by the farmers, rather than pure stands of individual crops.

Another characteristic of conventional research on crop production is the compartmentalization of the research according to disciplines. Plant breeders are responsible for developing improved varieties, soil fertility specialists determine fertilization practices, plant physiologists develop weed control measures, and entomologists study insect problems, for example. Our experience indicates that this is not an efficient approach for subsistence agriculture. There are two obvious advantages in studying all production practices for a crop or cropping system as a unit: (a) the interactions among many production practices are significant, and the best way to assure that these are properly taken into account in the recommendations is to study them together; and (b) the total cost of research on production practices, in terms of both human and financial resources, is much less when, in a given area, it is done by one research team than by two or more.

We feel that the following points should be observed in carrying out agronomic research in rainfed areas of subsistence agriculture: (a) assign the responsibility for research on crop production practices, including varietal performance, to a single research team; (b) work initially to develop improved

practices for the traditional cropping systems; (c) study the whole system, not just a single crop; (d) study alternatives to the traditional systems and recommend new ones as soon as it is clearly shown that they are superior in terms of net income and risk factor; and (e) in interpreting production functions that vary greatly among years due to natural causes, keep in mind that the objective of small, subsistence farmers may be to maximize net income in the least favorable years, not maximize average net income.

Let us assume, then, that the researcher has the responsibility for developing recommendations on crop production practices for the major cropping systems in an area. His first step in planning the research is to carefully study all information collected on the area. Based on the available data, he lists, in order of importance, the cropping systems used by farmers and the major producing systems in the area. Taking into account the resources available for the research, he then decides which cropping systems will be studied and in what producing systems.

Once the cropping x producing systems have been selected for study, the researcher proceeds to examine (a) which aspects of existing technology are probably deficient, (b) which of them can probably be improved economically, (c) which improvements are likely to produce the largest increases in yield and net income, and (d) whether or not local research is needed to decide how to make such improvements. It is expected this analysis of research needs will lead to a definition of the hypotheses that should be tested with each cropping x producing system.

In synthesis, we are suggesting that field research of the highest quality is necessary for developing the crop production technologies needed to improve subsistence agriculture in rainfed areas. Some people feel that this implies resources, of both highly trained research agronomists and finances, far greater than most developing countries can afford. The experiences in the Puebla Project (2) in Mexico, which report a benefit/cost ratio of 18 for agronomic research on maize practices, indicate that this criticism is not necessarily valid.

What is needed, we feel, is the availability of highly trained leadership and an organizational structure that will permit efficient use of that leadership. In Mexico, for example, one highly trained and experienced research agronomist can personally direct and supervise the work of five research teams (consisting of professionals with limited specialized training), each conducting agronomic research for an area of 50,000 to 200,000 ha of cultivated land. In 3 to 5 years, this highly trained agronomist can train other agronomists to the level where they can direct and supervise field research teams. With adequate organization, one highly trained research agronomist, and four associates with an intermediate level of preparation, can direct and supervise the work of 20 research teams servicing a total of some 2,000,000 ha of rainfed agriculture.

SELECTING A TREATMENT DESIGN

After hypotheses for testing have been defined, a decision is made as to which interactions among factors are probably important and, consequently, need to be studied together in the same experiment. In general, the interaction between two variables should be measured experimentally whenever (a) it is expected that the interaction may be large enough to affect the optimal levels of the variables, and (b) it is not possible a priori to estimate the approximate optimal level of either variable.

It is not possible to state with certainty which interactions are going to be important and which are not. This will vary somewhat with the environmental conditions and the species itself. In maize research, some of the variables that need to be combined in the same experiment, in such a way as to measure the interactions, are (a) the essential nutrients, particularly nitrogen, phosphorus, and potassium; (b) the essential nutrients and plant density; (c) the essential nutrients, plant density, and planting date[3]; and (d) rate of nitrogen and time of applying nitrogen. Variables that may be studied at a constant level (approximating the optimal) of the other productivity factors are (a) land preparation practices, (b) deep plowing, (c) weed control, and (d) insect control.

Clearly, the decision to treat a given factor as a variable or a constant in an experiment will be based on imperfect information and will be greatly influenced by the preparation and previous experience of the researcher. For this reason, it is most important that a highly trained, experienced agronomist participate, at least as a consultant, in this phase of research planning.

At this stage in the planning process the researcher has decided which cropping x producing systems will be studied, those aspects of the production technology that will be investigated, which factors are to be studied together, and whether one, two, or more levels of the factors are to be used. Also, by this time, the experimental levels of the factors will have been selected. The next step is to decide on an appropriate treatment design.

At this point we would like to digress a moment and relate the evolution of our thinking with respect to treatment design. During the 1950s and early 1960s, we used a small factorial, if only a few levels of two variables were involved, or a design in which one factor was varied at a time, if several levels of two or three factors were studied. In a rate study of nitrogen (N), phosphorus (P), and potassium (K), for example, a decision would be made a priori as to the probable optimal levels of the three elements, and several levels of each element would be studied at the estimated optimal levels of the other two. In the following example the estimated optimal levels of the three elements are N_3, P_3, and K_3:

$N_1P_3K_3$	$N_3P_1K_3$	$N_3P_3K_1$
$N_2P_3K_3$	$N_3P_2K_3$	$N_3P_3K_2$
$N_3P_3K_3$	$N_3P_4K_3$	$N_3P_3K_4$
$N_4P_3K_3$	$N_3P_5K_3$	$N_3P_3K_5$
$N_5P_3K_3$		

The data from an experiment of this kind were used to construct three graphs showing yield as a function of five levels of each element. A triangle was constructed to represent existing fertilizer costs and produce prices, and the optimal level of each nutrient was estimated graphically.

During this period, the work of Box and associates (5, 6), Heady and colleagues (11, 12, 13), and many others promoted the concept that yield was a continuous function of rates of the plant nutrients, and that data on plant response could be usefully expressed in the form of a mathematical function.

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[3]Under those circumstances where planting date is a controllable factor. For much of rainfed agriculture, planting date is not controlled by the farmer. When this is true, production practices are determined for specific planting dates.

The idea of expressing response data in the form of an equation and estimating economic optima by means of a marginal analysis of the response function was particularly appealing. Consequently, beginning in 1965, we began to use a variety of partial factorials in field studies of fertilizer use.

To our surprise, we encountered several limitations to the use of the quadratic polynomial for representing fertilizer response data. The difficulties we encountered had been experienced by others, but in our enthusiasm to use more sophisticated methods, we had tended to minimize their importance. Two such limitations will be illustrated and discussed: (a) economic analyses using prediction equations frequently give erroneous values for the economic optima; and (b) economic optima, estimated from prediction equations derived using different mathematical models, often vary greatly among themselves and from values estimated through a graphic interpretation of the data.

Prediction Equations that Give Erroneous Values for Economic Optima

The results obtained in experiments carried out in the state of Puebla, Mexico in 1967 (1), to determine fertilizer recommendations for rainfed maize, will be used to illustrate how prediction equations may estimate economic optima that are clearly unreliable.

The soils involved in this study are level to gently sloping and lie at elevations above sea level that vary from 2150 to 2400 meters. They have formed from volcanic ejecta varying in particle size from very fine ash to coarse pumice. Most of the soils show no evidence of profile development; a few have highly developed B horizons. Textures vary from sandy to sandy clay loam; pH values range from 6.0 to 8.1.

A triple square treatment design or 7^2 partial factorial[4], with 17 combinations of levels of nitrogen from 0 to 360 kg/ha and levels of P_2O_5 (phosphorus) from 0 to 150 kg/ha, was used in the experiments. The grain yields obtained in 14 experiments are given in Table 1. Quadratic polynomial prediction equations, calculated from the yield data, are presented in Table 2.

In seven of the experiments, the prediction equations contain a negative linear coefficient and a positive quadratic coefficient for phosphorus. This means that the slope of the response surface in the phosphorus plane is decreasing at P = 0 and has a concave curvature. As it was assumed that the slope of a fertilizer response curve or surface must be decreasing or convex at the point of the economic optimum, it was concluded that the economic optima calculated from these seven prediction equations were probably not reliable.

As can be seen by examining the data in Table 1 (or the points in Figure 6, No. 7), it is possible to study graphically the response to three levels of each element at three levels of the other. In addition, the yields at two levels of each element can be compared at four levels of the other. Therefore, a graphic analysis was made of the yield data from the 14 experiments. The graphic representation of the data permitted two things: (a) a study of the cause of the concave curvature; and (b) a graphic estimation of the economic optimal levels of nitrogen and P_2O_5.

The data from experiment 20 are shown graphically in Figure 1 as an example of the type of data that gave rise to a prediction equation with $-P$ and $+P^2$.

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[4]This design is shown later in Figure 6, No. 7 for a different factor space.

Table 1. Maize yields obtained with different fertilizer treatments in experiments carried out in the state of Puebla, Mexico 1967[1]
(yields are expressed in kilograms per hectare of grain containing 12% moisture)

Fertilizer treatment		Experiment													
N	P_2O_5	02	04	05	06	07	08	09	11	12	16	20	21	23	25
0 -	0	10	150	30	510	250	510	1010	30	200	1490	830	2290	970	320
360 -	0	4560	3930	4080	3590	2860	3100	3120	1590	2600	6510	3620	4090	4090	4450
60 -	25	2040	2450	2280	1750	2300	2610	2780	1980	2260	4660	2500	3920	3000	2750
180 -	25	4650	4690	4780	3890	3760	5100	3010	3280	3580	5780	4080	4550	4450	4580
300 -	25	5360	4470	4510	3680	3740	5390	3440	3510	2830	6300	3750	4060	4260	3550
120 -	50	4610	4540	4670	3480	4320	4160	3260	4050	3450	5870	3680	4330	3240	4030
240 -	50	5850	5030	4870	3360	4000	5740	3450	3910	3210	6030	3960	4200	3970	4830
60 -	75	1950	2220	2400	2020	2240	3050	2870	2170	2190	4990	2310	3330	2870	2750
180 -	75	5270	5280	4630	3970	4680	6210	3610	5080	3360	6100	4370	4480	3910	4470
300 -	75	6070	5030	5070	3850	4580	6320	3540	4470	3680	6030	3990	4600	3610	3810
120 -	100	4590	4770	4650	3660	4290	5080	3590	4650	3660	5780	3920	4090	3890	4250
240 -	100	6050	4700	4930	4170	4860	6360	3890	5370	3260	6040	4500	4350	3900	4530
60 -	125	1590	2320	2440	1919	2450	3210	3070	2170	2000	4720	2300	3380	2360	2460
180 -	125	5810	5750	5290	4620	5520	6130	4100	5110	3550	6350	4640	4480	3390	3520
300 -	125	5620	5710	4830	4120	5300	7020	3320	5210	3780	6230	4430	4050	3830	4610
0 -	150	60	180	160	440	150	360	1240	70	230	2400	380	2670	1200	570
360 -	150	6470	4960	5150	3760	5480	7500	3890	5660	3790	6080	4290	3670	3990	5050
LSD at 5% level		860	820	720	450	650	600	740	800	490	940	540	700	800	780
Coefficient of variation		12.72	12.50	11.09	8.63	10.90	7.75	11.48	13.91	10.05	10.41	9.03	10.72	14.29	13.17

[1]Source: Anonymous, 1969.

Table 2. Regression equations for experiments carried out in the state of Puebla, Mexico, 1967[1,2]

(These equations were calculated from yield data expressed in kilograms per hectare of maize grain and fertilizer levels expressed as kilograms of nitrogen (N) and P_2O_5(P) per hectare.)

Experiment no.	Yield without fertilizer	Linear effect		Quadratic effect		N x P interaction
		N	P	N	P	
02	56	+42.81a	- 2.416e	-0.0828a	+0.0053e	+0.0354b
04	241	+44.78a	-10.048d	-0.0985a	+0.0675d	+0.0235b
05	253	+40.59a	- 3.256e	-0.0855a	+0.0267e	+0.0153c
06	441	+34.58a	-13.276b	-0.0746a	+0.0959b	+0.0063d
07	400	+34.65a	- 4.195e	-0.0802a	+0.0287e	+0.0525a
08	496	+35.69a	+10.488c	-0.0775a	-0.0720c	+0.0759a
09	1276	+16.21a	+10.521b	-0.0332c	-0.0483d	+0.0054d
11	34	+30.82a	+12.932c	-0.0749a	-0.0810c	+0.0732a
12	641	+22.87a	+ 4.842d	-0.0508a	-0.0409d	+0.0255a
16	2146	+29.02a	+15.834c	-0.0510b	-0.0673d	-0.0209c
20	945	+32.25a	-12.369a	-0.0721c	+0.0676c	+0.0238b
21	2546	+17.73a	+ 0.966e	-0.0384a	-0.0031e	-0.0079e
23	1470	+22.88a	- 3.856e	-0.0441a	+0.0180e	-0.0047e
25	953	+27.87a	+ 0.011e	-0.0550a	-0.0085e	+0.0135c

[1]Source: Anonymous, 1969.

[2]The letters a, b, c, d, and e indicate the level of significance of the regression coefficients: a = < .01; b = .01 - .05; c = .051 - .20; d = .201 - .50; e = > .50.

It is seen that phosphorus applied alone or with 60 kg/ha of nitrogen caused a slight reduction in yield. With larger amounts of nitrogen, the application of phosphorus produced a small increase in yield. This general tendency in response to phosphorus was noted in the seven experiments in this category.

The data from experiment 08 are presented graphically in Figure 2 as an example of the type of data that gave rise to a prediction equation with +P and $-P^2$. There was a slight reduction in yield from applying phosphorus alone but large increases from adding phosphorus in combination with all other levels of nitrogen. The characteristics of the response curves for experiments 09, 11, and 16 were similar to those for experiment 08.

The tendencies of the phosphorus response curves for experiments 12, 21, and 25, which also have +P and $-P^2$ coefficients, were intermediate between those for experiments 08 and 20. The phosphorus response curves for experiment 12, for example, were horizontal with 0N, decreasing with 60N, concave with 180N, and increasing with 300N. As is seen in Table 2, these three experiments had very small positive linear phosphorus coefficients that were not significant at the 20 percent level. In the mathematical estimation of economic optima for these experiments, the values for phosphorus came out negative.

Thus, in 10 of the 14 experiments, there were doubts about the reliability of the economic optima estimated from the prediction equations. It was decided, therefore, to estimate the economic optimal levels for all experiments

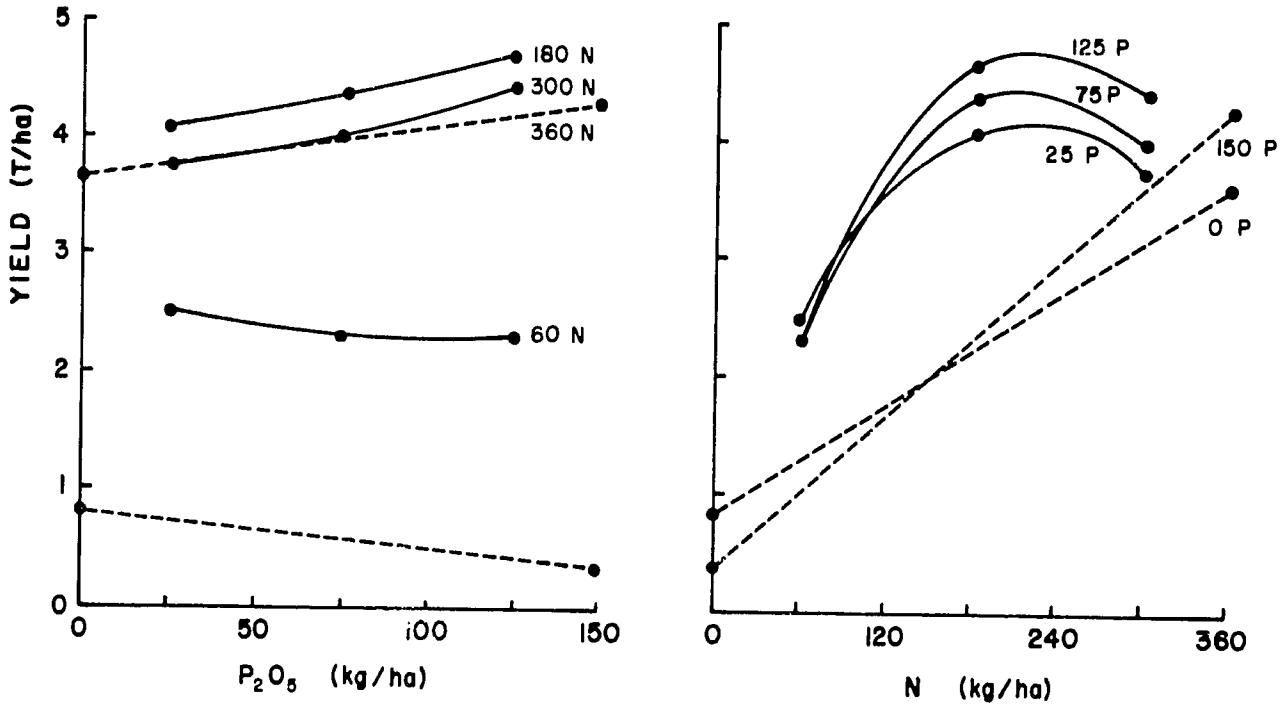

Figure 1. The response of maize to applications of phosphorus and nitrogen at five levels of the other element in experiment 20 carried out in Puebla, Mexico in 1967.

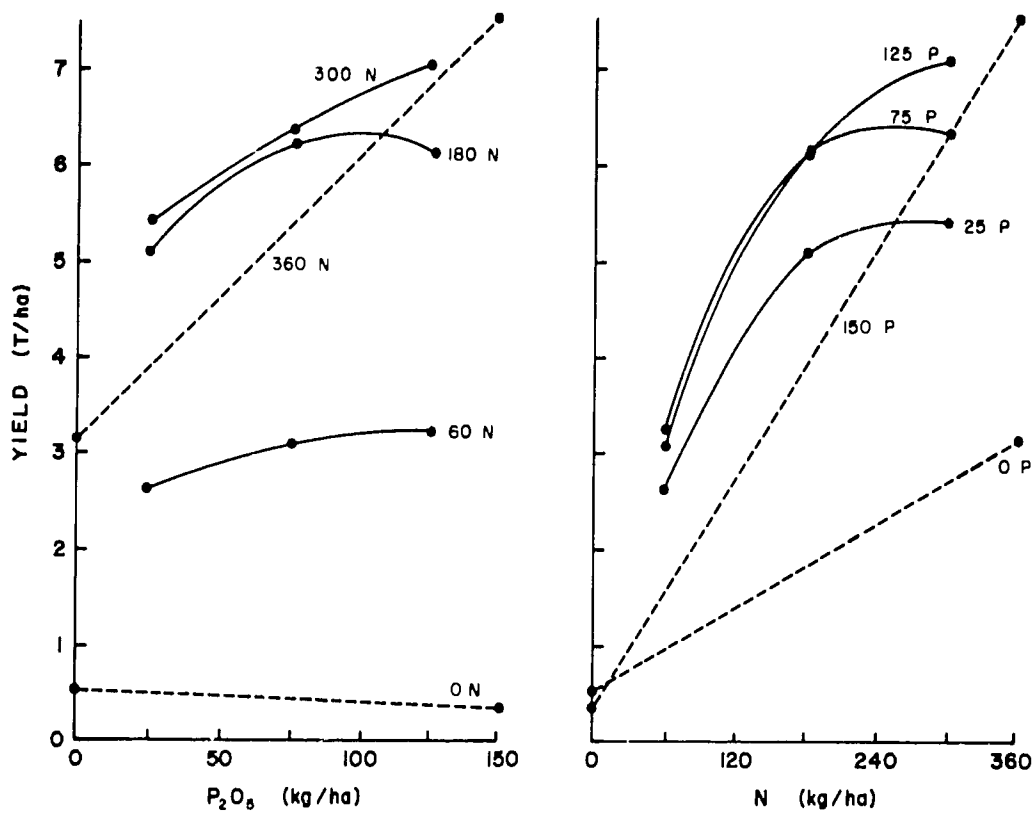

Figure 2. The response of maize to applications of phosphorus and nitrogen at five levels of the other element in experiment 08 carried out in Puebla, Mexico in 1967.

using the graphs, similar to those in Figure 1 and 2, that had been prepared. The economic optima for nitrogen and phosphorus, estimated both mathematically and graphically, are given in Table 3 for the 14 experiments.

It is seen that the optimal levels of phosphorus were greatly overestimated by the mathematical procedure in six out of seven experiments with -P and $+P^2$ coefficients. The optimal levels for nitrogen and phosphorus, estimated by the mathematical and graphic procedures, were similar for the seven experiments with +P and $-P^2$ coefficients. The largest difference occurred in the case of experiment 12; the prediction equation for this experiment has a highly significant NP interaction coefficient, yet the optimal level of phosphorus, estimated mathematically, was zero (in fact, negative).

The negative and very small positive values for the P coefficient in these prediction equations was the result of very low levels of available nitrogen in the soils and a negative response to phosphorus under such conditions. A very low level of nitrogen is characteristic of many soils of the temperate regions of Mexico and other countries that have been under cultivation for a century or more. Also, in highly weathered soils of the tropics and subtropics, a similar situation is common with respect to available phosphorus.

We believe this type of problem in estimating optimal levels of inputs from prediction equations can be expected to occur frequently. In recent years, we have tried to avoid or minimize complications of this type by (a) complementing the mathematical estimation of economic optima with a graphic evaluation, and (b) reducing the size of the factor space and adjusting it to the area of interest. By eliminating very low rates of nitrogen from the treatment design, for example, it has usually been possible to avoid a negative response by the other factor or factors under study.

Table 3. The economic optimal levels of nitrogen and phosphorus, estimated mathematically and graphically, for the 14 maize experiments carried out in Puebla, Mexico, 1967

Experiment no.	Optimal levels of nitrogen and P_2O_5 estimated (kg/ha)	
	Mathematically	Graphically
	N P_2O_5	N P_2O_5
	Experiments with -P and $+P^2$ coefficients	
02	244 - 247	210 - 40
04	184 - 108	150 - 25
05	188 - 173	150 - 0
06	162 - 110	150 - 0
07	170 - 72	160 - 75
20	168 - 128	150 - [illegible]
23	134 - 368	150 - 0
Average	179 - 172	160 - 24
	Experiments with +P and $-P^2$ coefficients	
08	221 - 128	210 - 115
09	79 - 22	80 - 20
11	185 - 109	160 - 75
12	116 - 0	150 - 25
16	171 - 25	170 - 0
21	87 - 0	90 - 0
25	153 - 0	150 - 0
Average	145 - 40	144 - 34

Variation Among Economic Optima Estimated from Response Data

A second concern about relying too heavily on prediction equations for estimating economic optima resulted from the growing evidence that the magnitude of these optima was greatly influenced by the particular model used in calculating the prediction equation. Heady, et al. (14), for example, reported that optimal levels of phosphorus, predicted by square root, quadratic, 1.5-power, and Cobb-Douglas production functions, varied by more than 100 percent. Moreover, there was no theoretical basis for deciding a priori which mathematical model would best represent a particular production situation.

Data presented by Rodriguez (18) can be used to illustrate the magnitude of the error that can be made in estimating economic optima by selecting an inadequate model for the prediction equation. He reported the effects of nitrogen and phosphorus fertilization on sorghum yields in three experiments carried out in 1964 in the Bajio region of west central Mexico. The soils were heavy clay Vertisols, with pH values around 7.0, located at about 1730 meters above sea level. The experiments were carried out under rainfed conditions. Experiment 01 was unaffected by drought, experiment 02 suffered a moderate effect of drought just before heading, and experiment 03 suffered a slight effect of drought just before heading.

A 5^2 complete factorial design was used. The rates of nitrogen were 0, 60, 120, 180, and 240 kg/ha, and the rates of P_2O_5 were 0, 25, 50, 75, and 100 kg/ha. The yield data for the three experiments are presented in Table 4. These data were used to estimate prediction equations using the quadratic, 1.5 power, and the square root models. The regression coefficients corresponding to the three models for each of the experiments are presented in Table 5.

The three prediction equations for each experiment were used to calculate optimal levels of nitrogen and phosphorus, using fertilizer costs and sorghum prices existing at the time. These optima are presented in Table 6, along with an estimation of the optimal levels by graphic procedure.

The graphic estimation of economic optima was made in the following manner. Rodriguez plotted, on one sheet of graph paper, the yield data needed for drawing the five nitrogen response curves for a given experiment and, on a second sheet, the data needed for drawing the five phosphorus response curves. He did this five times for each experiment. One set of graphs was given to each of five professionals with experience in fertilizer-use research. Each investigator was asked to draw the five nitrogen response curves and the five phosphorus response curves for each experiment. The curves were returned to Rodriguez who determined graphically the economic optima from each of the 15 sets (five investigators x three experiments).

Separate analyses of variance were made of the estimated optimal levels of nitrogen and phosphorus. The optima estimated from the curves drawn by one of the investigators were found to differ significantly from the values estimated from the curves prepared by the other four. The former optima were discarded, and the values shown in Table 6 are averages of the optima estimated from the curves prepared by the other four investigators.

Rodriguez considered that the economic optima determined graphically represented the best approximation to the true optima. Perhaps his most valid reason for arriving at this conclusion was that the optima, estimated from curves drawn by four experienced investigators, did not differ from one another significantly.

Table 4. Sorghum yields in tons per hectare in experiments carried out in 1964 in El Bajio, Mexico[1]

Fertilizer treatment (kg/ha) N	P_2O_5	Experiment no. 01	02	03
0 -	0	2.75	1.11	2.81
60 -	0	4.45	1.58	3.69
120 -	0	4.95	1.73	4.14
180 -	0	5.52	1.42	4.14
240 -	0	5.07	1.37	4.39
0 -	25	2.61	1.27	3.13
60 -	25	4.47	2.53	4.36
120 -	25	5.01	2.70	4.65
180 -	25	5.52	3.08	4.97
240 -	25	5.82	3.09	5.10
0 -	50	2.68	1.28	2.83
60 -	50	4.69	2.67	4.52
120 -	50	5.65	3.00	5.31
180 -	50	6.16	3.60	5.25
240 -	50	6.50	3.66	5.78
0 -	75	2.78	1.28	2.90
60 -	75	4.41	2.85	4.76
120 -	75	5.69	3.30	5.26
180 -	75	6.56	3.55	5.99
240 -	75	6.93	4.04	5.57
0 -	100	2.60	1.31	3.16
60 -	100	4.64	2.97	4.68
120 -	100	5.62	3.45	5.46
180 -	100	6.64	3.78	5.92
240 -	100	6.79	4.38	6.18
LSD at 5% level		0.91	0.54	1.14
Coefficient of variation		11.18	14.65	17.56

[1]Source: Rodriguez and Horacio, 1974.

If we accept the optima determined graphically as the most reliable values, it is seen in Table 6 that the quadratic and 1.5-power functions usually overestimated the true optima. The optima for nitrogen and phosphorus, predicted by the quadratic equation, exceeded the values determined graphically by as much as 50 percent and 38 percent, respectively. There are differences of similar magnitude between the values predicted by the 1.5-power function and those estimated with the graphic procedure. Optima predicted by the square root function were meaningless for experiment 01, due probably to the negative value of the b_4 coefficient (Table 5).

Table 5. The mathematical models used in estimating prediction equations from the sorghum yield data, and the corresponding regression coefficients for the three experiments[1]

Experiment no.	Coefficients b_0	b_1	b_2	b_3	b_4	b_5	Coefficients of determination (R^2)[2]
			Quadratic model: $Y = b_0 + b_1N + b_2P + b_3N^2 + b_4P^2 + b_5NP$				
01	2751	+27.25	+ 5.205	-0.0663	-0.0663	+0.0783	0.984
02	892	+12.99	+26.232	-0.0428	-0.2256	+0.0976	0.986
03	2690	+19.96	+15.584	-0.0564	-0.1084	+0.0602	0.976
			1.5 power model: $Y = b_0 + b_1N + b_2P + b_3N^{1.5} + b_4P^{1.5} + b_5NP$				
01	2717	+39.40	+ 8.723	-1.8614	-1.0482	0.0783	0.943
02	822	+21.05	+43.805	-1.1707	-3.9757	0.0976	0.956
03	2637	+30.01	+24.148	-1.5072	-1.9646	0.0622	0.990
			Square root model: $Y = b_0 + b_1N + b_2P + b_3N^{.5} + b_4P^{.5} + b_5N^{.5}p^{.5}$				
01	2925	-2.1024	+4.3916	+194.67	-78.11	+12.21	0.961
02	1119	-3.5488	-8.8171	+ 78.84	+94.18	+17.38	0.969
03	2817	-4.2229	-0.0342	+159.92	+23.28	+10.66	0.979

[1]Source: Rodriguez and Horacio, 1974.

[2]The regression equations were calculated using the 25 treatment means. The coefficient of determination is the quotient of the sum of squares due to regression divided by the total sum of squares for the 25 means.

Table 6. Economic optimal levels (expressed in kilograms per hectare) of nitrogen and P_2O_5 from three sorghum experiments, estimated from three prediction equations and by a graphic procedure[1]

Experiment no.	Equation: Quadratic N	Quadratic P_2O_5	1.5 power N	1.5 power P_2O_5	Square root N	Square root P_2O_5	Graphic procedure N	Graphic procedure P_2O_5
01	193	-100	200	-121	635	- 24	183	- 77
02	119	- 68	99	- 61	62	- 53	97	- 71
03	134	- 76	120	- 69	84	- 71	89	- 55

[1]Source: Rodriguez and Horacio, 1974.

Treatment Designs that Facilitate Graphic Analysis

The questionable accuracy of economic optima, estimated from prediction equations, led us to devote more time to two activities: (a) the development of treatment designs useful in generating data that are adequate for a graphic as well as a mathematical estimation of optimal levels of inputs, and (b) a study of the relative efficiency of different treatment designs in generating data for use in a mathematical estimation of economic optima.

The search for treatment designs that were appropriate for both a mathematical and graphic estimation of optimal levels of inputs also included the criteria that the designs should comprise a total number of treatments not greatly in excess of the number of effects to be determined, and that they should be flexible, both in number of factors and in number of levels of each factor. By early 1971, a family of treatment designs had been selected that appeared to satisfy these requirements reasonably well.

These designs have a 2^n factorial as a central core and additional treatments extending out from the corners. An example of a treatment design based on a 2^3 factorial, and with a total of 14 treatments, is shown in Figure 3. The four rates of each factor are selected in the following manner:

1. The lowest rate is the minimum level expected to provide useful information for farmers. This rate may or may not be zero.
2. The fourth rate is that expected to produce a yield just short of or equal to the maximum.
3. The second and third rates are equally spaced between the first and fourth rates.

The eight treatments of the 2^3 factorial are obtained by combining the second and third rates of the three factors. The six treatments outside the cube are prolongations through the southwest and northeast corners of the cube.

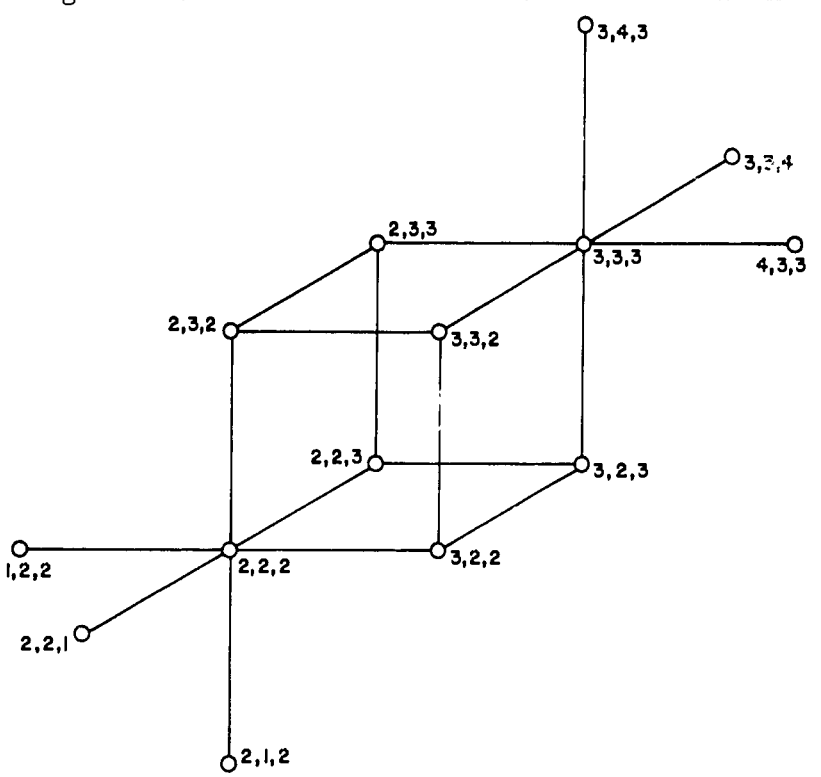

Figure 3. An "augmented 2^3" treatment design with 14 treatments.

Another example of this family of treatment designs, an "augmented 2^3" with the 12 treatments shown in Figure 4, was used in a series of maize experiments carried out in the state of Mexico, Mexico, in 1971. The factors studied in these experiments were nitrogen (N), phosphorus (P), and plant density (D). The results obtained in an experiment conducted near San Pedro El Alto are given in Table 7. In addition to the 12 treatments shown in Figure 4, the design included a check and a "potential yield" treatment.[5]

The following prediction equation was calculated from the data for the first 12 treatments in Table 7:

$$Y = 4440 + 23.73^{a}(N-50) - 7.967^{e}P + 34.57^{c}(D-50) - 0.4267^{a}(N-50)^2$$
$$-0.0982^{e}P^2 - 3.011^{b}(D-50)^2 + 0.5478^{b}(N-50)P + 1.2836^{a}(N-50)(D-50)$$
$$-0.5775^{c}P(D-50) \qquad \ldots(1)$$

The superscripts a, b, c, d, and e indicate the level of significance of the regression coefficients: a = < .01; b = .01 - .05; c = .051 - .20; d = .201 - .50; e = > .50. In order for the coefficients to be more meaningful in the area of interest, the nitrogen and plant density variables were coded as N - 50 and D - 50, respectively. Yield, nitrogen, and phosphorus were expressed as kilograms per hectare and plant density as thousands of plants per hectare.

The economic optima were estimated from the above prediction equation, using the current prices for maize and inputs. These were found to be 88 kg/ha of nitrogen, zero of phosphorus, and 64,000 plants per hectare.

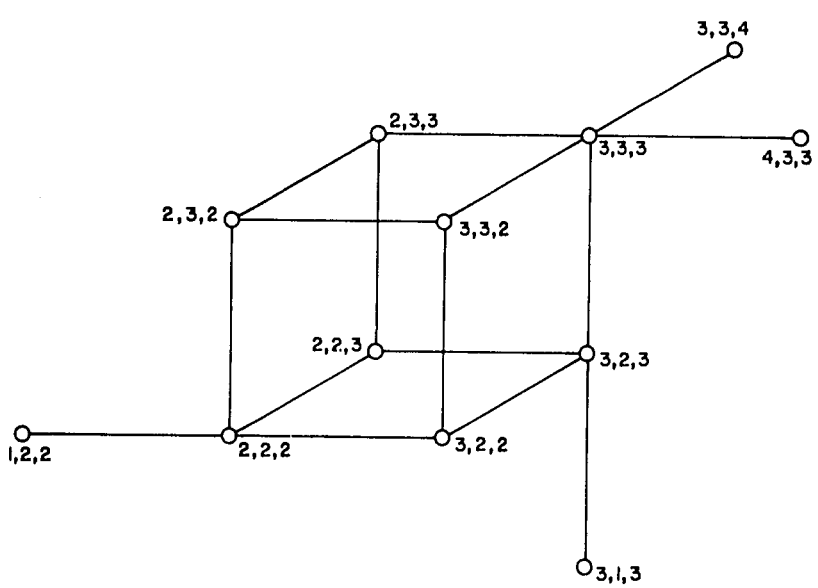

Figure 4. The "augmented 2^3" treatment design with 12 treatments used in maize experiments carried out in the State of Mexico, Mexico in 1971.

[5]We generally include a "potential yield" treatment in experiments to determine optimal levels of fertilizers. This treatment normally combines a high level of chemical fertilizers plus 10 ton/ha of chicken manure. With this treatment we expect to eliminate all mineral deficiencies.

Table 7. Grain yields obtained in a maize experiment conducted near San Pedro El Alto, State of Mexico, Mexico, using an "augmented 2^3" treatment design[1]

Coded levels of treatments[2]	Actual treatment levels: Nitrogen (kg/ha)	P_2O_5 (kg/ha)	Thousands of plants/ha	Yield (kg/ha)
2, 2, 2	80	30	50	4966
2, 2, 3	80	30	65	5065
2, 3, 2	80	60	50	5003
2, 3, 3	80	60	65	5010
3, 2, 2	110	30	50	5066
3, 2, 3	110	30	65	5805
3, 3, 2	110	60	50	5819
3, 3, 3	110	60	65	6067
1, 2, 2	50	30	50	4177
4, 3, 3	140	60	65	6266
3, 1, 3	110	0	65	5177
3, 3, 4	110	60	80	5823
-	0	0	50	2029
-	110	60 + 10 ton/ha of chicken manure	65	8491
		LSD at 5% level		518
		Coefficient of variation		6.69

[1]Data used by permission of Plan Maize, Direccion de Agricultura, State of Mexico, Mexico
[2]See Figure 4.

The yield data were also plotted as shown in Figure 5. The response curves for nitrogen, phosphorus, and plant density were graphed separately. For each variable there are four curves or straight lines. In the case of nitrogen, for example, the lower curve connects points 122, 222, and 322 (Figure 4); the upper curve passes through points 233, 333, and 433; and the two straight lines connect points 223 and 323 in one case and 232 and 332 in the other.

The triangles represent the input cost: maize price ratios are shown in Figure 5 below the set of curves for the three factors. These triangles were used to estimate graphically the optimal levels of the inputs, which were found to be 120 kg/ha of nitrogen, 50 kg/ha of P_2O_5, and 63,000 plants per hectare.

The large differences between the optimal levels of nitrogen and phosphorus, estimated by the two procedures, were probably due to the -P coefficient in the prediction equation. The economic optima estimated by the graphic method were considered the more reliable.

During the past 3 years, the "augmented 2^n" treatment designs have been used widely in Mexico and, to a lesser degree, in Colombia, Peru, and Honduras.

Efficiency of Treatment Designs

Considerable time has been devoted to the study of the relative efficiency of different designs for use in field research on crop production practices. Much of this work was done cooperatively with F. B. Cady, Cornell University, and the findings were published as a technical bulletin by the International Maize and Wheat Improvement Center (8). Other studies were carried out by graduate students at the Graduate College, Chapingo, Mexico (3, 10, 15, 17).

As a background, before summarizing the results of these studies, it should be emphasized that the failure of a prediction equation, estimated from field data, to express correctly the functional relationship between yield and the experimental variables is due to two types of error: variance error and bias error.

Variance error is the variance associated with a statistic arising from response function estimation. It has two distinct components. One of these, the experimental error, σ^2, arises due to random variation among experimental units or plots. In a completely randomized experiment it is recognized as the failure of replicated plots of a given treatment to produce the same yields. It is influenced by such things as variability in the plant, soil, and management, and by the way in which the treatments are applied to the experimental units.

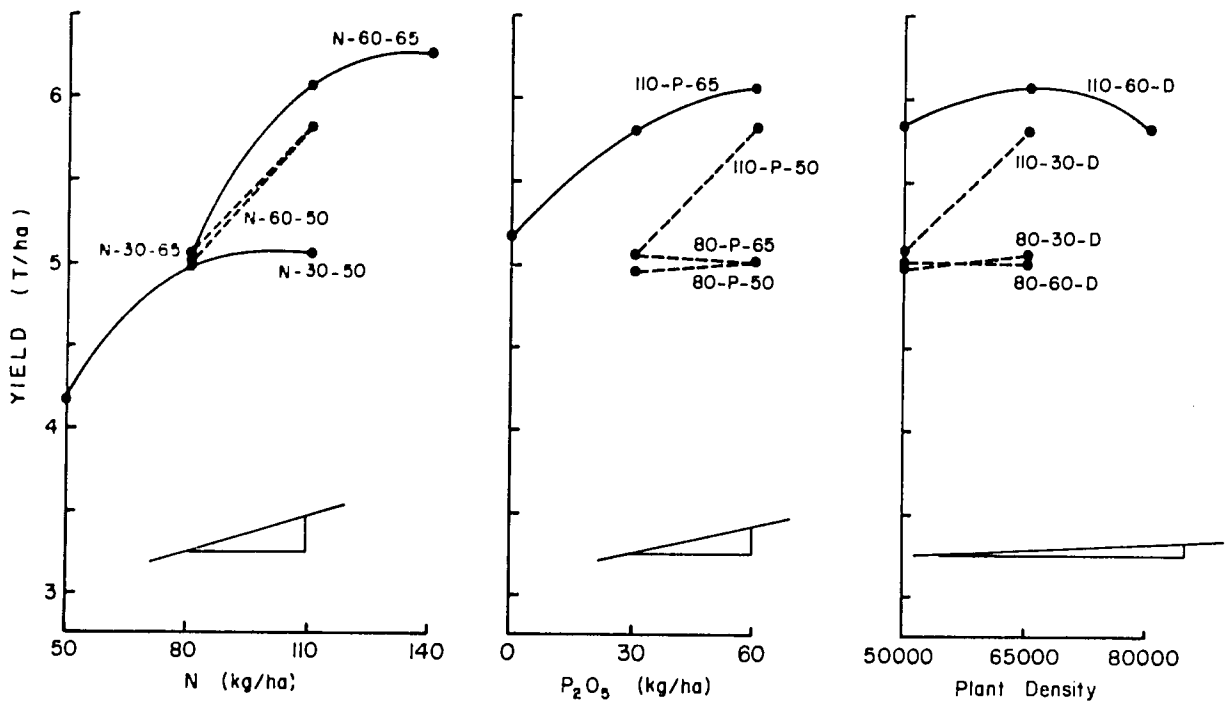

Figure 5. The response of maize to nitrogen, phosphorus, and plant density in an experiment carried out near San Pedro El Alto, State of Mexico, Mexico in 1971.

The second component of variance error is a function of the distribution of the treatment combinations in the factor space, and thus is influenced by the selection of the treatment design. As an illustration, consider the problem of estimating the slope of a function when it is accepted that the true relationship between the two variables is linear. It can be shown that the most efficient way to estimate the slope is to take one-half of the observations at each of the two extremes of the factor space. This component of the variance error that is related to the distribution of the treatments appears in the regression analysis as particular elements of the inverse matrix. The size of the elements in the inverse matrix depends upon the number of treatments, the distribution of the treatments within the factor space, and the number of times the set of treatments is replicated. The variance error is the product of these two components.

Bias error is the error that arises when the assumed model, used for representing a response function, is not the true model. To illustrate, let us assume (a) that we study the effects of nitrogen and phosphorus on crop yield and obtain a set of data, determined without error; and (b) we know that the true relationship between yield and the fertilizer variables is a square root function. If we use the data to estimate the square root prediction equation and also a second prediction equation using a different model, say the quadratic polynomial, the two will be different. The deviation of the quadratic prediction equation from the square root in this example is due to bias error.

In research on crop production practices the most that we can say a priori about the true relationship between yield and a given factor is that it has a certain tendency; that is, it is a diminishing returns type of response. Many mathematical models, however, can be fitted to a given type of response. Consequently, we can always assume that the model we select for representing response data will only approximate the true model, and that values estimated from the prediction equation will be affected by bias error.

Returning now to the studies of the efficiency of treatment designs, we will mention first the work of Cady and Laird (8). They compared the following nine designs, using both bias and variance criteria:

1. 5^2 factorial, 25 treatments
2. central composite, 9 treatments
3. central composite modification by Myers, 9 treatments
4. 3^2 factorial (rotated), 9 treatments
5. 5^2 partial factorial, 13 treatments
6. 5^2 partial factorial modification by Escobar, 13 treatments
7. 7^2 partial factorial, 17 treatments
8. 3^2 factorial, 9 treatments
9. central composite modification by Thompson, 12 treatments

The distributions of the treatment combinations corresponding to the nine designs are presented in Figure 6. The factor space, 0 to 320 kg/ha of nitrogen and 0 to 240 kg/ha of phosphorus, is the same for all designs, although in three of them no treatments are located on the boundaries of the factor space. The treatment combinations for the nine designs are given in Table 8.

It was assumed that the true model, with maize yield (Y), nitrogen (N), and phosphorus (P) expressed in kilograms per hectare, was

$$Y = 3000 + 300.5N^{0.5} + 374.4P^{0.5} - 15.10N - 23.33P + 15.00^{0.5}P^{0.5} \quad ...(2)$$

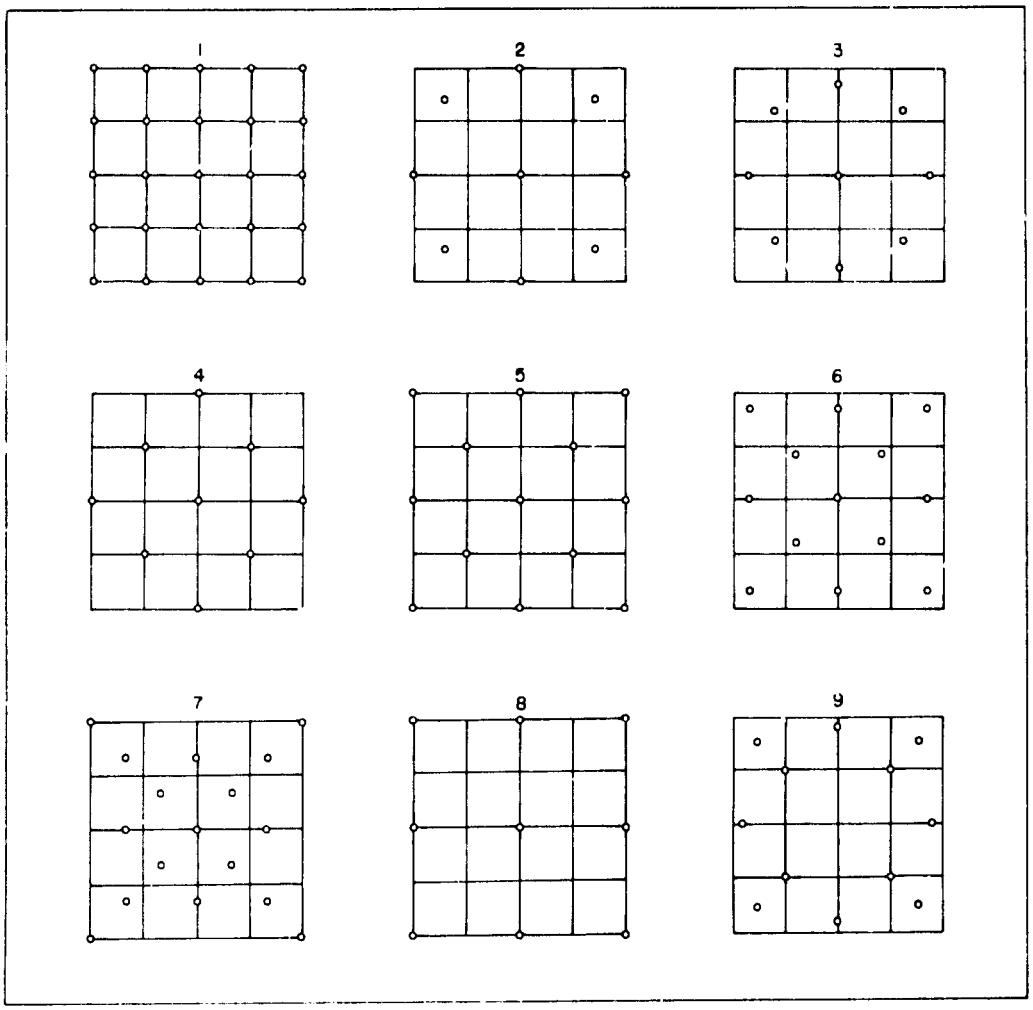

Figure 6. The treatment designs compared in the Cady and Laird (8) study: (1) 5^2 factorial, (2) central composite, (3) central composite modification by Myers, (4) 3^2 factorial (rotated), (5) 5^2 partial factorial, (6) 5^2 partial factorial modification by Escobar, (7) 7^2 partial factorial, (8) 3^2 factorial, and (9) central composite modification by Thompson.

Using this equation, the true responses for the treatments in each of the nine designs were calculated. A quadratic polynomial was fitted to the true responses for each design.

Indices of integrated bias were calculated for the nine designs by approximating the volume between the square root (true) response surface and the quadratic (predicted) response surface. A 30-x-30 grid was placed over the factor space, and the difference between the predicted yields using the square root and quadratic equations was calculated for the 900 intersections. Indices were calculated for the entire factor space and the central quarter of the factor space (80 to 240 kg/ha of nitrogen and 60 to 180 kg/ha of phosphorus). These indices of integrated bias are presented in Table 9 .

It is seen that three designs were outstanding in terms of integrated bias: number 3, central composite modification by Myers; number 6, 5^2 partial factorial modification by Escobar; and number 9, central composite modification by Thompson. For the central quarter of the factor space, the integrated biases with these three designs were less than one-third that of the 5^2 factorial.

Table 8. The treatment combinations for the nine designs studied by Cady and Laird (8) corresponding to a factor space of 0 to 320 kg/ha of nitrogen and 0 to 240 kg/ha of phosphorus

(The first value in each pair is the nitrogen rate and the second value the phosphorus rate.)

1		2		3		4		5		6		7		8		9	
5^2 factorial		Central composite		Central composite modification by Myers		3^2 factorial (rotated)		5^2 partial factorial		5^2 partial factorial modification by Escobar		7^2 partial factorial		3^2 factorial		Central composite modification by Thompson	
0	0	160	0	160	16	160	0	0	0	24	18	0	0	0	0	160	11
80	0	47	36	62	46	80	60	160	0	160	18	320	0	160	0	36	27
160	0	273	36	258	46	240	60	320	0	296	18	53	40	320	0	284	27
240	0	0	120	21	120	0	120	80	60	96	72	160	40	0	120	80	60
320	0	160	120	160	120	160	120	240	60	224	72	267	40	160	120	240	60
0	60	320	120	299	120	320	120	0	120	24	120	107	80	320	120	15	120
80	60	47	204	62	194	80	180	160	120	160	120	213	80	0	240	305	120
160	60	273	204	258	194	240	180	320	120	296	120	53	120	160	240	80	180
240	60	160	240	160	224	160	240	80	180	96	168	160	120	320	240	240	180
320	60							240	180	224	168	267	120			36	213
0	120							0	240	24	222	107	160			284	213
80	120							160	240	160	222	213	160			150	229
160	120							320	240	296	222	53	200				
240	120											160	200				
320	120											267	200				
0	180											0	240				
80	180											320	240				
160	180																
240	180																
320	180																
0	240																
80	240																
160	240																
240	240																
320	240																

Table 9. Indices of integrated bias for nine treatment designs studied by Cady and Laird (8)

Number of design	Number of design points	Indices of integrated bias ($X\ 10^3$)	
		Entire factor space	Central quarter of factor space
1	25	460	71
2	9	346	56
3	9	210	20
4	9	485	80
5	13	468	71
6	13	210	21
7	17	348	58
8	9	580	88
9	12	208	20

The designs were next compared using several variance criteria:

1. Indices of variance of a predicted response. The contribution of the design matrix to the variance of a predicted value was calculated for the 144 intersections of a 12-x-12 grid over the entire factor space. Average variances for the entire factor space and the central quarter of the factor space were calculated.
2. Indices of variance of the derivative of the response to nitrogen, $\partial Y/\partial N$. Individual variances were evaluated at the intersections of a 5-x-5 grid in the central quarter of the factor space. Variances were calculated by the Fuller (9) method.
3. Variances of the individual regression coefficients. These are the diagonal elements of the inverse of the X^1X matrix. This matrix is the sum of squares and cross products formed from the design matrix.

The calculated values for the several variance criteria are given in Table 10 for the 5^2 factorial and three designs that were outstanding in terms of bias error. In comparing the values of Table 10, it should be kept in mind that the magnitudes of the variances are inversely proportional to the number of treatments, and that the number of treatments is different for the four designs.

The 5^2 partial factorial modification by Escobar (number 6), after adjusting for number of treatments, is superior to the central composite modifications (numbers 3 and 9) in the eight variance comparisons. The variances with the 5^2 partial factorial modification by Escobar, after adjusting for number of treatments, were larger than those for the 5^2 factorial, except for the average variance of a predicted response for the central quarter of the factor space.

The 5^2 partial factorial modification by Escobar has a further advantage when compared to the two central composite modifications. As seen in Figure 6 with the Escobar modification, three levels of each factor are studied at each of three levels of the other factor. As mentioned earlier, this characteristic is desirable as it facilitates a graphic evaluation of the effects of the production factors.

The study by Cady and Laird (8) led to the conclusion that the 5^2 partial factorial modification by Escobar has several desirable qualities and should

be considered for use in research on crop production practices.

A similar computer simulation investigation of treatment designs was carried out by Hernandez, et al. (16). They compared the bias errors associated with the 11 designs presented diagrammatically in Figure 7. The treatment combinations for the 11 designs, coded with values between -1 and +1, are given in Table 11.

For their estimation of bias error, Hernandez, et al. (16) employed as true models, seven bivariate functions, representing a variety of responses of maize and sorghum to nitrogen, phosphorus, and plant density. For each of the assumed true models, they calculated the true responses corresponding to the treatments of the 11 designs. Next, using four representational models, they calculated prediction equations for each of the seven true models using the true responses for each of the 11 designs. Bias error was estimated by approximating the volume between the true response surface and that corresponding to a given prediction equation.

The bias errors associated with the 11 treatment designs, when the different representational models were used to estimate prediction equations, are presented in Table 12. It is seen that the effectiveness of the treatment designs in reducing bias error depends, to a limited degree, on the model used for the prediction equation.

As an average for the four representational models, the following seven treatment designs had bias errors of similar magnitude: central composite modification by Myers, central composite modification by Berardo, first augmented 2^2, second augmented 2^2, 5^2 partial factorial modification by Escobar, second Box-Berardo, and third Box-Berardo. Compared to the average value for these seven designs, the bias error for the first Box-Berardo was 16 percent greater; for the central composite, 45 percent greater; for the 5^2 partial factorial, 74 percent greater; and for the San Cristobal, 112 percent greater.

Table 10. The comparison of four treatment designs, studied by Cady and Laird (8), in terms of several variance criteria

Criteria	Design no. 1	3	6	9
Index of variance of a predicted response				
Entire factor space	0.189	1.270	0.498	0.682
Central quarter of factor space	0.134	0.674	0.232	0.587
Index of variance of the derivative of the response to nitrogen, $\frac{\partial Y}{\partial N}$ (X 10^{-7})	84	692	255	385
Diagonal inverse elements				
Nitrogen (X 10^{-4})	0.451	4.624	1.488	2.540
Phosphorus (X 10^{-4})	0.802	8.221	2.645	4.516
N^2 (X 10^{-9})	0.349	3.713	1.202	2.178
P^2 (X 10^{-8})	0.110	1.173	0.380	0.688
NP (X 10^{-9})	0.434	4.802	1.238	1.615

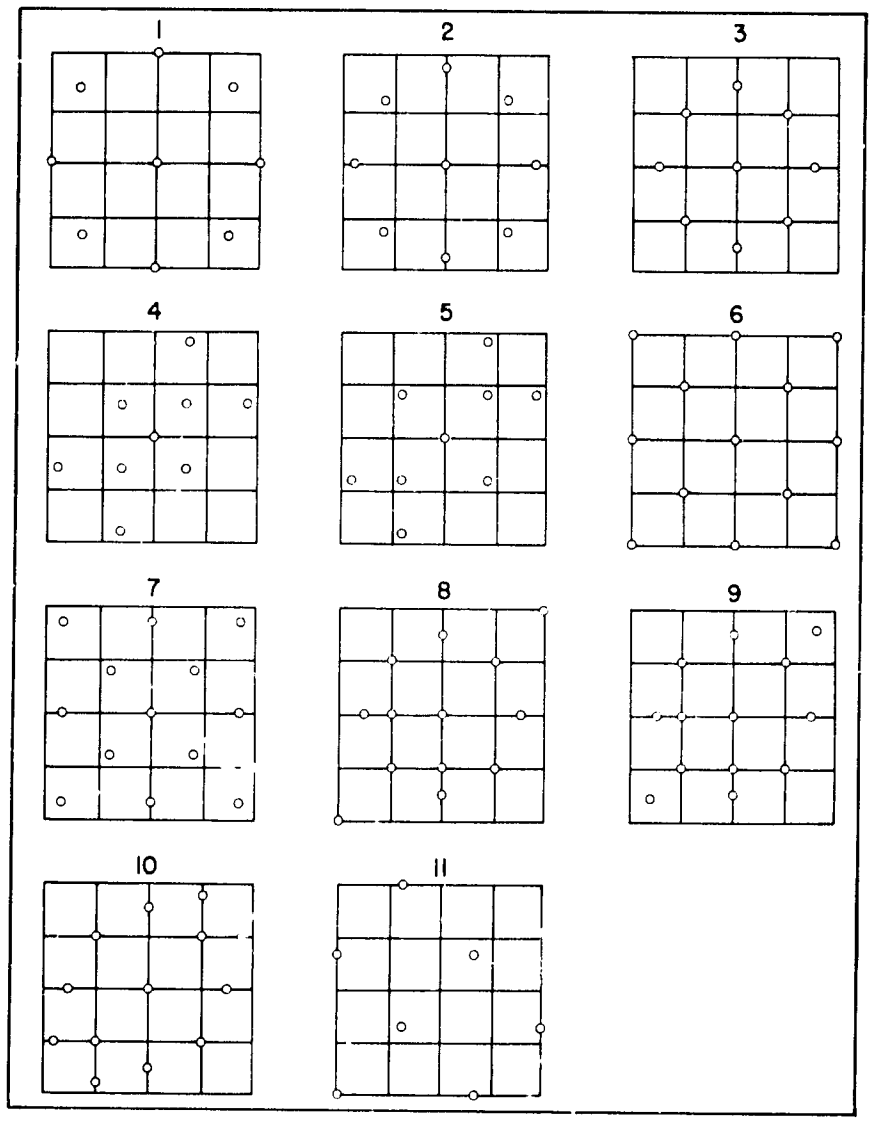

Figure 7. The treatment designs compared in the study by Hernandez, et al. (16): (1) central composite, (2) central composite modification by Myers, (3) central composite modification by Berardo, (4) first augmented 2^2, (5) second augmented 2^2, (6) 5^2 partial factorial, (7) 5^2 partial factorial modification by Escobar, (8) first Box-Berardo, (9) second Box-Berardo, (10) third Box-Berardo, and (11) San Cristobal.

This research by Hernandez, et al. (16) has been complemented recently by Martinez (17), who studied the relative efficiency of eight of their treatment designs (1, 2, 3, 4, 5, 6, 7, and 11 in Figure 7). Martinez used six assumed true models and four representational models. For each of the 24 prediction equations corresponding to each treatment design, he calculated the mean squared error (4), J, defined as

$$J = V + B \qquad \ldots(2)$$

where V is the average variance of $\hat{Y}(X)$, the prediction equation, and B is the average squared bias of $\hat{Y}(X)$.

Martinez found the smallest bias values to be associated with the central composite modification by Myers, the first augmented 2^2, the second augmented

Table 11. Coded values for the treatments of the 11 treatment designs studied by Hernandez et al.

Treatment no.	Treatment design no. 1		2		3		4		5		6	
1	-0.7	-0.7	-0.6	-0.6	-0.50	-0.50	-0.3	-0.3	-0.4	-0.4	-1.0	-1.0
2	-0.7	+0.7	-0.6	+0.6	-0.50	+0.50	-0.3	+0.3	-0.4	+0.4	-1.0	+1.0
3	+0.7	-0.7	+0.6	-0.6	+0.50	-0.50	+0.3	-0.3	+0.4	-0.4	+1.0	-1.0
4	+0.7	-0.7	+0.6	+0.6	+0.50	+0.50	+0.3	+0.3	+0.4	+0.4	+1.0	+1.0
5	0	0	0	0	0	0	0	0	0	0	-0.5	-0.5
6	-1.0	0	-0.9	0	-0.75	0	-0.9	-0.3	-0.9	-0.4	-0.5	+0.5
7	+1.0	0	+0.9	0	+0.75	0	+0.9	+0.3	+0.9	+0.4	+0.5	-0.5
8	0	-1.0	0	-0.9	0	-0.75	-0.3	-0.9	-0.4	-0.9	+0.5	+0.5
9	0	+1.0	0	+0.9	0	+0.75	+0.3	+0.9	+0.4	+0.9	0	0
10											-1.0	0
11											+1.0	0
12											0	-1.0
13											0	+1.0

Treatment no.	Treatment design no. 7		8		9		10		11	
1	-0.85	-0.85	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50	-1.00	-1.00
2	-0.85	+0.85	-0.50	+0.50	-0.50	+0.50	-0.50	+0.50	-1.00	+0.34
3	+0.85	-0.85	+0.50	-0.50	+0.50	-0.50	+0.50	-0.50	+0.34	-1.00
4	+0.85	+0.85	+0.50	+0.50	+0.50	+0.50	+0.50	+0.50	+0.34	+0.34
5	-0.40	-0.40	0	0	0	0	0	0	-0.34	-0.34
6	-0.40	+0.40	-0.75	0	-0.75	0	-0.75	0	+1.00	-0.34
7	+0.40	-0.40	+0.75	0	+0.75	0	+0.75	0	-0.34	+1.00
8	+0.40	+0.40	0	-0.75	0	-0.75	0	-0.75		
9	0	0	0	+0.75	0	+0.75	0	+0.75		
10	-0.85	0	-0.50	0	-0.50	0	-0.90	-0.50		
11	+0.85	0	0	-0.50	0	-0.50	-0.50	-0.90		
12	0	-0.85	-1.00	-1.00	-0.80	-0.80	+0.90	+0.50		
13	0	+0.85	+1.00	+1.00	+0.80	+0.80	+0.50	+0.90		

Table 12. Bias errors associated with prediction equations estimated using four representational models and data corresponding to 11 treatment designs (16)

Treatment design number	Name of design	Representational model				Average
		Quadratic	Square root	Quadratic square root	Square root quadratic	
1	Central composite	1517	1917	1195	1979	1652
2	Central composite modification by Myers	939	1293	779	1395	1101
3	Central composite modification by Berardo	924	1394	823	1514	1199
4	First augmented 2^2	944	1271	837	1545	1149
5	Second augmented 2^2	935	1245	788	1411	1095
6	5^2 partial factorial	1954	1830	1681	2464	1981
7	5^2 partial factorial modification by Escobar	960	1317	822	1482	1149
8	First Box-Berardo	1094	1556	953	1654	1314
9	Second Box-Berardo	937	1427	842	1538	1186
10	Third Box-Berardo	911	1230	777	1398	1079
11	San Cristobal	3363	2044	1768	2487	2416
	Average	1316	1502	1024	1748	

2^2, and the 5^2 partial factorial modification by Escobar. The central composite and the central composite modification by Berardo gave somewhat higher values of B, and the San Cristobal and the 5^2 partial factorial gave the highest values.

The variances of the prediction equations were smallest with the 5^2 partial factorial, the central composite, the 5^2 partial factorial modification by Escobar, the San Cristobal, and the central composite modification by Myers; intermediate values of V were associated with the central composite modification by Berardo and the second augmented 2^2; and the largest variance was found with the first augmented 2^2. In all cases, however, the variance error was very small in comparison with the bias error.

Based on these studies and others not reviewed here, we feel that the following criteria should be considered in selecting a treatment design for use in field experimentation to determine optimal levels of production inputs:

1. Appropriateness of the design for use in a graphic estimation of economic optima. Considering the present level of understanding of the reliability of economic optima estimated from prediction equations, this criterion should probably be given greatest weight in the selection of a design.
2. Magnitude of bias error. Apparently, this is a major cause of poor results in estimating economic optima from prediction equations. To the extent we expect to rely on economic analyses of prediction equations, it will be important to select designs with small bias errors.
3. Number of treatment combinations. The economics of field experimentation argue in favor of small designs.
4. Flexibility in number of factors and number of levels of each factor. This is a convenience more than a consideration influencing the reliability of economic optima estimated from the research data. It should not be given high priority.
5. Magnitude of variance error. This criterion should be given little or no importance in selecting a treatment design for the type of field experimentation considered here. The researcher should assure an acceptable level of variance error in his experiments through experimental design, for example, blocking and replication.

Using the data from the three papers discussed in this section (8, 16, 17) we have rated the several treatment designs for their appropriateness for use in a graphic estimation of economic optima and the magnitude of their bias errors. These ratings are presented in Table 13, along with the number of treatment combinations for each design. Those designs with 13 treatments or less, a graphic analysis rating of 2 or more, and a bias error rating of 1 or 2, are marked with an X in the last column of the table. It appears that the outstanding designs in this group for use in field experimentation to determine optimal levels of production inputs are the 5^2 partial factorial modification by Escobar, the augmented 2^2, and the three Box-Berardo designs.

SUMMARY

It is contended that field experimentation is needed to complement existing information and arrive at reliable recommendations on crop production practices for most of the rainfed agriculture of developing countries, particularly that portion in the hands of subsistence farmers.

Table 13. An evaluation of the appropriateness of several bivariate treatment designs for use in field experimentation to determine optimal levels of production inputs

Treatment design	Criteria for judging adequacy of designs			
	Treatment number	Appropriateness for graphic analysis[1]	Magnitude of bias error[2]	Good designs[3]
5^2 factorial	25	4	3	
Central composite	9	1	2	
Central composite modification by Myers	9	1	1	
3^2 factorial (rotated)	9	1	4	
5^2 partial factorial	13	3	3	
5^2 partial factorial modification by Escobar	13	3	1	X
7^2 partial factorial	17	3	2	
3^2 factorial	9	3	4	
Central composite modification by Thompson	12	1	1	
Central composite modification by Berardo	9	1	2	
Augmented 2^2	9	2	1	X
First Box-Berardo	13	2	2	X
Second Box-Berardo	13	2	1	X
Third Box-Berardo	13	3	1	X
San Cristobal	7	1	4	

[1]The ratings give the number of possibilities for plotting the response of one factor at three levels of the other. A rating of 1 may be zero or one; a rating of 4 may be four or more.

[2]The ratings give the relative magnitude of bias error from small (1) to large (4).

[3]Designs with 13 treatments or less, a graphic analysis rating of 2 or more, and a bias error rating of 1 or 2.

The first step in field experimentation is to assemble all relevant information about the area. The important sources of information available to the researcher are published and unpublished reports, the field staffs of agricultural service agencies, the local farmers, and the study area itself. In defining objectives and organizing research in rainfed areas of subsistence agriculture, it is suggested that: (a) the responsibility for all research on crop production practices should be assigned to a single team; (b) research should initially be directed toward developing improved practices for the traditional cropping systems; (c) the researcher should decide which cropping systems to study and in what producing systems, based on their relative importance in the area and the resources available for research; (d) the whole cropping system, not just a single crop, should be studied; (e) as time and resources permit, research should be conducted to discover alternatives to traditional cropping systems that are superior in terms of net income and the risk factor; and (f) in planning research and interpreting data, it should be kept in mind that often the primary objective of small, subsistence farmers is to maximize net income in the least favorable years.

It was suggested that one should not rely too heavily on prediction equations for estimating optimal levels of production inputs. Bivariate quadratic prediction equations, with negative or very small positive linear coefficients for one of the variables, were cited as examples of equations that lead to unreliable estimates of economic optima. Examples were given of economic optima that differed greatly, depending upon whether they were estimated graphically or from prediction equations corresponding to different mathematical models. Two ways of assuring greater accuracy in optimal levels of production inputs estimated from yield data were mentioned: (a) complementing the mathematical estimation of economic optima with a graphic analysis; and (b) reducing the size of the factor space.

Several studies of the relative efficiency of two-factor treatment designs using variance and bias error criteria were reviewed. It was concluded that the following points, in order of importance, should be considered in selecting a treatment design for use in field experimentation to determine optimal levels of production inputs: (a) appropriateness of the design for use in a graphic estimation of economic optima; (b) magnitude of bias error; (c) number of treatment combinations; (d) flexibility in number of factors and number of levels of each factor; and (e) magnitude of variance error.

These criteria were used to evaluate the adequacy of 15 treatment designs for use in research on crop production practices. The 5^2 partial factorial modification by Escobar, an augmented 2^2, and three Box-Berardo designs were selected as outstanding.

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Some Examples of the Use of Production Functions to Quantify Environmental Influences on Crop Productivity

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INTRODUCTION

During the past decade, crop and soil scientists have shown an increasing interest in considering the crop environment as a system resulting from the interaction of soil, climatic, and management factors, and in investigating methods to describe it in quantitative terms. Recognizing that actual yields obtained thus result from the combined levels of those factors, a new approach toward soil fertility evaluation is now being proposed in which quantitative relationships are searched for expressing yield as a function not only of the available soil nutrients and fertilizer rates, but also of the level of other factors of the plant environment, which might significantly interact with the former ones.

In order to express adequately the continuous relationship between crop production considered as a dependent variable and the factors considered as the independent variables, yield functions are established using statistical models approximating, with a reasonable degree of confidence, the unknown mathematical model that would describe the function unequivocally.

The tools are multifactorial analysis and, particularly, multiple regression, a few good examples of such use having already been published (Voss and Pesek, 1967; Laird and Cady, 1969; Voss, et al., 1970).

The problem, however, is the selection and the quantification of the factors to be included in order to describe the crop environment adequately. Potential factors are, of course, numerous; they are often interrelated, and for many of them the physical meaning of their influence on crop physiology is still unknown. Within an ecological region, however, the problem can be circumscribed in attempting to generate yield functions including, in addition to such factors as soil availability of plant nutrients and fertilization, other relevant factors of the environment that are known at least quantitatively through previous experience to influence yield either directly or in conjunction with the former ones.

Two ways have been described for collecting data that lend themselves to the quantitative analysis of the relationship between the yield of a crop and its causal factors (Ferrari, 1965).

In nonmanipulative experiments, the quantitative data are generated through observations and measurements of yields and factors under consideration within a network of observation sites distributed within fields in the area under study. The observation sites, generally farmers' fields, are selected in order to cover, as much as possible, the complete range of variation that each of the factors under consideration may reach. This method, however, has a strong drawback when the range covered by the levels of a factor within the area does not reach an optimum. Indeed, the validity of the quantitative relationships derived for it and for the other associated factors is strongly biased in such cases.

On the other hand, in manipulative experiments, a network of standardized experiments is established, within each of which measurements are made of the effect on yields of the systematic variation of the level of a few factors for which one knows an optimum level is not reached within the ecological and management conditions of the area. The sites are selected to cover among them a wide range of levels for the other factors thought to be important, which are quantified at each location. The whole set of data, thus obtained, is then processed in order to establish the yield-factor relationships that lead to the aforementioned yield function. If, furthermore, some management factors, such as variety, sowing rate, and weed control are thoroughly optimized, better insight can be given on the influence of the uncontrolled factors resulting from the environment. Two unpublished examples will be presented here to illustrate the use of soil production function in soil fertility investigations (FAO, 1973).

WHEAT PRODUCTIVITY IN THE CENTRAL VALLEY OF CHILE

Environment

Physiologically, the central valley of Chile is a tectonic depression enclosed between the Andes and a coastal range partly filled by alluvial and fluvioglacial sediments. The topography is flat, interrupted by transverse hills and rivers.

The area under study is located in the northern part of this valley between parallels 32°40' and 35°S. It is a region of irrigated agriculture, where the best land is occupied by orchards. The greatest portion of the agricultural land, however, grows wheat, corn, and other staple crops in a rotation frequently interrupted by artificial pastures. The climate is mediterranean maritime, with a maximum mean temperature during summer of above 25°C. Rainfall is about 400 mm, concentrated during winter, and irrigation takes place during the dry season beginning in September. As a consequence, the soil-water regime is mainly xeric, and the soil temperature regime limit is between mesic and thermic.

Three geomorphological regions are found:

1. A region of fluvial sedimentation where typical soil association encompasses Inceptisols and Entisols along the rivers, Mollisols on the levees and terraces, and Vertisols in the depressions along the hills. The majority of Mollisols and Vertisols are imperfectly drained and have a calcic horizon in the zone of fluctuation of the water table, which tends to rise during the summer as a result of the irrigation. Problems of moderate salinity are sometimes encountered.

2. A region of fluvioglacial sedimentation corresponding mainly to the last glaciation. Inceptisols predominate, and their depths rarely exceed 1 meter. Haploxeralfs are also sporadically encountered on older geomorphic surfaces formed before the last glaciation.

3. A region corresponding to a ground moraine of the Riess glaciation in the southern part of the area under study, covered by Fragiaqualfs.

From north to south, the soils pass from a slightly alkaline to a slightly acid reaction, and this change corresponds to an increase in rainfall and a decrease in carbonate content of the irrigation water, which is partly responsible for a slight calcification of the A horizon in the northern part of the valley.

Experimental Method

In 1968 and 1969, a network of 66 experiments was established in order to study the response of irrigated wheat to nitrogen and phosphorus fertilizers. Sites were selected to cover the main existing soil series of the area belonging to the following soils orders:

Entisols and Inceptisols	33 experiments
Alfisols	11 experiments
Mollisols and Vertisols	22 experiments

representing the following great soil groups: Xerorthents, Xerofluvents, Haplaquepts, Xerochrepts, Haploxeralfs, Palexeralfs, Ochraqualfs, Fragiaqualfs, Calciaquolls, Calcixerolls, Haploxerolls, Argixerolls, Pelloxererts, and Chromoxererts.

As far as possible, the many combinations for the soil management factors of major variability within the area, which eventually would differentially influence yields and the response to fertilization, were covered. Preliminary soil analysis helped in the selection of sites with defined levels of available nutrients. Furthermore, the sites selected all had the same previous crop (irrigated corn) and the accepted rotation in the area in order to minimize interferences due to previous management of the fields. The experiments were located on farmers' fields, and the work was carried out in collaboration with the farmers.

Installed at each site were 26 plots, divided into two blocks of 13 treatments. The rate combinations for nitrogen and phosphorus applied were derived from the incomplete design of double square for two factors at five levels, a design that explores the factor space evenly and still keeps the number of treatments relatively small. The doses were selected from previous information in order to have the central point corresponding to a mean optimum of 128 kg N and 160 kg P. Their combinations are given in Table 1.

At each site, a complete soil description was made and the main horizons were sampled for analysis. Composite samples of the A horizon were also taken in each block to study their chemical fertility. The differences between data and method of preparation were recorded. Sowing took place from May to July; even though the late sowing date was not recommended, it had to be included within part of the experiments to quantify its depressing effect on yield. Weeds were completely controlled during the entire growing period through chemical and cultural practices. As irrigation was known to be one of the major factors affecting yield, it was left as an uncontrolled variable managed by the

Table 1. Combination of treatments and doses of fertilizers applied in the network of experiments for studying wheat productivity in the central valley of Chile, 1968-1970[1]

	P				
N	0	80	160	240	320
0	*		*		*
64		*		*	
128	*		*		*
192		*		*	
256	*		*		*

[1]Doses are expressed in kg/ha N and kg/ha P_2O_5 added as sodium nitrate and triple superphosphate, respectively.

farmer. Between two and five irrigation applications took place, at variable intervals among sites, and nearly half of the experiments suffered some degree of water stress.

Soil humidity at three depths was monitored during the entire growing period through plaster blocks installed in the central treatments of all experiments. Trials were visited every 10 days to take phenological observations and measurements, to monitor irrigation, rainfall, and soil humidity, to register damage and other irregularities, and to apply phytosanitary treatments where relevant. Harvest was done by hand, and yields were expressed in quintals/hectare (qq/ha) at 14 percent humidity.

The data reduction and analysis took place in three steps. First, a second-degree polynomial model was adjusted to the data concerning the yield-fertilizer relationship at each site; thus, the six parameters obtained per experiment described the yield function at that specific site. In the second step, the correlation matrix between these parameters and the environmental factors considered was obtained as a guide to the choice of those which should be included in a generalized yield function. Furthermore, the correlation matrix of the factors among them was also constructed and studied in detail in order to restrict selection to factors reasonably uncorrelated to one another. In a third step, various yield functions including combinations of the measured factors were proposed and developed using stagewise and backward regression procedures.

Coefficients of determination (R^2), F tests, standard error, and significant levels of regression coefficients, as indicated by Student's t-test, were the criteria used throughout the regression analysis.

Results and Discussion

Soil and Management Factor Levels

Soil physical and chemical characteristics of the experimental sites showed a rather wide range of variation (Table 2). This was not unexpected because an attempt was made to sample a rather heterogeneous universe of soils belonging to distinct orders in the soil classification. Independently, the availability of nitrogen and phosphorus varied within a wide scale, ranging from 3.8 to 100.8 ppm NO_3N and 3.6 to 26.7 available P (Olsen P), respectively.

Table 2. Factors included to obtain a general equation of yields for an irrigated wheat crop in the central valley of Chile

Soil factor	Symbol	Measurement	Mean	Range
Uncontrolled factors				
Available nitrogen in the soil	n	ppm N	29.5	3.8 - 100.8
Available phosphorus	p	ppm P	12.3	3.6 - 26.7
Available potassium	k	meq/100 g	0.62	0.14 - 1.83
Clay content	A	%	32.4	9.6 - 55.0
Calcium carbonate content	Ca	%	2.5	0 - 18.8
Conductivity	Cd	mmhos	0.17	0.0025 - 0.50
pH	pH	units	7.2	5.7 - 8.5
Organic matter	MO	%	3.4	1.1 - 6.9
Soil depth	PR	cm	82.0	19 - 150
A horizon depth	PA	cm	23.0	12 - 48
Controlled factors				
Sowing date	E	days	33.9	1 - 97
Water stress between sowing time and tillering	DI	days	5.1	0 - 45
Water stress between stalking and flowering	DIII	days	4.7	0 - 20
Water stress between flowering and grain formation	DIV	days	7.7	0 - 29
Nitrogen fertilization	N	kg N/ha	128	0 - 256
Phosphorus fertilization	P	kg P/ha	128	0 - 320

Available potassium varied from 0.14 to 1.83 meq per 100 g soil. Among the management factors, water stress during several selected growing periods, sowing date, and length of fallow were those that showed major significant variations as shown in Table 2.

Yield and Physical Response to Fertilization

Yields without fertilization ranged from 11.3 to 55.6 qq/ha with a mean of 30.7. Maximum yield attained ranged from 25.8 to 75.2 qq/ha. Treatment 192/240 had the highest mean yield with 41.1 qq/ha.

Out of 66 experiments, 53 had data on nitrogen and phosphorus response. A significant response to nitrogen was observed in more than 60 percent of the cases; response to phosphorus was moderate, encompassing only 30 percent of the sites. The interaction coefficient result was significant and positive in only six cases; meanwhile, a significant negative interaction was observed in 10 cases. Response to nitrogen was major in soils either shallow or with low organic matter content; generally speaking, Alfisols did not respond to phosphorus. The quadratic model was used in these analyses.

Establishment and Interpretation of the Yield Function

A few preliminary trials were run with the results of the first year in order to check the methodology of building the yield function and particularly the selection of factors through their simple linear correlation coefficients with the parameters of the quadratic response function. It appeared that the

selection procedure was not completely satisfactory as it would have induced the discarding of some important factors having nonlinear relationships with those parameters. Furthermore, plotting data on graphs showed that in many cases the relationships were curvilinear, sometimes with asymptotic tendency. Selection of variables for the full model thus took place in the first instance through a combination of statistical and graphical methods. Different functions were proposed, the first of which had 34 terms, including interactions. Through backward regression, the function was reduced to 27 terms, 25 of which were significant to t-test. A coefficient of multiple correlation of 0.756 and an F value of 33.2, both significant at the 1 percent level, were obtained.

Expected yields were then calculated for the 858 treatments of the networks from the regression coefficient of the yield function and the level of the factors in each case. They were then compared with the mean yields obtained for each treatment, to calculate on each site a sum of the square of the difference between observed and expected values. The 66 values obtained were then tested for homogeneity after distributing them in classes according to soil types and years. Their homogeneity permitted the discard of the hypothesis of unaccounted influence of those factors on yields, meaning that their effects were already taken into account and adequately quantified in the production function.

This conclusion was important because it emphasized that for the ecological area considered here, the difference in wheat yields between soils belonging to different orders of the classification was satisfactorily explained by considering isolated soil factors. This was probably so because, for the soils under study here, the physico-chemical conditions to which nutrient availability was linked (clay type, pH, quality of the organic matter, kind of linkage of soil phosphorus with the colloidal complex) were of the same qualitative nature irrespective of the taxonomic unit to which they belonged.

For nine sites, however, the sums of squares of the difference between observed and expected yield were unduly high, passing a threshold of 3 sigma, which led one to consider that, for those experiments, the proposed model may not predict the yields satisfactorily. Going back to the original data, one could see that (1) in three cases, an important negative interaction occurred between nitrogen and phosphorus, not considered in the original model; (2) in two cases, strong nitrogen response occurred with high value of nitrogen in the soil; (3) in three cases, there were both a high coefficient of variation and poor adjustment of the original data to a quadratic response function; and (4) in one case, a strong water stress was observed in a period not considered in the general equation. As a consequence, these nine experiments were discarded as not belonging to the population that the production function aimed at describing, and new yield functions were calculated with 57 experiments, using both backward and stagewise regression procedures. The yield function obtained had 20 terms, the coefficients of which are given in Table 3. It explained 64 percent of the variation in yield for the 741 data considered in the analysis.

This yield function can be expressed by the following general regression model depicting the fertilizer response

$$Y = b_0 + b_1N + b_2P + b_3N^2 + b_4P^2 \qquad \ldots(1)$$

where the coefficients result from the combination of the pertinent terms of the detailed model given in Table 3.

B_0 allows the calculation of the yield in the absence of fertilization and takes into account the following characteristics of the superficial horizon of

Table 3. Regression coefficients for a production function of an irrigated wheat crop in the central valley of Chile

Variables[1]	Regression coefficient
n	0.4.064 **
$(n)^2$	-0.00048 +
A	1.0105 **
$(A)^2$	-0.0191 **
Ca	0.398 **
PR	0.0602 **
$(E)^2$	-0.00129 **
DIV	-0.580 **
$(DIV)^2$	0.0122 **
N	0.1688 **
N x n	-0.00210 **
N x DI	0.00302 *
N x DIV	-0.00493 **
$(N)^2$	-0.00418 **
$(N)^2$ x n	+0.00000472 *
$(N)^2$ x DI	-0.0000106 *
$(N)^2$ x DIV	0.0000122 **
P	0.091 **
P x p	-0.00567 *
$(P)^2$	0.000260 **

Constant: 7.918 - R = 0.807 ** - F = 63.20 **

(**), (*), and (+) significant at the 1, 5, and 10% probability levels, respectively.

[1]The meanings of the symbols are indicated in Table 2.

the soils at sowing time: available nitrogen, clay content, calcium carbonate content, and depth of the soil. Available phosphorus was not retained since its effect did not register a significant result at the t-test, probably because it was curtailed by an excessive loading of high soil P values. The same applied to interchangeable potassium. Other soil factors, which could also be sought as influencing yield--such as organic matter content, pH, total nitrogen, and depth of A horizon--did not appear either, because they are strongly correlated with the factors already present in the model. This term also included two important crop management factors: sowing date and water stress between tasseling and grain formation.

The coefficient of the linear response to nitrogen includes two negative interaction terms that describe a progressively diminishing response when nitrogen supplied by the soil increases and when water stress occurs at tasseling time, respectively. Furthermore, it includes a term of positive interaction of slight magnitude corresponding to a water stress early in the season, probably due to a better resistance to drought accompanying the faster development of the rooting system when nitrogen fertilizer is applied. The same factors are included as interaction terms in the quadratic response coefficient.

As far as phosphorus response is concerned, the yield function expresses that it is only affected by the content of available phosphorus in the soil.

No term is present to describe an interaction between nitrogen and phosphorus fertilizer application, probably because a low level of both nutrients is seldom encountered within the area under study.

This yield function could thus establish that, in general terms within the central valley of Chile, wheat response to nitrogen and phosphorus fertilizers depends essentially upon the availability of these nutrients in the soil. Furthermore, magnitude of the nitrogen response depends on the soil water availability at critical periods of the crop growth.

The Yield Function Application

The yield function can be used to calculate the response to fertilization for a specific set of soil conditions. Table 4, for example, was established for the interpretation of soil testing results in terms of economic doses of fertilizer to be applied.

The potential productivity of the soils under optimized soil and crop management conditions can also be derived. Indeed, it has been demonstrated here that yield depends on the combined levels of a series of soil factors. And, as soil classes are defined through quantitative criteria with fixed limits, one usually finds defined combinations of the levels of those factors, with a rather narrow range of variations for each soil class. In other words, a soil class can be defined in terms of crop productivity with the aid of a yield function. This is exemplified in Table 5, in which the results of rating four soil series in terms of wheat productivity for optimum crop and management conditions are shown. Needless to say, this constitutes a steady improvement on the so-called parametric methods.

On the other hand, the yield function obtained considers only the production factors of major variability within the area. Other important factors are missing, although it was observed that they had a strong influence on yield in a few particular cases. It is worthwhile mentioning them to complete the general picture of the ecological area.

Table 4. Mean recommendations of optimum economic fertilization rates[1] for an irrigated wheat crop in the central valley of Chile according to nitrogen and phosphorus availability in the soil

Soil NO_3N (ppm)	Soil P (ppm) (Olsen) 0 - 4		4.1 - 7.9		8 - 12		12.1 - +	
	N	P_2O_5	N	P_2O_5	N	P_2O_5	N	P_2O_5
	(kg/ha)							
0 - 9	130	120	130	80	130	45	130	0
10 - 19	105	120	105	80	105	45	105	0
20 - 29	80	120	80	80	80	45	80	0
30 - 39	55	120	55	80	55	45	55	0
40 - 49	35	120	35	80	35	45	35	0
50 - 59	15	120	15	80	15	45	15	0
60 - +	0	120	0	80	0	45	0	0

[1]Calculated for sodium nitrate 16% N and triple superphosphate 46% P_2O_5. Price ratio 0.052 and 0.019, respectively. Minor additional expenses of fertilization were ignored.

One particular transverse valley had consistently low values of interchangeable potassium. If more sites were located in this environment, with an experimental design aimed at checking the response to that element, a yield function could be derived for such specific conditions.

Two experiments in the lower valley of a transverse river suffered from slight soil salinity. The effect could not be quantified adequately. Moreover, three experiments located on Calciaquolls in the same location had to be discarded from the general yield function because of a strong negative response to P, and specific studies on this type of soil, as well as a zinc availability factor, are necessary to describe the crop environment adequately.

Generally speaking, Alfisols, and particularly the more acid ones, did behave slightly differently from the other soils in their productivity. They seem to require a higher rate of nitrogen fertilization for optimum growth at a given level of soil nitrogen and show consistently higher available phosphorus values. It is likely that with a higher number of experimental sites, a specific yield function could have been derived for them.

Standing as it is, nevertheless, one can reasonably accept this yield function as describing, at least partially, the quantitative relationship between wheat productivity and the level of the main production factors of the central valley of Chile environment.

Table 5. Mean potential yield of wheat in four main soil types of the central valley of Chile under good management conditions

		Characteristics of A horizon								
Area	Soil order	Organic matter (%)	Clay (%)	Carbonates (%)	Soil N (ppm)	Soil P (ppm)	Depth (cm)	Fertilization (units) N	Fertilization (units) P	Yields (qq/ha)
El Monte-Melipilla	Mollisol	4.5	35	15	50	10	150	76	66	57.5
Llano del Maipo-Santiago	Inceptisol	2.5	23	5	40	10	60	101	66	44.5
San Vicente-Rengo	Vertisol	5.0	35	0	50	10	150	76	66	51.5
Teno	Alfisol	3.1	35	0	25	18	80	140	0	42.6

WHEAT PRODUCTIVITY IN THE ANDES PIEDMONT OF SOUTHERN CHILE

Ecological Conditions

The area under study is located within a narrow strip of the Andes piedmont between 26°28' and 38°01' S and covers approximately 500,000 hectares. It is a dryland farming area of rolling topography where wheat is cultivated in rotation with natural pastures of around 4 years duration. Recently, other crops such as rape are also being introduced, as well as improved pastures of subterranean clover. In general, the technical level of farming is rather low.

Very little fertilizer, mainly phosphorus, is applied, and the mean yield of wheat does not reach 10 qq/ha, although potential yields are well above 35 qq/ha.

The weather type is cold mediterranean. Winter is colder and summer is shorter than in the central valley of Chile, and frost continues until spring. Rainfall amounts to approximately 1400 mm per year, but there is still a summer dry season of several months. The soil-water regime borders on the xeric limit, and the soil-temperature regime is mesic.

The soils belong to the Dystrandepts subgroup. They are made up of pyroclastic sediments known in Chile as volcanic ash, even though this origin has recently been disputed by Langhor (1971). The soils are very deep, very permeable, and well drained. Despite the rolling topography, there is no topographic sequence of associated soils, and the soils in the area are characterized by their extreme homogeneity. The physical and chemical characteristics were studied by Espinoza (1970). The soils are moderately acid, base saturation is very low, and organic matter content in the A horizon generally runs above 10 percent.

Experimental Method

During the cropping seasons of 1968-1969 and 1969-1970, a network of 37 experiments was carried out on Dystrandepts of the Santa Barbara association. Sites were selected to include several combinations of soils and management factors that were thought to influence yields. The experiments were located adjacent to farmers' crops, and work was done with their collaboration. The same design reported in the section on the central valley was also used in the study, but with different combinations of fertilizer rates, as shown in Table 6.

Site variables were quantified employing the same method described for the characterization of the central valley environment. The analysis of the soil samples did not include conductivity for carbonates because such factors are irrelevant for the Dystrandepts. Extractable aluminum and measurement of the structure of the A horizon, based on the quantification of the percentage of fine granular aggregates, were added as variables.

In most cases, natural grazing had been practiced during the preceding 3 years. In seven cases, however, subterranean clover was the crop grazed. In order to account for this difference, a dummy variable was used, which had zero value for natural grazing and a value of 1 for clover grazing land.

Table 6. Combination of treatments and doses of fertilizers applied in the network of experiments for studying wheat productivity in the Andes piedmont of southern Chile, 1968-1970[1]

	P				
N	0	100	200	300	400
0	*		*		*
75		*		*	
150	*		*		*
225		*		*	
300	*		*		*

[1]Doses are expressed in kg/ha N and kg/ha P_2O_5 added as sodium nitrate and triple superphosphate.

Soil preparation for sowing coincided with the work that the farmer normally carried out, that is, plowing once followed by up to six passes with an offset harrow. The time elapsed between plowing and sowing dates, however, varied from 10 to 90 days. 'Capelle Deprez' variety was sown with a density of 160 kg seeds/ha. The sowing period ranged from about mid-May to early August.

Full weed control was obtained by using a preemergence herbicide, with further applications whenever necessary. Rainfall gauges were installed to record rainfall data at each site. In order to measure soil moisture, Bouyoucous blocks were installed, but due to technical difficulties in reading their measurements, it was not possible to obtain full information regarding water stress days. To avoid this problem, rainfall was quantified between tillering and harvest time and was used as an index for water availability since during the middle of this period there were days with water stress.

The experiment grounds were visited every 10 to 15 days, depending on the growth stage, to collect observation data on crop phenology. Isolated cases of Ophiobolus graminis were noted, although the effect on yields was not quantified.

The yields obtained were expressed in qq/ha at 14 percent moisture.

The same methodology of data reduction, factor selection, and yield function establishment reported in the section on the central valley experiments was also followed in this case.

Results and Discussion

Soil and Management Factor Levels

The mean value and the range in variation of a part of the soil and management factors observed at each site are given in Table 7. Due to the great soil homogeneity, a smaller number of factors was indeed expected to be needed to describe site variations in yields. As soil management factors, only the sowing date and the previous crop, in addition to nitrogen and phosphorus fertilization, were retained. Rainfall distribution was divided into two periods: up to tillering time, where rainfall excess prevails and has a strong leaching effect on soil nutrients, and after tillering, where deficits may occur and yield is supposed to be directly related to the water supply.

Yield and Physical Response to Fertilization

Yields without fertilization ranged from 5.2 to 38.9 qq/ha, and the maximum yield ranged from 28.1 to 64.1 qq/ha. Treatments 150/400 and 225/300 had major mean yields of 45.3 and 44.9 qq/ha, respectively, an increase over the mean check yield of 249 and 242 percent, respectively. These data thus indicate the enormous productivity potential of the area when adequate fertilization is applied.

The adjustment of a second-degree polynomial model in two variables to describe the yield response at each site provided 37 sets of 6 coefficients, which were then checked for their significance. Thirty-six of the experiments provided results adjusting themselves statistically to the proposed model. A significant response to nitrogen was observed in 29 cases and to phosphorus in 27 cases. The interaction coefficient of the combined effect of nitrogen and phosphorus produced a significant result in 23 cases, thus accounting for the

Table 7. Factors included to obtain a general equation of yields for nonirrigated wheat crop on dystrandepts in the Andes piedmont of southern Chile

Soil factor	Symbol	Measurement	Mean	Range
Uncontrolled factors				
Available nitrogen in the soil	n	ppm N	48.3	16.6 - 77.4
Available phosphorus	p	ppm P	5.6	3.2 - 12.3
Available potassium	k	meq/100	1.04	0.52 - 2.00
Organic matter	MO	%	11.05	7.5 - 16.2
A horizon depth	PA	cm	27.0	12 - 56
Granular structure	ST	%	50.5	0 - 100
Soluble aluminum	AL	ppm	340.0	257 - 655
Rainfall between sowing and tillering period	LS	dm	6.4	1.28 - 13.16
Rainfall between tillering and harvest	LC	dm	3.9	0.18 - 8.43
Slope	PD	%	3.0	0 - 15
Controlled factors				
Sowing date	E	days/10	2.6	0.1 - 6.7
Nitrogen fertilization	N	kg N/ha	150	0 - 300
Phosphorus fertilization	P	kg N/ha	200	0 - 400
Previous crop rotation (with or without legumes)	A	without dimension	--	0 - 1

acute fertilizer needs of the wheat crop in such soils.

Establishment and Interpretation of the Yield Function

The selection of factors for the yield function took place according to a procedure similar to the one described in the previous section on the experiments in the central valley. Linear and quadratic terms for the variable were retained, and some interaction terms were proposed through this selection procedure.

After several runs, a yield equation with 17 terms was obtained, the regression coefficients of which are given in Table 8, with their significance level. A coefficient of multiple correlation of 0.8058 was reached, the yield function accounting for 64 percent of the yield variation among experimental plots.

There are eight site factors which together determine the yield level in absence of fertilization. Positive terms include the available soil phosphorus, the organic content of the A horizon and its thickness, the water availability during the last growing stages, and the presence of clover in the rotation. The effect of this latter factor introduced as a dummy variable is important in quantitative terms as it accounts for 899 qq/ha of yield alone. Negative effects are observed, on the other hand, for the late sowing date and a major percentage of fine granular aggregates in the A horizon, the meaning of which remained unexplained.

Moreover, the yield function indicates the extent of the nitrogen response and how it is tempered by the level of soil nitrogen and an excess of winter rainfall favoring fertilizer leaching.

On the other hand, the response to phosphorus fertilization takes into account an interesting interaction with the sowing date. Indeed, the depressive effect of late sowing on yield may be partly compensated by a major application of phosphorus fertilizer. It is also interesting to mention here that the yield function failed to indicate a negative interaction between the level of soil phosphorus and the intensity of the crop response to fertilization, probably because of the narrow range of variation in soil available phosphorus encountered among sites.

Another noticeable feature is depicted in the N x P interaction term. Indeed, while nitrogen and phosphorus fertilization have a strong interaction on yield when wheat follows natural pasture in the rotation, the interaction disappears when wheat is grown after clover, supposedly because of the residual effect that this crop produces through its nitrogen fixation. In that respect, attention is called to the magnitude of the regression coefficients, which are practically equal and of opposite signs.

The yield function application is rather straightforward, as it allows the calculation of potential wheat yield on the Dystrandepts of the Andes piedmont of southern Chile under adequate management. As an example, for soil series Corcovado, known for its high yield potential and characterized by an A horizon of 45 cm thickness and an organic matter content of 14 percent, a yield potential of 60.7 qq/ha was calculated under adequate spring rainfall.

Nevertheless, the function presented failed in one of its aims, that is in establishing fertilizer recommendations based on a phosphorus soil test. In-

Table 8. Regression coefficients for a production function of wheat crop in the Andes piedmont of southern Chile

Variable[1]	Regression coefficient
P	0.4311 *
MO	0.920 *
PF	0.251 **
E	-1.018 *
LC	2.714 **
$(LC)^2$	-0.3502 **
ST	-0.0591 *
A	8.0415 **
N	0.171 **
N x n	-0.000746 *
N x LS	-0.00127 +
$(N)^2$	-0.000358 **
P	0.0777 **
P x E	0.0048 **
$(P)^2$	-0.000164 **
N x P	0.000120 **
N x P x A	-0.000121 **

Constant: -2.129 - R = 0.8058 ** - F = 46.18 **

(**), (*), and (+) significant at the 1, 5, and 10% probability levels, respectively.

[1]The meanings of the symbols are indicated in Table 7.

deed, the sites were not sufficiently contrasting with respect to available phosphorus content (nearly all the values were low, a reflection of the common situation in the area). In similar situations, this is a common mistake we made.

CONCLUDING COMMENTS

In our presentation of these two examples of yield function to describe the wheat productivity within two important ecological environments of Chile, you will have noticed that we tried to emphasize mostly the soils and agronomic implications that lie behind them. We deliberately left aside discussions on such topics as optimization of factor space exploration, choice of statistical models minimizing bias due to lack of fit, and alternative methodologies for factor selection and yield function establishment, which, we feel, will be covered with more competence by other members of this workshop.

Neither do we claim having used the most effective paths in generating yield functions and, indeed, recognize the inherent weakness of the semi-empirical approach used in selecting the factors. But we strongly believe, technical and conceptual difficulties aside, in the usefulness of yield functions for the following purposes:

1. Expressing crop yield as a function of applied fertilizer variables, productivity factors affecting yield and fertilizer response and interaction variables, thus permitting accurate decisions with respect to the optimization of controlled production factors by the farmers.
2. Accurately describing the crop growth environment, thus providing the background information needed for the transfer of knowledge and experience for an improved utilization of world soil resources.
3. Objectively rating soil productivity, a major tool in land evaluation for agricultural land use planning.
4. Promoting and guiding research in soil fertility and crop productivity toward real problems, thanks to the better description of the crop environment they provide.

Up to now and to the best of our knowledge, the application of yield functions, already published, is restricted to the ecological environment in which they were generated, and the latter is generally only loosely described. A system for the complete and quantitative definition of the boundaries of such environments should thus be searched if we want to widen the applicability of the yield functions to ecologically similar areas. The collection of the quantitative data, the starting point of the whole exercise, is undoubtedly also the most important and calls for the standardization of field and management techniques, not only to reduce experimental error but also to ensure the compatibility and completeness of the data. It is felt that research projects like those under discussion here should substantially contribute to that goal.

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No authorship is claimed for this research, as the whole staff of both departments participated actively in the several phases of its development.

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Design and Analysis of Soil Fertility Experiments in the Tropics

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Formulation of a soil fertility problem with a general objective of increasing food production begins with a definition of the population. The population includes those units of cultivated land to which fertility recommendations are to be made. The units in the population can be defined in terms of acres, blocks, or in natural units of cultivated land. These units usually are not delineated, but a geographical boundary can be drawn to define the enclosed units. Not all the units within the defined geographical area need to be included in the population. In fact, the units within the population exist by definition and need not be contiguous. Therefore, a soil family or phase of a soil family can be defined as a population even though units in the population might be on several continents. The soil family can then be a working definition of a population in soil fertility research. In the practice of making recommendations, however, a population is usually defined as a geographical area with well-defined rules for including or not including units within the overall boundary. These rules can be based on soil classification information, for example, closely associated families.

Clearly, experiments cannot be done on all units within the population, and, historically, soil fertility workers have used Experiment Station plots. The practice is to sample or select plots from the accessible subpopulation of Station plots and to make recommendations to the entire population. Unfortunately, the Experiment Station plots sometimes are selected for special reasons.

Ideally, the areas chosen for experimentation are randomly selected from the units in the population. In the projects, random sampling will not be feasible primarily because a limited number of countries can be involved. Consequently, only part of the population is, in reality, available for selection of plots. It is implicitly assumed that inferences made to those units having zero probability of being selected for the experiments will not be affected.

The major hypothesis of the projects is that information from one set of experiments may be transferred to sites within the same soil family. The vehicle for transfer is a model estimated from the experimental data. For example, if applied phosphorus (P) is a factor of interest and experiments with one level are carried out, the calculated average response to the applied P is then used as a predictor for other sites in the same soil family. Usually more than one level is used and the estimated model is

$$\hat{Y} = b_0 + b_1P + b_2P^2 \qquad \ldots(1)$$

This estimated quadratic polynomial, where P is the level of applied P, is only one possibility for the transfer model. The square root is commonly used in fertility experimentation. Other possibilities are given in papers presented at the workshop by R. L. Anderson and B. G. Capō.

A major difficulty arises in using an estimated model for predicting the potential response to applied P at another location. Some factors known to influence yield, such as date of planting, can be held constant so that the estimated transfer function will perform well when used at another location, assuming the same planting date. Other factors influencing yield, however, cannot be controlled. Soil phosphorus will vary from one site to another within the same soil family due to past management of the surface horizon. Most climatic variables will also vary. Certain management variables, but probably not all, can be held constant with sufficient resources. The effects of a variable which is specific to a site, and therefore called a site variable, is shown using soil phosphorus, p, as an example. Suppose two sites are used and the effect of the site variable is due only to the main effect. Then,

$$\hat{Y} = b_0 + b_1P + b_2P^2 + b_3p \qquad \ldots(2)$$

The estimated coefficient, b_3, can be estimated from soil phosphorus information at the two sites. In general, one numerical value will be available from each site for each site variable, and, for each additional site parameter added to the model, an additional site has to be added in order to estimate the parameters of the model regardless of the number of plots at each site.

Suppose the measured soil phosphorus at the two sites is coded +1 and -1 for convenience. Then,

$$\hat{Y} = (b_0 + b_3) + b_1P + b_2P^2 \quad \text{for site 1} \qquad \ldots(3a)$$

and

$$\hat{Y} = (b_0 - b_3) + b_1P + b_2P^2 \quad \text{for site 2} \qquad \ldots(3b)$$

Note that the curve representing the response to the applied phosphorus is the same for the two sites but the curves have different intercepts. It then follows that the economic optimum, found by equating $b_1 + 2b_2P$, the derivative of Y with respect to X, to the price-cost ratio is not affected by the soil phosphorus site variable.

However, the situation changes if the site variable interacts with the controlled variable; for example, the difference between two levels of applied phosphorus depends on the level of soil phosphorus. The transfer model is

$$\hat{Y} = b_0 + b_1P + b_2P^2 + b_3p + b_4pP \qquad \ldots(4)$$

and

$$\frac{\partial\hat{Y}}{\partial P} = (b_1 + b_4p) + 2b_2P \qquad \ldots(5)$$

Now the economic optimum does depend on the level of soil phosphorus.

The response equation can also be written as

$$\hat{Y} = b_0 + (b_1 + b_4 p)P + b_2 P^2 + b_3 p \qquad \ldots(6)$$

showing that the estimated coefficient for the linear effect of P depends on the amount of soil phosphorus; that is, the b_1 in the equation

$$\hat{Y} = b_0 + b_1 P + b_2 P^2 \qquad \ldots(7)$$

calculated from data at each site varies from one site to another. Later a method is described for testing the hypothesis that the linear coefficients are the same. If so, the response model, estimated from the data at all the sites, can be used for testing the transfer hypothesis. Invariably, however, the hypothesis of equal linear coefficients cannot be accepted. Now the transfer hypothesis has to be tested conditional upon the level of soil phosphorus. From a series of experiments, the estimated response model, including the coefficients b_3 and b_4, can be calculated. Then yield for additional (new) sites can be predicted using the estimated response model based on the series of experiments and p values from the new sites. Positive evidence for the transfer hypothesis is given by "good" agreement between the predicted yields and the actual yields from the new sites.

One site variable, soil phosphorus, has been introduced. A large number of potential site variables exist and the approach described with only one site variable appears to be overly simplified. Indeed, soil experimenters are aware of a large number of interactions. The relative importance of these interactions, however, when predicting yields for new sites could be overestimated. (Unfortunately, this statement is not documented well in the literature but it is the feeling of some soil fertility experimenters who have done extensive field experimentation. C. B. McCants also made this comment during the workshop.) It is also interesting to note that in the combined analysis of the Laird data, only drought had an important interaction with applied nitrogen when the prediction sum of squares was used in place of the residual sum of squares as a criterion for variable selection.

Using farmers' fields is not a new idea, but the practice of planning a series of experiments on farmers' fields to obtain basic information on soil fertility relationships has been limited and sporadic, and sometimes it gave disappointing results. In the past, limited resources of trained experimentalists, finances, and equipment have narrowed the soil fertility specialist's experimentation. Furthermore, procedures for measuring variables reflecting the productivity status of a given environment--for example, a measurement of drought, which is associated with yield--have not been available. Also data analysis and interpretation have been difficult when combining several sets of data. Fortunately, many of these limitations are now removed, and with the world population pressures for reducing the time period between initiation of research and recommendations, strategy has to be developed for going directly to a relatively large number of experiments in a single stage of experimentation (as compared with the past) with perhaps a year or two of preliminary experiments.

The proposed strategy includes the selection of experimental sites over

several years, determination of treatment and experimental designs, collection of both plot and site data, analysis of the data, and evaluation of the transfer hypothesis.

SELECTION OF EXPERIMENTAL SITES

If the units in the population are blocks of land of specified size, then, ideally, a random sample of blocks is selected and the experiments are carried out within the selected blocks. If the population is a geographically defined area, the randomization might include certain restrictions to insure a uniform distribution of experimental sites. Certain areas within the defined population might be more important than others, and the sampling would be done in proportion to the weights of importance assigned to the various areas. Within these restrictions, the basic procedure remains the same; namely, that random sampling procedures are used in the selection of experimental sites. In practice, the goal of random sampling without modification cannot be reached. A master list of all units in the population usually cannot be constructed easily. A substitute procedure is the use of a grid system across the area and a random sample of intersection points selected. For each selected point, for example, an experiment can be established in the grid north and east of the intersection point. Various schemes can be devised for selecting the particular site within the selected grids, and, again, compromises will have to be made for practical considerations but with the retention the spirit of random sampling.

The number of sites and replications at each site have to be determined. For reasons more fully developed in a later section, the desired number of sites is probably larger than the resources available. Briefly, certain soil variables and most environmental and management variables are measurable only at a site level. For example, even though multiple measurements are made on drought effects, and careful rainfall and soil moisture records are kept, a single valued index is calculated for an individual site for a given year. For response data and certain soil variables, however, observations are measured each year on all plots at an individual site. For each site variable used in the combined analysis of data, it is important that a range of values for each site variable exist. If the range does not exist in the population, then that variable should not be used. Additional restrictions on the site-selecting procedure are sometimes needed to insure a sufficient range in the sample for each of the site variables. The site variables are used in the analysis to interpret the expected interaction between sites and treatments. The number of locations has to equal at least the number of site variables, and, hopefully, the number of locations will be much larger than the number of site variables to allow for testing the adequacy of the site variables in explaining the treatment by location interaction. Twenty locations per year would not be a large number for many soil fertility experiments. With a relatively large number of locations per year, the number of replications per location can be minimized unless the analysis of data at each site is important. Otherwise, two replications per location is sufficient for detection of gross plot errors, for obtaining standard errors and coefficients of variation at each location, and for providing sufficient degrees of freedom for the pooled error term in the combined analysis of the data.

Ideally, sufficient years are necessary so that a range and distribution of climatic conditions covered during the experimental stage approximates the long-term range and distribution. Again, compromise with resources has to be made. In any case, an analysis and interpretation is made after each year of

experimentation and predictions made for the forthcoming year. With this type of sequential approach, the magnitude of the prediction errors can be considered each year and, together with the range of climatic conditions experienced, a decision can be made concerning the additional number of years needed. As a general statement, a minimum of 3 or 4 years seems necessary.

DETERMINATION OF TREATMENT AND EXPERIMENTAL DESIGNS

The treatments--combinations of factors known to be most important in increasing yields--are inputs under the control of farmers. The number of factors is usually held to two or three and frequently are major nutrients or management factors, such as date of planting. Management factors can be difficult to define and handle in a series of experiments over a large geographical area. These combinations of controllable factors usually consist of complete or incomplete factorials. Response surface designs can be considered as special cases of incomplete factorials. The particular set of combinations used in a series of experiments depend on several considerations. A practical need exists for plotting the data at each site soon after the yields are available and for preliminary examination of the data before any combined analysis is attempted. The treatment combinations also depend on variance and bias of various statistical estimators, for example, regression coefficients and yield predictions. A more detailed discussion of treatment design is being given by R. J. Laird at this workshop.

The experimental design can usually be a randomized complete block design. The additional cost of having blocks instead of a completely randomized design is minimal, while the experimental error reduction could be considerable. Trying to improve the precision of the individual experiments through experimental design is a secondary consideration in a series of experiments where the focus is the analysis and interpretation of data combined over the environments. Complications with unexpected happenings, such as a missing plot, usually would preclude use of incomplete block designs.

COLLECTION OF PLOT AND SITE DATA

Soil fertility experimentation has a history of collecting plot data but experience in measuring site variables is much less extensive. Site variables are factors believed to affect crop yields but cannot be controlled at a constant level across the experiments. Neither is it desired to control these site variables at a constant level, since the effect of site variables on the relationship between yield and the controlled factors is one of the major reasons for the series of experiments. Recently, extensive work has been done measuring climatic variables under field conditions. Equipment is becoming available and numerical work on correlations between plant symptoms in the field, as indicators of drought and disease, and yield is now receiving increased attention.

ANALYSIS OF DATA

The data include one or more response variables measured from the experimental plots where a particular combination of controlled fertility or management factors had been applied. In addition, data are collected on a number of uncontrolled site factors, including soil, climatic, and management variables.

For a given crop, yield is a function of soil, environmental, and management factors. Conceptually, this function can be written as a statistical model, but several problems arise. There is no general agreement on the true functional form expressing the relationship between yield and an input variable. Polynomials and various nonlinear (in the parameters) functional forms have been tested over the years with no clear-cut indication that one form is best overall. Consequently, at least for convenience, a linear functional form, such as the quadratic polynomial or the square root model, is more generally chosen. Discontinuous models could also be considered. A second problem is a subject matter problem in that all the factors for each of the soil, climatic, and management classes are not known. If all the variables for each class could be listed from basic subject matter considerations, it would not be known if all are sufficiently important to be included in the functional model. Or if a given variable is important in general, it might not be important in the defined population for several reasons:

1. A sufficient range of values for the variable might not exist in the population;
2. A sufficient range of values exists but most of the range is beyond the "critical level" and, consequently, variability in yield cannot be explained by that variable;
3. The variable cannot be measured sufficiently well under field conditions, at least relative to the magnitude of the effect;
4. The variable is important but is supressed by another variable especially within a given year;
5. The variable has an important interaction effect with another input variable but, in the sample of sites, low values of one variable are associated with low values of the other variable or high with high, and the low-high and high-low combinations do not appear in the data.

Consequently, in the model-building problem, the data are used first for making tentative decisions on which of the measured variables should be included and on their functional form, and then the parameters of the model are estimated with the same data.

The first step in the data analysis should be an analysis of the individual experiments. Suppose a two-factor fertility experiment with a partial factorial of 13 nitrogen and phosphorus treatment combinations in a randomized complete block design with two replications was used at each location. Analysis of variance calculations would give the usual sum of squares for blocks, treatments, and experimental error. The regression of yield on nitrogen and phosphorus, including the intercept term, the linear and quadratic effects, and the linear-by-linear interaction will give a fitted model sum of squares. The difference between the treatment sum of squares and the fitted model sum of squares is the lack of fit, which can be tested against the experimental error mean square for adequacy of the fitted model. Other checks include examination of the signs and magnitudes of the estimated coefficients, and the magnitude of the calculated coefficient of variation.

The regression model could be fitted using the yield data from all the experiments. Experience has shown that the overall model with applied nitrogen and phosphorus terms will give a poor fit, using R^2 as a criterion for goodness of the fitted model. This is not surprising since the uncontrolled variables are affecting the response to fertilizer at each location differentially. For example, the levels of soil nitrogen and phosphorus can be expected to affect the response to the applied quantities. Consequently, a major objective in the interpretation of data from a series of experiments is the determination of a general yield model or equation with the inclusion of

the uncontrolled variables. The functional relationship between yield and the applied fertilizer variables as influenced by the site variables can be calculated and used in estimating fertilizer needs for specific conditions.

Historically, the general yield equation has been estimated by least squares using linear, quadratic, and cross-product terms of the measured independent variables. Again, the results usually are not satisfactory; the sign or magnitude of the estimated coefficients will not be consistent with known information, and an unexpectedly high proportion of the estimated coefficients will be smaller than their estimated standard errors. Even worse will be the performance of these estimated equations when used for predictions with different but similar sets of data.

The number of terms in the estimated equation is then usually reduced using a sequential procedure where variables are selected if the entering variable statistically lowers the residual sum of squares. Improvements through the stepwise regression procedure can be noticed with the selected reduced models, but most of the basic problems remain and there occurs the additional problem of certain supposedly important variables not appearing in the selected reduced model.

It is known that introducing an additional variable into a yield equation cannot decrease the variance of a predicted observation; in fact, the variance will be increased in practical situations. However, failure to include a variable may result in a biased predicted observation. An ideal procedure would select variables that are important in reducing bias without selecting those that would unnecessarily add to the variance of a predicted value.

A new procedure has been developed for selecting predictor variables from a large number of potential ones. The procedure uses as a criterion the prediction sum of squares (PRESS) defined as

$$\sum_{i=1}^{n} (Y_i - \hat{Y}_{(i)})^2 \qquad \ldots(8)$$

that is, the sum of squares between Y_i, the observed response, and $\hat{Y}_{(i)}$, the predicted response, using a prediction equation where coefficients have been estimated excluding the ith observation. The squared deviations are then added over the n observations. A sequential procedure is used to determine the order that variables will enter the yield equation. The first variable will be the one with the smallest value of PRESS. It appears that for each of the p potential predictor variables, n regression equations would be calculated, the omitted observation predicted, and the n-squared deviations added. The pn regressions are not calculated in practice due to an algorithm developed by Allen (1971). After the first predictor variable is selected, the procedure is repeated among the remaining p-1 potential variables to find the variable that will give the smallest value of PRESS at the second stage.

One problem with using stepwise regression is that the criterion, the residual sum of squares, is reduced with each additional variable and a completely arbitrary decision is made for the cut-off point. In practice, the entering variable is usually tested at a significance level of .05 or .10. PRESS has a distinct advantage in that the criterion, the prediction sum of squares, decreases with entering variables to a minimum and then increases. The cut-off point can then be at the minimum or perhaps before, depending on the nature of the decreasing prediction sum of squares function. The main advantage of PRESS is that it should give better predictions of future responses

for new combinations of the independent variable values. An example of the use of the PRESS criterion is given by Cady and Allen (1972).

The problem encountered in the described variable selection procedures can be traced in a general sense to multicollinearity resulting from existing correlations among the uncontrolled variables and induced correlations from including quadratic and cross-product terms. This problem can be avoided in part by preliminary tests on each of the uncontrolled factors before inclusion into a general yield equation. Returning to the individual site analyses, it can be seen that the estimated regression coefficients in the function between yield and the applied fertility variables are summary statistics or condensations of the original plot data. These calculated random variables can be used in preliminary tests of significance for information on the inclusion of certain site variables in the overall yield equation as main effects or as interactions with the applied fertility variables. Details of this approach will now be given.

At each site, a model relating yield to the applied fertility variables will be fitted by least squares. For example, if the treatments were combinations of applied nitrogen and phosphorus and a quadratic polynomial is fitted to the yields, the fitted model for site t would be

$$\hat{Y}_t = b_{0t} + b_{1t}N + b_{2t}P + b_{3t}N^2 + b_{4t}P^2 + b_{5t}NP \qquad \ldots(9)$$

The six estimated regression coefficients attempt to explain the non-random variability at site t. If there were no other factors affecting yield, the same response would be observed at each site. For example, if β_{0t}, the parameter, is the same for all sites, that is, $\beta_{0t} = \beta_0$ for all values of t, t = 1, 2, . . . s sites, then all the b_{0t} are estimating the same parameter and all the uncontrolled factors have no effect on the mean yield at site t, that is, the main effect of all the uncontrolled variables is zero. This hypothesis can be tested with an F test:

$$F = \frac{\sum_{t=1}^{s} (b_{0t} - \bar{b}_0)^2 / s - 1}{c_{00}s^2} \qquad \ldots(10)$$

where $\bar{b}_0$ is the mean of the b_{0t}, s^2 is the estimated experimental error from pooling the individual site experimental errors, and c_{00} is the first diagonal element from the inverse of the matrix of sum of squares and cross products formed from the applied fertility variables. If the same treatment design is used at each site, that is, the same treatment combinations, then the inverse will be the same and c_{00} is a constant.

The same argument holds for all β_{it}, i = 0, 2, . . . 5. For example, if all the b_1 are estimating a single β_1, the linear effect of applied nitrogen is the same at all sites and no interaction exists between applied nitrogen (linear) and the uncontrolled site variables.

F tests for the homogeneity of the mean and linear terms will usually be significant, and the next step is to identify those measured site or uncontrolled variables associated with the significant F values. The b_{it} values will now be used as the dependent variable. The correlations between b_{it} and the measured site variables and basic soil fertility knowledge can be used to

indicate those site variables that undoubtedly are important. At this stage, each of the b_{it}, for example the b_{0t}, values can be regressed on the site variables,

$$b_{0t} = \alpha_{00} + \alpha_{01} X_{1t} + \ldots + \alpha_{0p} X_{pt} + e_{0t} \qquad \ldots(11)$$

where the α_{0j}, j = 0, 1, . . . p, are the parameters relating the estimated site means to the p uncontrolled variables and e_{0t} is a random error component.

Estimating the α_{0j} has some of the same problems as previously mentioned, namely that of multicollinearity among the X. Two kinds of X can usually be identified:

1. Factors with ranges sufficient to almost always affect the regression coefficients, and
2. Factors with ranges that may or may not affect the regression coefficients depending on the sampling in the given series of experiments.

Factors of type 1 should definitely remain in the model and the parameters should be estimated by least squares. With factors of type 2, a criterion such as the residual sum of squares (or a function of the residual sum of squares such as R^2 or the C_p statistic) or the prediction sum of squares (PRESS) should be used for a decision on inclusion or exclusion. For the included variables, the least squares procedure can be used for estimation, or a biased estimation procedure such as ridge regression should be considered.

These multiple regressions are run for each of the coefficients where a significant F was found in an earlier step and the regressions are then substituted for the b_i in the original equation relating yield to the applied fertility variables to give a general yield equation.

EVALUATION OF THE TRANSFER HYPOTHESIS

Two data analysis procedures were outlined in the previous sections for selecting the variables to be included in a general yield equation and for estimating their parameters. The estimated final yield equation only has value if the estimated parameters can be used for new sets of input variable values (new values of the selected independent variables) which are similar to those in finding the estimated equation.

As stated in the introduction, the estimated response function for the applied nutrients can be transferred to another location if all the other factors are at the same level. Within the same soil family, certain soil properties and long-term climatic factors are the same. Consequently, information from one country hopefully could be transferred, at least qualitatively, to another country. The transfer vehicle, however, is a model estimated from yield data. Yields depend not only on the applied treatments but also on factors not constant within a soil family, for example, management variables. In addition, the variation among sites within a country, for a variable supposedly constant within a soil family, can be important quantitatively, and annual variation in climatic variables can be relatively large. These important site variables must be included in a general yield equation or transfer model. A procedure for evaluating the transfer hypothesis is now formulated.

Let $Y_{ijk\ell}$ be the yield from the ith country, the jth site within the country, the kth treatment or controlled variable, and the ℓth replication. For convenience, the following discussion will include two countries, i = 1,

2, s sites within each of the two countries, j = 1, 2, ..., s, and the same treatment design at each site, k = 1, 2, ..., t. Treatment means will be used in the analysis and the fourth subscript deleted. Also for convenience, applied phosphorus will be the only controlled variable and soil phosphorus the only site variable.

From the Y_{11k}, Y_{12k}, ..., Y_{1sk} means within country one, an estimated model can be calculated as

$$\hat{Y}_1 = a_1 + b_1P + c_1P^2 + d_1p + e_1Pp \qquad \ldots(12)$$

where a_1, b_1, c_1, d_1, and e_1 are the partial regression coefficients estimated from country one data. Similarly, the estimated model for country two is

$$\hat{Y}_2 = a_2 + b_2P + c_2P^2 + d_2p + e_2Pp \qquad \ldots(13)$$

Note that the values of P are the t applied phosphorus levels that are constant at all sites and the values of p are the s soil phosphorus levels within each country--that is, one value of p exists for each site, as measured from a composite soil sample. Also note that both estimated models can be written as

$$\hat{Y}_i = (a_i + d_ip) + (b_i + e_ip)P + c_iP^2 \qquad \ldots(14)$$

By knowing the numerical values of the estimated coefficients and assuming that no other factors influence yield, this model can hopefully be transferred to another site in the same or different country and do equally well in predicting yield using the measured soil phosphorus level at the new site.

Additional notation is needed. Let $\hat{Y}_{i(i)}$ be the predicted mean yields when the transfer model estimated from one country is used to predict yields for sites in the same country, for example, $\hat{Y}_{1(1)}$ and $\hat{Y}_{2(2)}$. $\hat{Y}_{i(i')}$, where $i \neq i'$, denotes the predicted mean yields using a transfer model with the regression coefficients estimated from one country predicting yields for the other country using the soil phosphorus values for the latter country, for example, $\hat{Y}_{1(2)}$ and $\hat{Y}_{2(1)}$. In all four cases, t treatment means are predicted for each site. The values of P will vary, depending on the level of the controlled factor, while the value of p will be constant for a given site but vary from site to site.

If the estimated model can be transferred to the other country, then intuitively the $\hat{Y}_{1(2)}$ and $\hat{Y}_{2(2)}$ prediction models should perform equally well. Similarly, $\hat{Y}_{1(1)}$ and $\hat{Y}_{2(1)}$ should do equally well. A measure of discrepancy is the squared deviation between the observed mean yield and the predicted mean yield. These squared deviations can be summed over the treatments at a site and over the sites within a country. Following this reasoning, the expected value of the following ratio would be one if the transfer models were doing equally well predicting within the country as across countries.

$$\frac{\sum_{jk}\sum(Y_{1jk} - \hat{Y}_{2(1)})^2 + \sum_{jk}\sum(Y_{2jk} - \hat{Y}_{1(2)})^2}{\sum_{jk}\sum(Y_{1jk} - \hat{Y}_{1(1)})^2 + \sum_{jk}\sum(Y_{2jk} - \hat{Y}_{2(2)})^2} \qquad \ldots(15)$$

If the ratio is much larger than 1, the transfer hypothesis would have to be rejected. If near 1, the transfer hypothesis is supported in the sense that prediction is no worse going across countries than it is within countries. A ratio value of 1 does not necessarily support the hypothesis that response information can be transferred from one site to another within a country. The theoretical properties of the ratio are not known so that a test statistic could be used in the evaluation. Additional work is needed in this area of evaluation of the transfer hypothesis.

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A Family of Models and Experimental Designs for Evaluating Response to Fertilizer Nutrients When the True Model Is Not Known

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INTRODUCTION

As indicated in a previous paper (1), quadratic models are often used to approximate the response patterns of crops to fertilizer. These models are easily fitted and are well adjusted to the fractional factorial designs used in response surface exploration. Estimates of optimal fertilizer rates are readily obtained by standard techniques (4), and, in addition, exact confidence limits can be computed for the optimal combination of fertilizer nutrient rates.

We have observed that for many crop-soil conditions, particularly in developing nations, the underlying response model is not well defined; hence, the experimental design must provide for some information by which to evaluate the response model itself. In many cases, some environmental or management factor may impose a ceiling on the yield; in this case, the top of the true response surface often has the appearance of a plateau. Boyd (3), who conducted studies involving many rates of fertilizer for the express purpose of characterizing the form of the single nutrient response curves for a number of crops, reported that plateaus were reached at low or intermediate rates of fertilizer for a number of different crop-nutrient combinations. Yields of some small grains and potatoes even decreased with large applications of nitrogen. In the case of small grains, lodging may have caused the decline. This latter type of response pattern for small grains has also been observed for rice at the International Rice Research Institute, Los Baños, the Philippines (7).

In (1) we stressed the problem of estimating residual nutrient levels when quadratic, square root, or exponential response functions are used for experimental situations with yield plateaus; we mentioned similar problems in estimating the optimal amount of nutrient to be added and considered the use of a quadratic-plateau model. This current paper discusses some new models that have been developed to estimate the optimal rates of fertilizer under experi-

mental space restrictions. The problem discussed in this paper is important because of the spiralling price of fertilizer. Procedures that tend to produce upward biases in estimated optimal fertilizer rates cannot be recommended, particularly when farmers in the developing nations have great difficulty in obtaining capital to purchase fertilizers. Also, overfertilization, especially of nitrogen, may have a deleterious effect upon the environment.

USE OF QUADRATIC AND SQUARE ROOT MODELS FOR SINGLE NUTRIENT EXPERIMENTS

The bias problem is illustrated by three sets of data for single nutrient experiments. The first set consists of two nitrogen-sugarcane experiments in Thailand (Table 1).

For each experiment, P and K were applied at respective rates of 12, 24, and 36 kg/rai. A quadratic prediction function, $\hat{Y} = b_0 + b_1 N - b_{11}N^2$ was fitted by least squares to each set, producing the values of the b's. The maximum value of N is $N_0 = b_1/2b_{11}$. If the ratio of the cost of N to the price of sugarcane is r, then the economic optimal N is $N_e = (b_1 - r)/2b_{11}$. For the experiments, r = .440/.0132 = 33.33. Values of N_e are also presented in Table 1. For each experiment there is an apparent upward bias in both N_0 and N_e because the yields actually declined for N > 12.

We consider both sites to show plateau patterns. A partial explanation for the quadratic bias in plateau response situations was reported in (1). If a plateau is reached at low or intermediate levels of the added nutrient, b_1 and b_{11} will be biased downward, but the percentage bias of b_{11} is greater than that of b_1; hence, N_0 and N_e will be biased upward. The biases in regression coefficients are pronounced when the nutrient being studied is deficient initially and, therefore, the response to the first increment of fertilizer is marked. The parabolic curve is not flexible enough to accommodate the sharp initial rise and subsequent flattening. The top of the arc is to the right of the point where the response to fertilizer ceases. It is also higher than any of the observed yields unless there is decreasing yield at the high rates.

The other two sets of data (Tables 2 and 3) exhibit the plateau effect of nitrogen-corn experiments in the United States. The North Carolina experiments

Table 1. Yields (kg/rai) of sugarcane, regression coefficients, and estimated nitrogen applications, Thailand[a]

Place	Applied N(kg/rai)				Regression coefficients			Estimated N applications	
	0	12	24	36	b_0	b_1	b_{11}	N_0	N_e
Petburi	5,430	8,028	7,459	7,274	5,630	213.2	4.79	22.3	18.8
Supanburi	10,654	12,414	11,566	11,887	10,843	113.7	2.50	22.7	16.1

[a]Data provided by Sanga Duangratana, Statistician, Planning Division, Agriculture Department, Ministry of Agriculture, Bangkok, Thailand.

Table 2. North Carolina average corn yields and estimated economic optimal values of N using quadratic (Q), square root (S), and linear-plateau (P) models[a]

	Location										
N	553	554	555	559	650	651	652	653	656	657	660
0	33.8	11.7	25.1	24.4	46.6	41.7	41.4	31.2	56.9	29.1	41.4
62.5	77.8	39.7	66.2	67.1	89.6	71.1	78.4	67.1	103.0	72.2	78.8
125.0	92.5	40.1	89.4	72.9	110.9	83.6	104.2	76.6	114.8	96.7	100.7
187.5	83.2	35.4	94.6	75.9	110.0	86.4	105.9	78.0	118.3	101.3	105.7
250.0	94.8	39.8	87.2	70.1	111.1	84.1	106.7	73.3	114.9	101.6	102.9
$R^2(Q)$	.951	.644	.999	.912	.968	.985	.984	.955	.952	.990	.997
$R^2(S)$	.991	.912	.944	.995	.968	.977	.948	.989	.995	.969	.958
$R^2(P_4)$	.998	.955	.987	.986	.999	.995	.998	.989	.995	.993	.992
$N_{e1}(Q)$	176	146	175	159	176	172	185	161	170	188	182
$N_{e1}(S)$	196	98	227	131	213	190	315	140	169	324	285
$N_{e2}(Q)$	151	96	155	133	154	138	161	133	147	165	158
$N_{e2}(S)$	114	54	131	84	124	93	154	83	105	165	142
$N_e(P_4)$	85	63	99	72	93	91	108	79	81	103	104

N	661	751	752	753	754	556	658	654	655	659	662
0	28.8	51.6	27.8	19.6	52.5	45.6	64.1	22.6	55.2	32.1	42.2
62.5	74.9	95.4	70.4	67.1	86.2	78.8	86.4	62.1	90.6	83.7	76.6
125.0	99.6	130.8	81.9	95.9	93.8	83.6	92.4	77.7	104.0	107.5	97.1
187.5	101.4	134.7	86.9	102.8	92.0	89.1	97.0	84.8	111.7	114.9	104.8
250.0	104.6	138.5	82.4	95.8	90.6	85.0	92.8	81.8	112.4	116.2	100.7
$R^2(Q)$	.977	.985	.955	.999	.912	.924	.975	.988	.982	.986	.999
$R^2(S)$	.973	.950	.992	.945	.993	.987	.981	.980	.993	.986	.954
$R^2(P_4)$	.995	.992	.989	.945	.993	(.975)	(.967)	(.982)	(.965)	(.984)	(.980)
$N_{e1}(Q)$	187	198	170	181	156	165	164	181	192	191	185
$N_{e1}(S)$	295	542	172	277	126	151	154	241	330	340	327
$N_{e2}(Q)$	165	177	147	163	125	131	117	155	160	172	159
$N_{e2}(S)$	160	243	106	162	73	81	64	126	138	184	147
$N_e(P_4)$	99	116	82	104	74	(76)	(86)	(93)	(96)	(98)	(106)

[a]Yields in bu/acre; N in lb/acre. No. of observations = 8,16,20,16,12 for successive N-levels. See text for definition of R^2. N_{e1} = economic optimum for r = 1/30: N_{e2} for r = .12; N_e for both. P_4 refers to Model IV; parentheses refer to experiments for which Models VI and VII are best. The best fits for these experiments were as follows:

Experiment	Model	R^2	N_{e1}	N_{e2}
556	VI	.989	188	76
654	VII	.996	147	147
655	VII	.999	162	162
658	VI	.976	188	86
659	VII	.999	146	146
662	VII	.992	143	143

Model III was used for 554. Standard errors for successive N-means at each location: 3.40; 2.41; 2.15; 2.41; 2.78.

Table 3. Tennessee average corn yields and estimated economic optimal values of N using quadratic (Q), square root (S), and linear-plateau (P) models[a]

	Knoxville location					Jackson location				
N	1962	1963	1964	1965	1966	1962	1963	1964	1965	1966
0	44.6	45.1	60.9	59.4	63.0	46.5	29.3	28.8	25.8	23.4
67	73.0	73.2	75.9	67.4	61.3	59.0	55.2	37.6	47.6	45.2
134	75.2	89.3	83.7	69.6	63.4	71.9	77.3	55.2	60.5	53.3
201	83.3	91.2	84.3	62.9	59.4	73.1	88.0	66.8	70.2	61.3
268	78.4	91.4	81.8	67.0	57.8	74.5	89.4	67.0	68.0	57.6
335	80.9	88.0	84.5	61.2	58.3	75.5	87.0	67.8	73.0	59.6
$R^2(Q)$	.895	.977	.922	.561	--	.977	.988	.969	.982	.966
$R^2(S)$	.976	.972	.968	.710	--	.955	.954	--	.977	.977
$R^2(P)$	.986	.995	.989	.403	--	.996	.998	.991	.991	.993
	P-Model									
	VI	IV	IV	III	I	IV	IV	III	VI	VI
$N_e(Q)$	218	219	209	118	0	238	250	284	260	230
$N_e(S)$	189	217	170	60	0	349	568	---	595	261
$N_e(P)$	201	107	101	67	0	147	162	201	201	201

[a]Yields in quintal/ha; N in kg/ha. Economic optimal rates (N_e) based on R = 0.0244 per kg (1.635 for 67 kg). Square root model could not be used for J-64. Yields are averages of nine observations; approximate standard error of each average is 1.7.

were conducted on Norfolk soil, using an 18-treatment, central composite response surface design for three factors (N, P, K); the 22 experiments considered in Table 2 had drought-free soils and responded only to N. Descriptions of sites, experimental procedures, and yield data are reported in (1) and (2). Estimates of N_e were obtained for two vastly different values of r and for three models: quadratic (described above); square root (N is replaced by $\sqrt{N}$ in the quadratic); and linear-plateau (to be described later). The proportion of the treatment sum of squares attributed to regression (R^2) was calculated for each experiment and model. For many experiments, the values of N_e for the quadratic and square root models appear high, especially when one compares N_e with an estimate based on a careful comparison of the mean yields and their standard errors. For nine locations with small r and the square root model, the estimate of N_e is outside the range of applied N.

The Tennessee data (Table 3) are taken from experiments of Engelstad and Parks (5), conducted for 5 years at two locations (near Knoxville and Jackson). For the Knoxville data, the quadratic model seemed to overestimate N_e for 1963-1965 and the square root model for 1963-1964. For the Jackson data, the square root model could not be used in 1964 and vastly overestimated N_e for 1962, 1963, and 1965; the quadratic model also seemed to overestimate N_e for 1962-1965.

DEVELOPMENT OF THE LINEAR-PLATEAU FAMILY OF SINGLE NUTRIENT MODELS

After it became apparent that the calculated optimal rates obtained by fitting the quadratic and square root models to these three sets of data generally were biased upward, a new model that would mitigate these biases was sought. The analysis of such a model might:

1. lead to reasonably accurate estimates of the optimal treatments;
2. produce a satisfactory goodness of fit to the data; and
3. be amenable to easy calculation.

The latter condition is included because the resulting model would be used in developing nations where computing equipment is often not very sophisticated, if it exists at all. The spline models (6, 9) were rejected because they require considerable calculation, and our data did not have enough levels in the region of the join points.

It was deemed impossible to use a single continuous model that would apply to and fit all response situations and produce unbiased estimates of optimal rates. Instead, we have developed a system of models belonging to a "linear-plateau family," which generally involve intersecting lines rather than a continuous curve. The fertilizer response data are used to estimate the parameters of each of the models of the family, to test the significance of these estimates, and to decide which model of the family provides the best fit. The name "linear-plateau" implies a region of linear response (with possibly more than one slope) and a plateau.

For five nutrient levels, seven different models are diagrammed in Figure 1. A brief description of each follows.

I: Plateau only (no response to added nutrient).

II: Single sloping line.

III_3: Single sloping line intersecting with a plateau at $X = 3 (b_1 > 0)$. Similar models are III_2 (intersection at $X = 2$) and III_1 (intersection at $X = 1$).

IV_3[1]: Single sloping line intersecting with a plateau between $X = 3$ and $4 (b_1 > b_3 > 0)$ or two sloping lines; insufficiency of data prevents distinguishing between the two, but we choose to use the sloping-line plateau. Similar models are IV_2 (intersection between $X = 1$ and 2).

V_2: Two sloping lines intersecting at $X = 2 (b_1 > b_2 > 0)$. One other (rarely occurring) model is V_1 (intersection at $X = 1$).

VI: Two sloping lines intersecting at $X = 1$ with the second sloping line intersecting with a plateau at $X = 3 (b_1 > b_2 > 0)$. If the second sloping line joins only two points, one could use either IV or VI; we prefer IV, especially if the cost/price data suggest that addition in the second phase of VI would be unprofitable.

VII_3[1]: Two sloping lines intersecting at $X = 1$ and the second sloping line intersecting with a plateau between $X = 3$ and $4 (b_1 > b_2 > b_3 > 0)$. A similar model is VII_2 (last intersection between $X = 2$ and 3).

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[1] In models IV and VII, if the analysis indicates that $b_3 = 0$, it is assumed that Models III and VI, respectively, will apply.

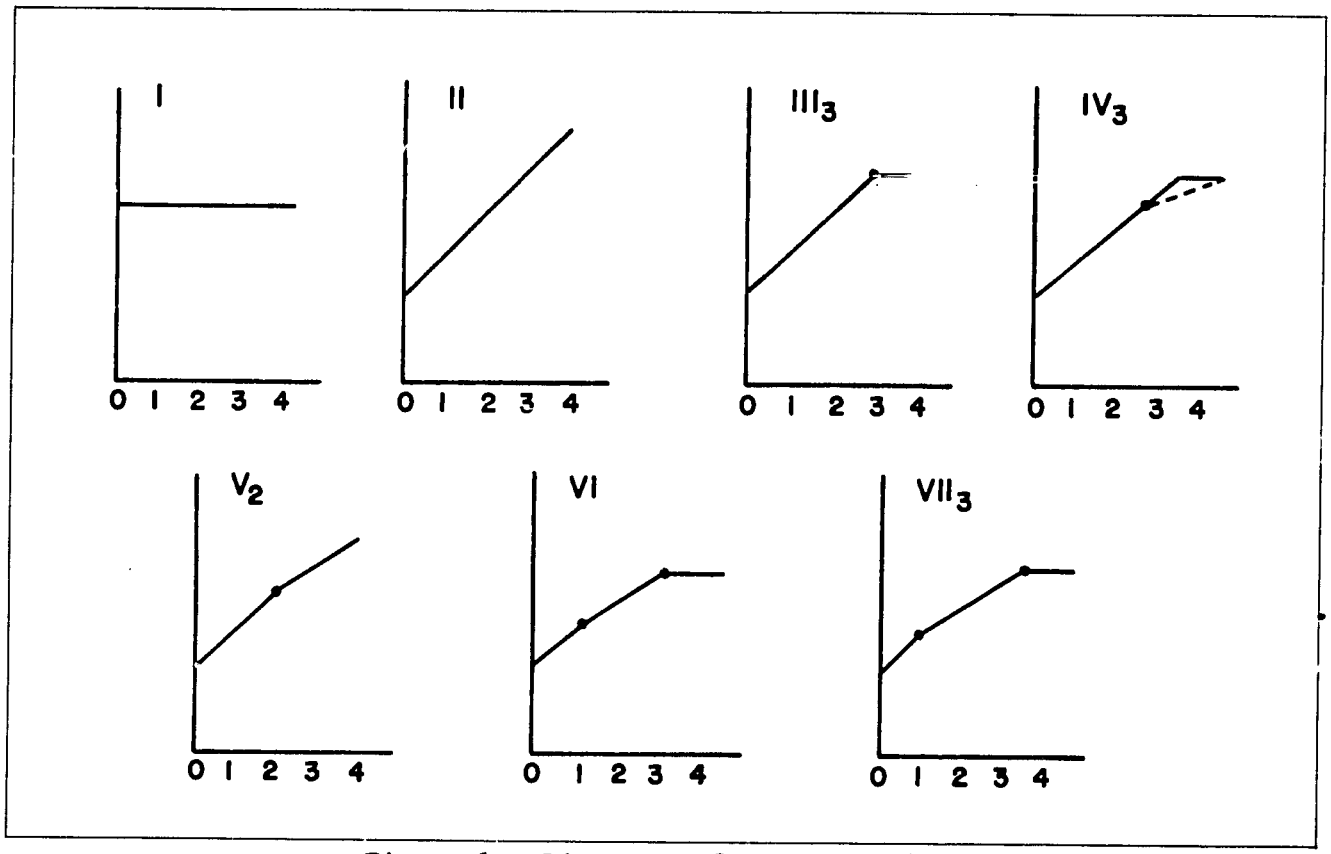

Figure 1. Diagrams of seven models.

The models will be of the type

$$\hat{Y} = b_0X_0 + b_1X_1 + b_2X_2 + b_3X_3 \qquad \ldots(1)$$

where $X_0' = (1,1,1,1,1,)$; b_1 and b_2 will represent sloping lines and b_3 the distance of the plateau above the value of $\hat{Y}$ at the last data point before the start of the plateau. Note that we have limited to two the number of sloping lines, plus, at most, one plateau; thus, the maximum number of regression coefficients is four. Intersection of two sloping lines will always be at a data point. If the right-hand sloping line intersects with a plateau, the intersection may be at a data point or between data points; the data are used to determine which is the case, that is, if $b_3 > 0$. In general, it is required that $b_1 > b_2 > b_3 > 0$; if b_2 or $b_3 < 0$, either a second-order response model should be used or the data for declining yields should be discarded.

In order to indicate the ease of computing, the Y, X_1, X_2, and X_3 vectors are presented in Table 4 for each model; model I has only the vector X_0. For models with several submodels, we will use the notation X_{ij} to refer to the ith vector for the jth submodel.

The entire series just described can be fitted readily without sophisticated computing equipment. Sets of least squares equations can be developed for calculating the b's and their standard errors for experiments involving various numbers of levels of nutrients. The yields obtained in a given experiment would be substituted into these equations and the parameter estimates calculated efficiently using only a pocket or desk calculator. This extends the

Table 4. Vectors of models II - VII

	Model II	Model III			Model IV					
Y	X_1	X_{13}	X_{12}	X_{11}	X_{13}	X_{33}	X_{12}	X_{32}	X_{11}	X_{31}
Y_0	0	0	0	0	0	0	0	0	0	0
Y_1	1	1	1	1	1	0	1	0	1	0
Y_2	2	2	2	1	2	0	2	0	1	1
Y_3	3	3	2	1	3	0	2	1	1	1
Y_4	4	3	2	1	3	1	2	1	1	1

	Model V				Model VI		Model VII					
Y	X_{12}	X_{22}	X_{11}	X_{21}	X_1	X_2	X_{13}	X_{23}	X_{33}	X_{12}	X_{22}	X_{32}
Y_0	0	0	0	0	0	0	0	0	0	0	0	0
Y_1	1	0	1	0	1	0	1	0	0	1	0	0
Y_2	2	0	1	1	1	1	1	1	0	1	1	0
Y_3	2	1	1	2	1	2	1	2	0	1	1	1
Y_4	2	2	1	3	1	2	1	2	1	1	1	1

usefulness of the method to developing countries and isolated Experiment Stations. If an electronic computer is available, it may be programmed to fit the entire series for each number of levels of nutrient and to print out regression statistics and information on goodness of fit. It is assumed that enough design points are replicated to provide a good estimate of the error variance.

If there are more than five levels of X, the modifications of the models described for five levels are simple except, perhaps, for Models V, VI, and VII, where X = 3 must also be considered.

The economic implications of the linear-plateau family are quite simple and straightforward. In the rules described below, r refers to the cost of a unit of fertilizer nutrient divided by the price of a unit of crop produced. The value of r must be coded in the same unit as the b's. For example, for the Tennessee data, the coded N rates represent 67 kg units. Therefore, r must be multiplied by 67 when comparing it with the coded b's. The rules for the addition of coded amounts (X) of nutrient are as follows:

I(and other models with $b_1 < r$): Add none or only maintenance rate.

II: If $b_1 > r$, add to largest X in experiment (further experiments needed to establish exact optimum).

III_j: If $b_1 > r$, add to $X = j$ ($X = 3$ for III_3, etc.).

IV_j: If $b_1 > r$, add to $X = j + b_3/b_1$.

V_j: (1) If $b_1 > r > b_2$, add to $X = j$ (intersection of the two lines).
(2) If $b_2 > r$, same as II.

IV: Same as V_1 except (2); add to $X = 3$.

VII_j: Same as V_1 except (2); add to $X = j + b_3/b_2$.

To illustrate the computing procedures, consider the J-65 data of Table 3. For Model VI, the least squares equations are

$$6\ b_0 + 5\ b_1 + 7\ b_2 = 345.1 = \Sigma Y \qquad \ldots(2)$$

$$5\ b_0 + 5\ b_1 + 7\ b_2 = 319.3 = \Sigma Y - Y_0 \qquad \ldots(3)$$

$$7\ b_0 + 7\ b_1 + 13\ b_2 = 482.9 = \Sigma X_2 Y \qquad \ldots(4)$$

The solutions are $b_0 = 25.8 = Y_0$; $b_1 = 22.36$; and $b_2 = 11.21$. Since $b_1 > b_2 > r = 1.64$, we use $X = 3$ or $N_e = 201$ kg/ha. If Model VII_2 were used, the solutions would be $b_0 = 25.8$; $b_1 = 21.8 = Y_1 - Y_0$; $b_2 = 12.9 = Y_2 - Y_1$; and $b_3 = 9.9 = \bar{Y}_3 - \bar{Y}_2$, where $\bar{Y}_3 = (Y_3 + Y_4 + Y_5)/3$. Since the increase in R^2 is trivial (.991 to .992), it was decided to use Model VI with fewer parameters.

FITTING QUADRATIC, SQUARE ROOT, AND LINEAR-PLATEAU MODELS TO MULTI-NUTRIENT DATA

A fourth set of data (Table 5) illustrate a plateau pattern for an NPK experiment on corn conducted at the Praputhabat Agricultural Experiment Station, Saraburi, Thailand, in 1962. Significant response to N generally leveled off at 8 kg/rai and that of P at 3.49 kg/rai. There was significant response to K only at the 0 level of N. A three-variable quadratic surface was modified because the coefficient of K^2 was positive with an estimated standard error twice the estimated coefficient; the modified quadratic prediction model was

$$\hat{Y}(Q) = 279.17 + 166.018\ N - 35.706\ N^2 + 85.954\ P - 27.141\ P^2 + 18.319\ NP + 60.474\ K - 26.539\ NK - 6.437\ PK \quad \ldots(5)$$

where N, P, and K are in coded units (0,1,2,3). The corresponding square root prediction model (omitting the coefficient of K) was

$$\hat{Y}(S) = 270.01 - 56.111\ N + 201.161\ \sqrt{N} - 70.577\ P + 122.064\ \sqrt{P} + 59.165\ \sqrt{NP} + 100.785\ \sqrt{K} - 69.361\ \sqrt{NK} - 14.928\ \sqrt{PK} \quad \ldots(6)$$

Table 5. Selected mean corn yields from a 4 x 4 x 3 NPK experiment, Saraburi, Thailand[ab]

	NK	P 0	1	2	3	Average (P > 0)
	00	298.24	320.34	254.10	275.95	283.47
	01	309.44	367.49	397.04	293.17	352.57
	02	446.42	517.44	414.62	419.92	450.66
Average P (N = 0; K = 0 - 2)		351.37	401.76	355.25	329.68	362.23
	1-	437.66	541.46	530.94	523.63	532.01
	2-	431.33	579.03	569.30	587.40	578.58
	3-	446.09	577.95	576.56	590.14	581.55
Average P(N > 0)		438.59	566.15	558.93	567.06	564.05

Standard errors of means

NPK	NP	P(N > 0)	N(P > 0)	(N,P > 0)
56.2	32.5	18.7	18.7	10.8

[a]Data provided by Sorasith Vatcharothayan, Head, Department of Soil Science, Kasetsart University, Bangkok, Thailand.

[b]Yields in kg/rai; N in units of 8 kg/rai; P in units of 3.49 kg/rai; K in units of 6.64 kg/rai. NPK means based on three replications.

The prices per kg were as follows: corn ($0.117), N($0.440), P($.352), and K($0.176). Therefore, the cost/price ratios for the coded units were $r_n = 30.08$, $r_p = 10.50$, and $r_k = 9.99$. The resulting optimal fertilizer combinations (in kg/rai) had K=0 and $N_e(Q) = 19.81$, $N_e(S) = 21.24$; $P_e(Q) = 7.77$, $P_e(S) = 6.34$. These results for both N and P seem biased upward because the predicted optimal yields $\hat{Y}(Q) = 629.15$ and $\hat{Y}(S) = 615.05$ exceed by a considerable amount any mean in Table 5, which indicates little if any response beyond 8 kg N/rai and 3.49 kg P/rai. From Table 5, it appears that one can obtain a yield of about 451 kg/rai with N = 0, P = 0, and K = 13.28 kg/rai. For N, P > 0, optimal K = 0 and the linear-plateau Model III is appropriate for P and Model III or IV for N. For P, $b_1 = 564 - 439 = 125 > 10.5$; hence, $P_e = 3.5$ kg/rai. For N, using Model IV, $b_1 = 170$ and $b_2 = 580 = 48 > 30.1$. If we use Model IV, $N_e = 8(1 + 48/170) = 10.3$ kg/rai. The estimated gain would be 580(.117) - 10.3(.440) - 3.5(.352) = $62.10 per rai as compared to $50.42 using only K. The estimated gain would be $62.16 per rai using the quadratic model and $60.39 using the square root model; however, these gains are overestimated because the predicted optimum yield ($\hat{Y}$) is too large.

For experiments in which there are two or more nutrients varied factorially and which exhibit a plateau response pattern, the procedures outlined for a single nutrient can be applied individually to means, the choice of which depends upon the response pattern as reflected in the ensemble of means and corresponding analyses of variance. In the most complicated situation, it would be necessary to make estimates of the optimal rates on individual rows and columns, assuming only two variables, a procedure which is not too efficient. The optimal values would then be connected by contours between the row and column optima and the contours then plotted. The point where the two contours intersect is taken for the optimal combination. If it is possible to average over levels of the other factor (no interaction), a more stable estimate should be obtained.

It should be pointed out that decisions made on individual rows and columns cannot be completely independent since a common plateau may extend over several rows and columns. Independent estimates for the various rows and columns may be made first, and then some adjusting in individual row models may be necessary to make the row or column conform more to adjacent rows or columns.

Our methods work well in multi-nutrient situations where there are no sizeable interactions in the vicinity of the optimum. The more complicated response patterns will need additional study. We hope to develop a set of general rules for the multi-nutrient case in a manner similar to that developed for single nutrient models.

DESIGN OF EXPERIMENTS FOR CHOICE OF MODEL AND DETERMINATION OF OPTIMAL RATES OF FERTILIZER

Most soil fertility experiments involve the major nutrients, N, P, and K. If one were to make an assessment of the overall importance of these nutrients, in decreasing order of response occurrence, the ordering would be N > P > K. There are many crop locations in which K may not produce response. Preliminary information should be used to control the size of experiments by not varying factors which are known to be at adequate levels. If the model is not well known, the ideal design arrangement may be a complete factorial experiment with many levels of each factor (say, 5 to 7). If possible, the levels should be spaced so that there is some concentration of treatment points in the region of the expected optimal rate. This is not impractical if the number of nutrient

factors is not large (say, 2). As mentioned above, preliminary information may serve as the basis for exclusion of 1 or 2 nutrient factors from the design.

The North Carolina State University International Soil Fertility Evaluation and Improvement Program in Latin America obtains preliminary information about optimal fertilizer rates on each crop-soil by the following procedures:

1. Soil test, accompanied by soil calibration with field results; and
2. Greenhouse pot trials and exploratory 2^3 factorials of N, P, and K. These preliminary trials indicate if any nutrients can be ignored or added at low maintenance levels. They also provide estimates of the proper levels for each of the important factors in the subsequent randomized complete block experiments which utilize a sequential one-factor-at-a-time approach, with the other factor(s) held at constant (preliminary optimal) levels.

Assuming preliminary information suggests that the respective optimal rates of N, P, and K are 25, 12, and 24 kg/ha, an experiment might be conducted using the 14 treatments in Table 6. Treatments 1 through 5 should provide a good picture of the model appropriate for nitrogen response and an estimate of the optimal rate of N. Treatments 6, 3, 7, 8, and 9 provide the P response information; treatments 10, 11, 3, 12, and 13 provide the information for K. A check treatment, 14, probably should be included. This information would be used to center the design for the soil fertility trial conducted the following year. This cycle may be repeated for several years for a given crop-soil until the estimated optimal levels of all factors stabilize.

The arrangement described above does not provide information on interactions, but it might be argued that much of the interaction occurs in comparing the results for 0 and 1 applications, which are below the preliminary optima. The data from Saraburi, Thailand (Table 5) demonstrate this type of interaction (N x K), which is not important in the region of the optimum. It should be added that, although a complete factorial with many levels of each factor would have been preferred in the above case, space in the farmer-cooperative fields in Latin America is extremely limited. During some phase of the cycle, however, the design should provide for estimation of interacting effects.

The following exploratory experimental design involving two nutrients is being used in the highlands of Ecuador where space is severely limited.[2] Greenhouse and soil test studies have provided initial estimates of the optimal levels of N and P required for a specific crop-soil. Suppose these estimates of optimal levels of N and P are each coded rates of 3. The design then consists of the X-points in the design picture. The one-factor-at-a-time approach

Table 6. Treatments using various N, P, and K levels

	Treatment no.													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
N	0	12	24	36	48	24	24	24	24	24	24	24	24	0
P	12	12	12	12	12	0	24	36	48	12	12	12	12	0
K	24	24	24	24	24	24	24	24	24	0	12	36	48	0

[2]We acknowledge the efforts of Dr. Sam Portch of North Carolina State University in the development of this design.

provides the design points for P = 3 and N = 3; treatments along the diagonal are included to check for interaction and the stability of (3,3) as the optimal point (Figure 2). The experiment probably will be conducted several years in succession with slight adjustments in rates until the optimal levels appear to stabilize. The 0-treatments might be included to complete a 3 x 3 factorial, which would prove useful should the model prove to be truly of second order.

If the experimenter has good reason to believe that there is one very important nutrient (X_1) and one less important (X_2), the experimental design could be a less 7 x 3 factorial. If there are two less important nutrients, (X_2 and X_3), an incomplete 3 x 3 factorial could be used for the latter, as in Figure 3. The matrix in Figure 4 would be used if Model IV were appropriate:

$$Y = b_0x_0 + b_{21}x_{21} + b_{23}x_{23} + b_{31}x_{31} + b_{33}x_{33} \qquad \ldots(7)$$

Using all seven points, there would be two degrees of freedom for goodness-of-fit (test of interaction). The variance of b_0 would be $V(b_0) = 11\sigma^2/15$; for others $V = 14\sigma^2/15$. If Y_{22} were omitted, $V(b_{23})$ and $V(b_{33})$ would increase to $7\sigma^2/4$, $V(b_{21})$ and $V(b_{31})$ to σ^2, and $V(b_0)$ to $3\sigma^2/4$. Hence, the extra point not only furnishes additional information on goodness-of-fit but considerably reduces the variances of the plateau estimates (b_{23} and b_{33}). Each of these design points might have a complete 5 to 7 level experiment for the X_1-factor.

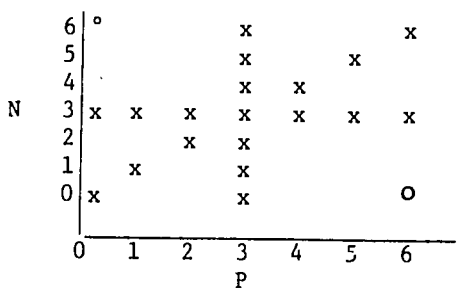

Figure 2. Design points for N x P experiment used in Ecuador.

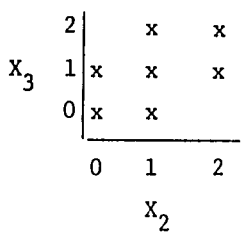

Figure 3. Design points for incomplete 3 x 3 factorial for two less important nutrients.

	X_0	X_{21}	X_{23}	X_{31}	X_{33}
Y_{00}	1	0	0	0	0
Y_{01}	1	0	0	1	0
Y_{10}	1	1	0	0	0
Y_{11}	1	1	0	1	0
Y_{12}	1	1	0	1	1
Y_{21}	1	1	1	1	0
Y_{22}	1	1	1	1	1

Figure 4. Matrix used with model IV.

SUMMARY AND CONCLUSIONS

For many cropping situations, especially in developing countries, quadratic surfaces do not fit the responses of certain crops to fertilizer. In these cases, experimental designs used to estimate the optimal rate of fertilizer should also have provisions for evaluating the model. This requires a number of levels of each factor at various levels of the other factors. Use of the second order designs with standard statistical and economic interpretive techniques may result in sizable biases in the estimates of the optimal fertilizer rate. These biases could be very costly, especially in developing countries where it is difficult to convince farmers to use fertilizer because of a lack of capital. Also, there is a potential pollution problem.

A family of linear plateau models consisting of intersecting straight lines is proposed for fitting fertilizer response data that exhibit a plateau effect. The fit usually is good, and the resulting optimal estimates seem to be relatively unbiased. The regression coefficients are easily computed using a desk calculator or computer, and the economic interpretations are simple. Techniques for fitting, parameter estimation, and economic interpretation are described.

For multi-nutrient experiments, a complete factorial experiment with a number of levels of each nutrient is considered to be the best design for both evaluating the model and estimating the optimal nutrient levels. Preliminary information in the form of soil tests, greenhouse experiments, and 2^3 factorials in the field may provide a basis for deciding which fertilizer nutrients are apt to produce response. In many soil-crop situations, the importance of the three major nutrients is in the order N > P > K. Consequently, some crop-soils require only NP or N experiments because the other nutrients are already at adequate levels; hence, the amount of experimental material may be redistributed by having fewer factors, but more levels of each factor studied.

Descriptions are presented of two fertilizer response designs that are being used in an exploratory manner in developing countries where farmer-cooperative experiments are conducted under severe space restrictions. Both designs are based on the availability of preliminary information on optimal nutrient levels for estimating optimal rates; however, the one-factor-at-a-time design has the disadvantage of providing no estimate of interaction. Several other designs are suggested.

Based on these results, it appears that more consideration should be paid to the distribution of treatment levels. At present, we recommend concentrating several treatment levels in the vicinity of the anticipated optimum. Since the sloping phase of the response pattern is more important than the plateau phase, it should receive more attention when distributing treatment levels.

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An Application of a Fractional Factorial Design to a Fertilizer Experiment in Japan

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INTRODUCTION

The yield of rice per hectare in Japan has shown a near threefold increase in the last 100 years, mainly because of the increased application of nitrogen fertilizer. The amount applied to a hectare in 1880 is estimated as 60-80 kg in terms of N, whereas most farmers now apply nearly 200 kg in main rice-producing areas. The total amount of N is distributed in different stages during the growth of rice: as a basal dressing and at the time of irrigation, late-tillering, young-panicle-formation, heading, and so on. This procedure of divided application is one of the newly developed techniques and can protect the rice plants from the excess-flourish at the early growing stage and secure a high grain-yield. Various kinds of fertilizer experiments have been undertaken for the determination of the optimum amounts of nitrogen, phosphorus, and potassium, in respective stages.

It should be noted, however, that the study of a production function has not been done on the basis of the experimental data. The following two reasons may explain why.

1. The cost of fertilizer has been very small in comparison to the price of rice, so that the farmer has been able to increase production with no heed of cost-benefit performance. The cost of an increased application of N by 10 kg/ha was comparable to an increase in the rice crop of 20 kg/ha, and this ratio has not changed greatly up to the present. The increase of 20 kg/ha in rice production was an easy accomplishment for farmers considering an average yield of about 5 tons/ha.
2. The prices of fertilizer and of rice have been determined independently in government policy in Japan, which has led to the deferment of input-output analyses based on the nominal prices of rice and fertilizer.

In this paper, the design and analysis of a fertilizer experiment are presented, in which comparison is made among three levels of N application at each of four stages of growth and among three levels of the time of application in one of the four stages.

USE OF FRACTIONAL FACTORIAL DESIGN

Many agricultural, biological, and industrial experiments are of a factorial nature--that is, each treatment (plot) consists of a number of factors each at two or more levels. Generally, interest is in estimating the main effects and two-factor interactions. For high design efficiency, the total number of parameters to be estimated should be as large as possible under a given number of observations or plots. In general, this requirement is satisfied with an appropriate selection of the "defining identities" associated with a fractional factorial design.

The National Bureau of Standards, U.S. Department of Commerce, has already published three monographs on the fractional factorial designs for factors at two levels (1), at three levels (2), and at mixed levels(3). The first one contains $1/2^P$ fractional replicate of 2^n factorial designs for $n = 5(1)16$ and for a range of $P = 1(1)8$, $P < n$, where n denotes the number of factors. The second presents the integral collection of $1/3^P$ fractional factorial designs of n factors each at three levels for $n = 4(1)10$ and for the fractions of 1/3, 1/9, 1/27, 1/81, and 1/243. The third one shows several types of fractions of $2^n \times 3^m$ factorial designs. In all of these monographs, the experiment plans are also constructed so that the treatment combinations are grouped into blocks.

T. Okuno and M. Shiyomi (4), writing in Japanese, constructed 120 different fractional factorial designs as shown in Table 1. These designs are grouped in families in which all designs belonging to a particular family have the same number of plots as well as the same number of blocks, but differ in the number of factors and, hence, in the number of fractions.

Complexity in the use of fractional factorial designs, especially for the nonstatistician, is evident in writing down the required treatment combinations and in computing the estimates of the main effects and interactions and the indispensable analysis of variance tables. With the specially devised "Tables of Orthogonal Arrays" (4), however, and with a computer program for the analysis of 2^n- and 3^n-type fractional factorial designs (5), the use of these designs has become feasible.

Every year a few tens of 3^n-type and several tens of 2^n-type fractional factorial designs are conducted in Japanese agricultural experiments. In each of these experiments, 10 to 20 characteristics (variates) are processed on the computer.

Table 1. 120 designs constructed by Okuno and Shiyomi (4)

Designation of orthogonal table	Number of units required	Number of blocks	Number of factors, n	Fractions, $1/2^P$ or $1/3^P$
$L_{16}(2^{15})$	16	1,2,4,8	4(1)8	$1, 1/2, \text{---} 1/2^4$
$L_{32}(2^{31})$	32	1,2,4,8	5(1)16	$1, 1/2, \text{---} 1/2^{11}$
$L_{64}(2^{63})$	64	1,2,4,8,16	6(1)32	$1, 1/2, \text{---} 1/2^{26}$
$L_{27}(3^{13})$	27	1,3,9	3,4	1,1/3
$L_{81}(3^{40})$	81	1,3,9	4(1)10	$1, 1/3, \text{---} 1/3^6$

AN EXAMPLE OF FERTILIZER EXPERIMENTS

Saga (prefectural) Agricultural Experiment Station conducted a 1/3 fractional replicate of a 3^5 factorial experiment in 1972 to explore the optimum condition of the nitrogen applications in the four different stages on direct sowing of paddy rice. The factors and the levels are tabulated in Table 2.

The number of all the treatment combinations is $3^5 = 243$ and the appropriate one-third fraction is selected by using

$$1 = F^2 I\ E\ L\ T$$

$$B = F^2 I^2 E\ T^2 = F\ E^2 L = I\ L^2 T \cdot \qquad \ldots(1)$$

for the defining identity and the block confounding effects.

This relationship is displayed in Table 3 by assigning all the main effects and the two-factor interactions, as well as block and error components, to the 40 arrays of the $L_{81}(3^{40})$ orthogonal table shown in Table 4. The specification of 81 plots thus selected, together with their grain yields, is given in Table 5 and the field layout in Table 6. The area of each plot is 15 m^2, and the total area, including the marginal areas, reaches about 15 a, which is divided into 3 blocks of 5 a each. In each block, 27 different treatment combinations are arranged at random.

As is easily seen from Tables 5 and 6, three levels of each of five factors F, I, E, L, and T are replicated 27 times, and every combination of levels of any two factors is replicated 9 times. The levels of factor I consist of the N applications at two stages: time of irrigation and late-tillering stage. In Table 5, the total amount of N application for each plot is also shown. The smallest amount of N is 9 kg/10a in plot No. 1 and the largest is 26 kg/10a in plot No. 81.

Table 2. Factors and levels for the nitrogen experiment

Factor		Level 1	Level 2	Level 3
1. Amount of nitrogen applied (kg/10a):				
Basal dressing	F	0	2	4
2. Time of irrigation	I	5	7	10
3. Stage of young panicle formation[a]	E	4	6	8
4. Heading date	L	0	2	4
5. Time of application (days)[b]	T	-25	-20	-15
Block	B	1	2	3

[a]Time of application is expressed by the level of the fifth factor T.
[b]Number of days before young panicle formation.

DATA ANALYSIS

The output of our computer for grain yield is illustrated in Table 7 as an example. Each step of the analysis is explained as follows.

1. Order of input data. "Natural Order" designates the order of the data input according to the row number in the L_{81} table or in Table 5. In this computer program, a device of "derandomization" is provided when the data input is in the order of the randomized arrangement as shown in Table 6. A series of random numbers is typed out in the latter case.
2. Basic table. This table shows the grand total, general mean, correction factor, and level totals with the corresponding sum of squares for each of the 40 orthogonal arrays. The array labels are the same as shown in Table 3, except that the components of a two-factor interaction are written, for instance, as EL* in place of EL^2 or as *EL* in place of E^2L^2.
3. Analysis of variance table with level means. At the left are displayed the level means of the factorial effects with 2 degrees of freedom and at the right the usual ANOVA table.
4. Least significant difference. The L.S.D.'s given are for comparing three levels of each main effect and for comparing among means in the combinations of the levels of two factors.
5. Estimated cell means for two-way tables. The means in the combinations of the levels of any pair of the five factors are calculated and given.

The computation takes 5 seconds, on two programs written in FORTRAN by Chieko Okuno (5) on our computer HITAC 8450 with the core-memory of 756K Bytes.

Table 3. Assignment of factorial effects to the arrays of L_{81}

	Array number																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Array label	a	b	a b	a^2 b	c	a c	a^2 c	b c	a b c	a^2 b c	b^2 c	a b^2 c	a^2 b^2 c	d	a d	a^2 d	b d	a b d	a^2 b d	b^2 d	a b^2 d
Factorial effects, etc.	B	F	e	E L^2	I	e	L T^2	F I	E T^2	e	F^2 I	e	e	E′	F L	e	F E	F^2 L	E^2 L^2	F^2 E	L

	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Array label	a^2 b^2 d	c d	a c d	a^2 c d	b c d	a b c d	a^2 b c d	b^2 c d	a b^2 c d	a^2 b^2 c d	c^2 d	a c^2 d	a^2 c^2 d	b c^2 d	a b c^2 d	a^2 b c^2 d	b^2 c^2 d	a b^2 c^2 d	a^2 b^2 c^2 d
Factorial effects etc.	I T	I E	e	e	e	E^2 T^2	e	L^2 T^2	I L	I^2 T	I^2 E	e	F T	e	e	F^2 T	e	I^2 L	T

Table 4. $L_{81}(3^{40})$ orthogonal table

Group	1	2			3									4																										
Array	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
	a	b	a b	a^2 b	c	a c	a^2 c	b c	a b c	a^2 b c	b^2 c	a b^2 c	a^2 b^2 c	d	a d	a^2 d	b d	a b d	a^2 b d	b^2 d	a b^2 d	a^2 b^2 d	c d	a c d	a^2 c d	b c d	a b c d	a^2 b c d	b^2 c d	a b^2 c d	a^2 b^2 c d	c^2 d	a c^2 d	a^2 c^2 d	b c^2 d	a b c^2 d	a^2 b c^2 d	b^2 c^2 d	a b^2 c^2 d	a^2 b^2 c^2 d
Label																																								
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
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39	2	2	3	1	1	2	3	2	3	1	3	1	2	3	1	2	1	2	3	2	3	1	3	1	2	1	2	3	2	3	1	3	1	2	1	2	3	2	3	1
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48	2	3	1	2	1	2	3	3	1	2	2	3	1	3	1	2	2	3	1	1	2	3	3	1	2	2	3	1	1	2	3	3	1	2	2	3	1	1	2	3
49	2	3	1	2	2	3	1	1	2	3	3	1	2	1	2	3	3	1	2	2	3	1	2	3	1	1	2	3	3	1	2	3	1	2	2	3	1	1	2	3
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51	2	3	1	2	2	3	1	1	2	3	3	1	2	3	1	2	2	3	1	1	2	3	1	2	3	3	1	2	2	3	1	2	3	1	1	2	3	3	1	2
52	2	3	1	2	3	1	2	2	3	1	1	2	3	1	2	3	3	1	2	2	3	1	3	1	2	2	3	1	1	2	3	2	3	1	1	2	3	3	1	2
53	2	3	1	2	3	1	2	2	3	1	1	2	3	2	3	1	1	2	3	3	1	2	1	2	3	3	1	2	2	3	1	3	1	2	2	3	1	1	2	3
54	2	3	1	2	3	1	2	2	3	1	1	2	3	3	1	2	2	3	1	1	2	3	2	3	1	1	2	3	3	1	2	1	2	3	3	1	2	2	3	1
55	3	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2
56	3	1	3	2	1	3	2	1	3	2	1	3	2	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3
57	3	1	3	2	1	3	2	1	3	2	1	3	2	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1
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59	3	1	3	2	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	3	2	1	3	2	1	3	2	1	1	3	2	1	3	2	1	3	2
60	3	1	3	2	2	1	3	2	1	3	2	1	3	3	2	1	3	2	1	3	2	1	1	3	2	1	3	2	1	3	2	2	1	3	2	1	3	2	1	3
61	3	1	3	2	3	2	1	3	2	1	3	2	1	1	3	2	1	3	2	1	3	2	3	2	1	3	2	1	3	2	1	2	1	3	2	1	3	2	1	3
62	3	1	3	2	3	2	1	3	2	1	3	2	1	2	1	3	2	1	3	2	1	3	1	3	2	1	3	2	1	3	2	3	2	1	3	2	1	3	2	1
63	3	1	3	2	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	2	1	3	2	1	3	2	1	3	1	3	2	1	3	2	1	3	2
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66	3	2	1	3	1	3	2	2	1	3	3	2	1	3	2	1	1	3	2	2	1	3	3	2	1	1	3	2	2	1	3	3	2	1	1	3	2	2	1	3
67	3	2	1	3	2	1	3	3	2	1	1	3	2	1	3	2	2	1	3	3	2	1	2	1	3	3	2	1	1	3	2	3	2	1	1	3	2	2	1	3
68	3	2	1	3	2	1	3	3	2	1	1	3	2	2	1	3	3	2	1	1	3	2	3	2	1	1	3	2	2	1	3	1	3	2	2	1	3	3	2	1
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71	3	2	1	3	3	2	1	1	3	2	2	1	3	2	1	3	3	2	1	1	3	2	1	3	2	2	1	3	3	2	1	3	2	1	1	3	2	2	1	3
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76	3	3	2	1	2	1	3	1	3	2	3	2	1	1	3	2	3	2	1	2	1	3	2	1	3	1	3	2	3	2	1	3	2	1	2	1	3	1	3	2
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80	3	3	2	1	3	2	1	2	1	3	1	3	2	2	1	3	1	3	2	3	2	1	1	3	2	3	2	1	2	1	3	3	2	1	2	1	3	1	3	2
81	3	3	2	1	3	2	1	2	1	3	1	3	2	3	2	1	2	1	3	1	3	2	2	1	3	1	3	2	3	2	1	1	3	2	2	1	3	2	1	3

Table 5. Treatment combinations of 81 plots and their yields

Factors[a] and levels							Amount of N application (kg/10a)							Yield
Factor	B	F	I	E	L	T	F	I	E August 12	E August 17	E August 22	L	Total	Grain wt. (kg/10a)
Array no.	(1)	(2)	(5)	(14)	(21)	(40)								
No. 1	1	1	1	1	1	1	0	4+1	4			0	9	66.70
2	1	1	1	2	2	2	0	4+1		6		2	13	61.00
3	1	1	1	3	3	3	0	4+1			8	4	17	59.25
4	1	1	2	1	1	3	0	5+2			4	0	11	55.85
5	1	1	2	2	2	1	0	5+2	6			2	15	73.70
6	1	1	2	3	3	2	0	5+2		8		4	19	64.10
7	1	1	3	1	1	2	0	7+3		4		0	14	54.95
8	1	1	3	2	2	3	0	7+3			6	2	18	59.60
9	1	1	3	3	3	1	0	7+3	8			4	22	71.50
10	1	2	1	1	3	3	2	4+1			4	4	15	57.90
11	1	2	1	2	1	1	2	4+1	6			0	13	63.60
12	1	2	1	3	2	2	2	4+1	8			2	17	67.30
13	1	2	2	1	3	2	2	5+2		4		4	17	64.55
14	1	2	2	2	1	3	2	5+2			6	0	15	51.65
15	1	2	2	3	2	1	2	5+2	8			2	19	65.00
16	1	2	3	1	3	1	2	7+3	4			4	20	56.90
17	1	2	3	2	1	2	2	7+3		6		0	18	59.80
18	1	2	3	3	2	3	2	7+3			8	2	22	67.40
19	1	3	1	1	2	2	4	4+1		4		2	15	64.70
20	1	3	1	2	3	3	4	4+1			6	4	19	51.35
21	1	3	1	3	1	1	4	4+1	8			0	17	62.25
22	1	3	2	1	2	1	4	5+2	4			2	17	34.25
23	1	3	2	2	3	2	4	5+2		6		4	21	62.80
24	1	3	2	3	1	3	4	5+2			8	0	19	63.05
25	1	3	3	1	2	3	4	7+3			4	2	20	61.80
26	1	3	3	2	3	1	4	7+3	6			4	24	71.75
27	1	3	3	3	1	2	4	7+3		8		0	22	66.95
28	2	1	1	1	2	3	0	4+1			4	2	11	57.60
29	2	1	1	2	3	1	0	4+1	6			4	15	56.90
30	2	1	1	3	1	2	0	4+1		8		0	13	52.05
31	2	1	2	1	2	2	0	5+2		4		2	13	52.90
32	2	1	2	2	3	3	0	5+2			6	4	17	50.25
33	2	1	2	3	1	1	0	5+2	8			0	15	52.50
34	2	1	3	1	2	1	0	7+3	4			2	16	63.60
35	2	1	3	2	3	3	0	7+3		6		4	20	63.30
36	2	1	3	3	1	3	0	7+3			8	0	18	53.25
37	2	2	1	1	1	2	2	4+1		4		0	11	60.85
38	2	2	1	2	2	3	2	4+1			6	2	15	53.70
39	2	2	1	3	3	1	2	4+1	8			4	19	61.00
40	2	2	2	1	1	1	2	5+2	4			0	13	60.75
41	2	2	2	2	2	2	2	5+2		6		2	17	63.15
42	2	2	2	3	3	3	2	5+2			8	4	21	59.30
43	2	2	3	1	1	3	2	7+3			4	0	16	66.50
44	2	2	3	2	2	1	2	7+3	6			2	20	67.00
45	2	2	3	3	3	2	2	7+3		8		4	24	63.78
46	2	3	1	1	3	1	4	4+1	4			4	17	55.10
47	2	3	1	2	1	2	4	4+1		6		0	15	56.30
48	2	3	1	3	2	3	4	4+1			8	2	19	55.05
49	2	3	2	1	3	3	4	5+2			4	4	19	58.05
50	2	3	2	2	1	1	4	5+2	6			0	17	62.90
51	2	3	2	3	2	2	4	5+2		8		2	21	57.50
52	2	3	3	1	3	2	4	7+3		4		4	22	61.70
53	2	3	3	2	1	3	4	7+3			6	0	20	65.90
54	2	3	3	3	2	1	4	7+3	8			2	24	68.25
55	3	1	1	1	3	2	0	4+1		4		4	13	57.00
56	3	1	1	2	1	3	0	4+1			6	0	11	52.95
57	3	1	1	3	2	1	0	4+1	8			2	15	57.30
58	3	1	2	1	3	1	0	5+2	4			4	15	59.10
59	3	1	2	2	1	2	0	5+2		6		0	13	50.25
60	3	1	2	3	2	3	0	5+2			8	2	17	53.30
61	3	1	3	1	3	3	0	7+3			4	4	18	55.05
62	3	1	3	2	1	1	0	7+3	6			0	16	61.20
63	3	1	3	3	2	2	0	7+3		8		2	20	61.00
64	3	2	1	1	2	1	2	4+1	4			2	12	53.10
65	3	2	1	2	3	2	2	4+1		6		4	17	51.30
66	3	2	1	3	1	3	2	4+1			8	0	15	57.40
67	3	2	2	1	2	3	2	5+2			4	2	15	56.35
68	3	2	2	2	3	1	2	5+2		6		4	19	60.65
69	3	2	2	3	1	2	2	5+2			8	0	17	58.33
70	3	2	3	1	2	2	2	7+3		4		2	18	62.75
71	3	2	3	2	3	3	2	7+3			6	4	22	49.40
72	3	2	3	3	1	1	2	7+3	8			0	20	66.20
73	3	3	1	1	1	3	4	4+1			4	0	13	54.25
74	3	3	1	2	2	1	4	4+1	6			2	17	53.10
75	3	3	1	3	3	2	4	4+1		8		4	21	58.65
76	3	3	2	1	1	2	4	5+2		4		0	15	63.30
77	3	3	2	2	2	3	4	5+2			6	2	19	55.70
78	3	3	2	3	3	1	4	5+2	8			4	23	63.40
79	3	3	3	1	1	1	4	7+3	4			0	18	66.10
80	3	3	3	2	2	2	4	7+3		6		2	22	66.30
81	3	3	3	3	3	3	4	7+3			8	4	26	57.90

[a]F=basal dressing; I=time of irrigation + late tillering stage; E=young panicle formation stage; L=heading date; T=time of application; B=block.

Table 6. Random arrangement of 81 treatment combinations

No.	6	22	12	5	18	9	24	15	19	1	26	14	17	27
F	1	3	2	1	2	1	3	2	3	1	3	2	2	3
I	2	2	1	2	3	3	3	2	1	1	3	2	3	3
E	3	1	3	2	3	3	3	3	1	1	2	2	2	3
L	3	2	2	2	2	3	1	2	2	1	3	1	1	1
T	2	1	2	1	3	1	3	1	2	1	1	3	2	2
No.	2	13	8	25	21	10	20	7	3	16	4	23	11	45
F	1	2	1	3	3	2	3	1	1	2	1	3	2	2
I	1	2	3	3	1	1	1	3	1	3	2	2	1	3
E	2	1	2	1	3	1	2	1	3	1	1	2	2	3
L	2	3	2	2	1	3	3	1	3	3	1	3	1	3
T	2	2	3	3	1	3	3	2	3	1	3	2	1	2
No.	31	51	44	33	54	36	41	46	38	32	48	39	30	47
F	1	3	2	1	3	1	2	3	2	1	3	2	1	3
I	2	2	3	2	3	3	2	1	1	2	1	1	1	1
E	1	3	2	3	3	3	2	1	2	2	3	3	3	2
L	2	2	2	1	2	1	2	3	2	3	2	3	1	1
T	2	2	1	1	1	3	2	1	3	3	2	1	2	2
No.	43	53	34	52	29	40	49	37	28	50	42	35	70	55
F	2	3	1	3	1	2	3	2	1	3	2	1	2	1
I	3	3	3	3	1	2	2	1	1	2	2	3	3	1
E	1	2	1	1	2	1	1	1	1	2	3	2	1	1
L	1	1	2	3	3	1	3	1	2	1	3	3	2	3
T	3	3	1	2	1	1	3	2	3	1	3	2	2	2
No.	76	66	73	61	71	56	79	60	75	67	81	59	64	74
F	3	2	3	1	2	1	3	1	3	2	3	1	2	3
I	2	1	1	3	3	1	3	2	1	2	3	2	1	1
E	1	3	1	1	2	2	1	3	3	1	3	2	1	2
L	1	1	1	3	3	1	1	2	3	2	3	1	2	2
T	2	3	3	3	3	3	1	3	2	3	3	2	1	1
No.	58	72	62	77	65	78	68	63	80	57	69	82	83	84
F	1	2	1	3	2	3	2	1	3	1	2			
I	2	3	3	2	1	2	2	3	3	1	2			
E	1	3	2	2	2	3	2	3	2	3	3			
L	3	1	1	2	3	3	3	2	2	2	1			
T	1	1	1	3	2	1	1	2	2	1	2			

DISCUSSION

Referring to the F table, it is found from the ANOVA table that main effects I and T are highly significant (at the 1% level) and that the main effect B and the two-factor interactions F x L and E x T are significant at the 5% level.

The effects of N applied at the time of irrigation are as follows:

N application (per 10a)	Yield (kg/a)
I_1 (5 kg)	57.7
I_2 (7 kg)	58.3
I_3 (10 kg)	62.6

L.S.D. = 2.6 kg/10a

Table 7. Computer output

ANALYSIS OF EXPERIMENT BASED ON ORTHOGONAL ARRAY 3 TO THE N

N = 4

SIZE OF EXPERIMENT 81

ORDER OF INPUT DATA ##### NATURAL ORDER

DATA IDENTIFICATION ##### 14 GRAIN YIELD

INPUT DATA

66.7000	61.0000	59.2500	55.8500	73.8000	64.1000	54.9500	59.6000	71.5000
57.9000	63.6000	67.3000	64.5500	51.6500	65.0000	56.9000	59.8000	67.4000
64.7000	51.3500	62.2500	34.2500	62.8000	63.0500	61.8000	71.7500	66.9500
57.6000	56.9000	52.0500	52.9000	50.2500	52.5000	63.6000	63.3000	53.2500
60.8300	53.7000	61.0000	60.7500	63.1500	59.3000	66.5000	57.0000	63.7800
55.1000	56.3000	55.0500	58.0500	62.9000	57.5000	61.7000	65.9000	68.2500
57.0000	52.9500	57.3000	59.1000	50.2500	53.3000	55.0500	61.2000	61.0000
53.1000	51.3000	57.4000	56.3500	60.6500	58.3300	62.7500	49.4000	66.2000
54.2500	53.1000	58.6500	63.3000	55.7000	63.4000	66.1000	66.3000	57.9000

BASIC TABLE

GRAND TOTAL = 4820.1900
GENERAL MEAN = 59.508519
CORRECTION FACTOR = 286842.365878

ARRAY NO.	LABEL	LEVEL TOTAL 1	2	3	SUM OF SQUARE
1	B	1659.7500	1599.1100	1561.3300	182.605363
2	F	1576.2500	1625.5900	1618.3500	52.583496
3	ERR	1622.9800	1595.1500	1602.0600	15.554353
4	ELH	1661.4600	1602.0000	1556.7300	204.360956
5	I	1557.6300	1572.7300	1669.8300	387.867407
6	ERR	1647.7100	1589.4800	1583.0000	94.075400
7	LTH	1617.2500	1603.3800	1599.5600	6.418585
8	FI	1601.4300	1624.8300	1593.9300	19.242222
9	ETH	1575.7000	1643.9100	1600.5800	88.260585
10	ERR	1576.7600	1640.8500	1602.5800	77.022141
11	HFI	1647.1300	1582.5300	1590.5300	91.860741
12	ERR	1609.7800	1623.2000	1587.2100	24.503474
13	ERR	1609.4800	1623.1600	1587.5500	23.902956
14	E	1581.6300	1595.6000	1642.9600	76.537030
15	FL	1541.1300	1625.8600	1653.2000	252.917696
16	ERR	1590.4800	1605.0300	1624.6800	21.820556
17	FE	1634.5600	1621.8800	1563.7500	105.604141
18	HFL	1596.1500	1625.8300	1598.1600	20.448289
19	HELH	1619.0300	1610.6800	1590.4800	15.961296
20	HFE	1596.0000	1614.2100	1609.9800	6.727622
21	L	1605.7600	1612.5000	1601.9300	2.121252
22	IT	1593.0800	1598.2800	1628.8300	27.634630
23	IE	1627.9100	1581.5300	1610.7500	40.733067
24	ERR	1630.0000	1599.3300	1590.8600	31.411474
25	ERR	1620.3300	1588.9300	1610.9300	19.238519
26	ERR	1592.0500	1602.0600	1626.0800	22.656807
27	HETH	1555.7600	1624.9500	1639.4800	148.239696
28	ERR	1569.0300	1607.1300	1644.0300	104.175556
29	HLTH	1629.8800	1633.7000	1556.6100	139.826585
30	IL	1646.2300	1592.7100	1581.2500	89.112622
31	HIT	1602.7300	1625.1300	1592.3300	20.811852
32	HIE	1634.5600	1586.0300	1599.6000	46.438363
33	ERR	1635.6800	1605.0600	1578.6500	60.272067
34	FT	1640.4000	1593.8000	1585.9900	64.111163
35	ERR	1619.2000	1594.7100	1606.4800	11.292289
36	ERR	1643.3500	1568.4300	1608.4100	104.101363
37	HFT	1637.4400	1573.2500	1609.5000	76.729163
38	ERR	1614.2300	1606.4500	1599.5100	4.016919
39	HIL	1589.5600	1625.9000	1604.7300	24.677696
40	T	1653.9000	1626.5400	1539.7500	263.102422

ANALYSIS OF VARIANCE TABLE WITH LEVEL MEANS

ARRAY NO.	FACTOR	LEVEL MEANS 1	2	3	DEGREES OF FREEDOM	SUM OF SQUARE	MEAN SQUARE	F
1	D	61.47222	59.22630	57.82704	2	182.605363	91.302681	4.163
2	F	58.37963	60.20204	59.93889	2	52.583496	26.291748	1.199
4	ELH	61.53556	59.33333	57.65667				
19		59.96407	59.65481	58.90667	4	220.322252	55.080563	2.512
5	I	57.69000	58.24926	62.58630	2	387.867407	193.933704	8.843
7	LTH	59.89815	59.38444	59.24296				
29		60.36593	60.50741	57.65222	4	146.245170	36.561293	1.667
8	FI	59.31222	60.17889	59.03444				
11		61.00481	58.61222	58.90852	4	111.102963	27.775741	1.267
9	ETH	58.35926	60.88556	59.28074				
27		57.62074	60.18333	60.72148	4	236.500281	59.125070	2.696
14	E	58.57889	59.09630	60.85037	2	76.537030	38.268515	1.745
15	FL	57.07889	60.21704	61.22963				
18		59.11667	60.21778	59.19111	4	273.365985	68.341496	3.116
17	FE	60.53926	60.06963	57.91667				
20		59.11111	59.78556	59.62889	4	112.331763	28.082941	1.281
21	L	59.47259	59.72222	59.33074	2	2.121252	1.060626	0.048
22	IT	59.00296	59.19556	60.32704				
31		59.36037	60.19000	58.97519	4	48.446481	12.111620	0.552
23	IE	60.29296	58.57519	59.65741				
32		60.53926	58.74185	59.24444	4	87.171430	21.792857	0.994
30	IL	60.97148	58.98926	58.56481				
39		58.87259	60.21852	59.43444	4	113.[illegible]0319	28.447580	1.297
34	FT	60.75556	59.02963	58.74037				
37		60.64593	58.26352	59.61111	4	140.840326	35.210081	1.606
40	T	61.25556	60.24222	57.02778	2	263.102422	131.551211	5.999
	ERROR 1				28	614.043881	21.930139	1.000

LEAST SIGNIFICANT DIFFERENCE

	ERROR 1
T VALUE (ALPHA = 0.05)	2.048
LSD FOR MEAN EFFECTS	2.6103
LSD FOR 2-WAY TABLES	4.5211

ESTIMATED CELL MEANS FOR 2-WAY TABLES

FACTOR NAME

		E (1)	E (2)	E (3)
ELH				
	L (1)	61.0256	58.2833	59.1089
	L (2)	56.3389	61.4833	61.3444
	L (3)	58.3722	57.5222	62.0978

		L (1)	L (2)	L (3)
LTH				
	T (1)	62.4667	59.4889	61.8111
	T (2)	58.0844	61.8444	60.7978
	T (3)	57.8667	57.8333	55.3833

		F (1)	F (2)	F (3)
FI				
	I (1)	57.8611	58.4589	56.7500
	I (2)	56.8944	59.9700	57.8833
	I (3)	60.3833	62.1922	65.1833

		E (1)	E (2)	E (3)
ETH				
	T (1)	57.2889	63.4333	63.0444
	T (2)	60.2978	59.3556	61.0733
	T (3)	58.1500	54.5000	58.4333

		F (1)	F (2)	F (3)
FL				
	L (1)	55.5222	60.5622	62.3333
	L (2)	60.0111	61.7500	57.4056
	L (3)	59.6056	58.3089	60.0778

etc.

This indicates that the largest amount (100 kg/ha) of N will give an additional yield of 430 ± 260 = (170 ~ 690) kg/ha to the yield of 70 kg/ha application.

Since there is significant interaction between factors T and E, the effects of T are investigated for each level of E. The cell means of F x L and E x T are taken from Table 7:

Heading date	Basal dressing $F_1(0)$	$F_2(2)$	$F_3(4)$	Mean	Time	Young panicle formation $E_1(4)$	$E_2(6)$	$E_3(8)$	Mean
$L_1(0)$	55.5	60.6	62.3	59.5	$T_1(-25)$	57.3	63.4	63.0	61.3
$L_2(2)$	60.0	61.8	57.4	59.7	$T_2(-20)$	60.3	59.4	61.1	60.2
$L_3(4)$	59.6	58.3	60.1	59.3	$T_3(-15)$	58.2	54.5	58.4	57.0
Mean	58.4	60.2	59.9	59.5	Mean	58.6	59.1	60.9	59.5

L.S.D. = 4.5 kg/10a

As for the combination of factors F and L, no significant effects are found, except that the combination of F_1L_1 will yield less. In the N application for young panicle formation, few differences are found among the levels of E at T_2 and T_3; however, the highest yields were obtained for E_2(60 kg/ha) and E_3(80 kg/ha) at T_1, that is, 25 days before young panicle formation. The block-mean yields are 61.5 kg, 59.2 kg, and 57.8 kg/10a for B_1, B_2, and B_3, respectively, which reflects the different fertility in the blocks.

Integration of the above results indicates that the optimum condition of the N application is $I_3E_2T_1$ (or $I_3E_3T_1$) with all combinations of the levels of factors F and L except F_1L_1. It specifies the application of 100 kg/ha at the time of irrigation, of 60 kg (or 80 kg) at 25 days before young panicle formation, and of at least 20 kg as basal dressing or at heading, the total amount of N being 180 kg or more. As an example, the expected yield under the condition $I_3E_2T_1F_2L_1$ is estimated as

Mean	Effect of I_3	Effect of F_2L_1	Effect of E_2T_1
59.5 +	(62.6 - 59.5) +	(60.6 - 59.5) +	(63.4 - 59.5)
= 59.5 +	3.1 +	1.1 +	3.9 = 67.6 (kg/10a)

and its standard error is calculated as

$$s_0 = \sqrt{\frac{1+2+8+8}{81} V_e} = \sqrt{\frac{19}{81} \times 21.93} = 2.27$$

The 95% confidence interval of the expected yield under $F_2I_3E_2T_1L_1$ is, therefore, obtained as

$$67.6 \pm t_{(28;0.05)}\, s_0 = 67.6 \pm 2.048 \times 2.27 = 67.6 \pm 4.7 = (62.9 \sim 72.3).$$

Referring to Table 5, the treatment combinations including I_3, E_2 or E_3, T_1 and excluding F_1L_1 are:

No. 9	$F_1I_3E_3T_1L_3$	71.5	(kg/10a)
No. 26	$F_3I_3E_2T_1L_3$	71.75	
No. 44	$F_2I_3E_2T_1L_2$	67.0	
No. 54	$F_3I_3E_3T_1L_2$	68.25	
No. 72	$F_2I_3E_3T_1L_1$	66.20	

The yields of plots 9 and 26 are higher owing to the high fertility of the first block, B_1, while the poor fertility of the third block, B_3, influences the yield of plot 72. Nevertheless, these five yields all lie within the above-obtained interval of the expected yield.

The relationship between the total amount of N and yield is illustrated in Figure 1, which indicates the inadequacy of the total amount of N to explain the variability of the yield. It should be noted, therefore, that the yield is effectively dependent on the time of N application.

CONCLUSION

The fractional factorial designs obtained by use of the tables of orthogonal arrays presented here are shown to be competent for the determination of the optimum amounts of fertilizer applied at several different stages of the growth of rice.

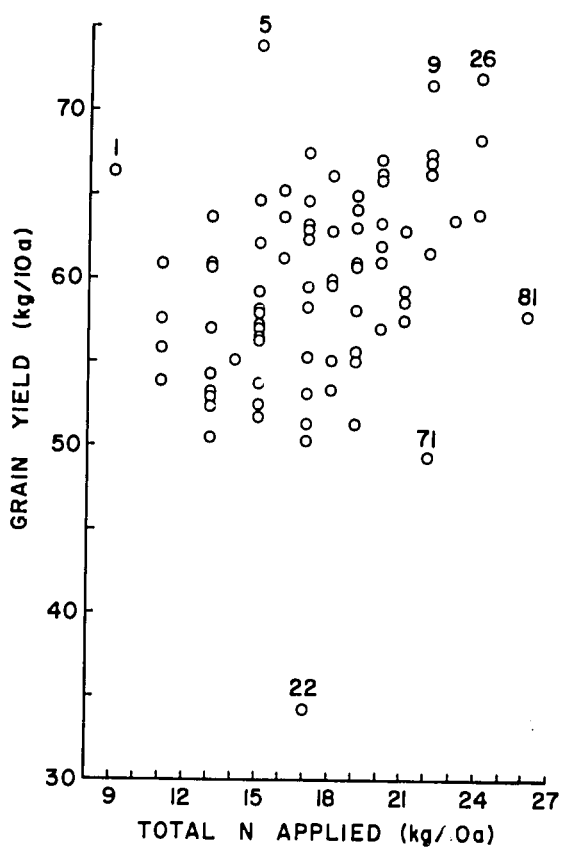

Figure 1. Relationship between the total amount of N and the yield of rice.

Similar analyses can be made of 20 characteristics including culm length, number of tillers at different stages, panicle length, number of panicles per ear, nitrogen content in dry-matter at different stages of growth, and so on. Investigation of these characteristics through various growth stages could lead to the feasibility of the estimation of factorial effects in the yield constitution.

The production function can also be calculated by using the data obtained from this kind of experiment, although the result is not presented in this paper.

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Consideration on Experiment Design and Production Functions

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INTRODUCTION

The estimation of the optimum economic change of the level of a given factor that exerts some influence on the yield of a crop requires knowledge of:

1. the yield production function that expresses the combined influence on the crop yield of the levels of all such factors;
2. the actual levels of the factors in the place where the crop is to be grown;
3. the unit cost of change of the level of the given factor;
4. the unit costs of harvesting, handling, and marketing the produce;
5. the selling price of the produce.

A project should seek to develop procedures that may be used in LDC's to provide items 1 and 2 at a reasonable cost. Items 3, 4, and 5 may be estimated from whatever knowledge may be available for the corresponding site at the time of deciding whether or not to engage in the production of the crop.

PRODUCTION FUNCTIONS

Many different types of equations have been proposed to express the quantitative influence on crop yield of one or more yield-controlling factors. These vary from the simple straight-line relationship within certain limits of Liebig's "Law of the Minimum" to complex exponential equations which include many factors.

To be really useful, a production function should be precise; that is, it should be truly representative of the relation between the levels of the variables involved. In addition, it should be simple enough to be usable in a practical way. It is also essential that adequate and practical procedures be available to properly evaluate or assess the levels of the factors included in the function, both in the experimental designs used to provide the data for the estimation of the function's parameters and in the sites or places where the function is to be used to set the levels of the factors for commercial or subsistence production of the crop.

In a recent article, Pesek (11) reviewed a number of production functions and discussed procedures for their utilization. He rejected some of them because they provide for response surfaces which are asymptotic to a plane and others because they rise with unlimited increases in the levels of the yield-controlling factors. He favored the use of the second order polynomial or its square-root transformation.

None of the equations mentioned by Pesek, however, provides for a point of inflexion in the yield curve at relatively low levels of a yield-controlling factor whose existence, as Russell (12) pointed out, has been known for a long time, nor for the point of inflexion, as Capó (3, 4) showed, that exists at relatively high levels of such a factor. The equation, proposed by Capó, for the influence of a yield-controlling factor on the corresponding yield is

$$Y = \frac{A}{1 + B\,(X - C)^2} \qquad \ldots(1)$$

where Y is the crop yield, X is the level of the yield-controlling factor, A is the maximum yield, C is the level of the factor required for the maximum yield, and B is a constant that depends on the nature of the controlling factor and the particular crop.

This equation has proved useful in explaining the influence of such limiting factors as nutrients and temperature, as may be seen in Tables 1 and 2.

Table 1. Fit of fertilizer-yield equation to pineapple yield data with nitrogen applications[1]

Pounds of nitrogen applied per acre	Yield of pineapple fruit in tons per acre	
	Actual	Calculated
0	21.12	23.05
125	27.07	26.85
250	31.11	31.13
375	35.48	35.68
500	43.83	40.09
625	42.94	43.70
750	44.08	45.79
875	43.89	45.83
1000	46.04	43.83

[1]Fertilizer-yield equation:

$$Y = \frac{46.08}{1 + 0.0000015029\,(N - 815.35)^2}$$

Coefficient of determination (r^2) = 0.9537.

Data obtained by Gonzalez-Tejera at Manati, Puerto Rico (7).

Table 2. Fit of fertilizer-yield equation to Physalospora rhodina growth data with temperature variation[1]

Centigrade temperature	Yield of fungus (dry weight in milligrams per Petri dish)	
	Actual	Calculated
12	0	5.16
16	7	7.86
20	15	13.04
24	25.75	23.79
28	42.75	42.95
32	47.50	48.93
36	36.25	29.86
40	8	16.01

[1]Fertilizer-yield equation:

$$Y = \frac{50.97790}{1 + 0.025321473\ (T - 30.72)^2}$$

Coefficient of determination (r^2) = 0.936.
Data obtained by Alvarez-Garcia (1).

Equation 1 may be modified to include the combined influence of various factors on crop yield, by including the corresponding additional factors in the denominator, for example

$$Y = \frac{A}{(1 + B_N(N - C_N)^2)\ (1 + B_P(P - C_P)^2\ (1 + B_K(K - C_K)^2)} \quad \ldots(2)$$

where N refers to nitrogen, P to phosphorus, and K to potassium. Table 3 shows how the modified equation may be used to explain the combined influence of these three nutrients.

Equation 2 seems to fit better within levels of the limiting factors that do not differ too markedly from the levels needed for maximum yield. This may be seen clearly in Table 2, in which Equation 1 overestimates the yields obtained with very low or very high temperatures. It may also be seen in Table 4, which shows the overestimation of the yields with zero applications of nitrogen and phosphorus.

Equation 2, as well as others that should be studied, may be further modified in attempts to develop production functions which, without being unnecessarily complex, may explain variations in yield due to interaction between the varying levels of the limiting factors. In fact, the following modification of the equation, which does not increase the number of parameters to be evaluated, has improved the explanation of yield variations over that offered by a modified equation of the types used for Tables 3 and 4:

$$Y = \frac{A}{(1 + B_N(N - C_N)^2)\ (1 + B_P(P - C_P)^2)\ (1 + R)} \qquad \ldots(3)$$

where R is the larger of the ratios $N\ C_P\ /P\ C_N$ and $P\ C_N\ /N\ C_P$.

The factor levels to be tested in the experiments to be carried out under this project should be able to provide data for the various types of equations that should be compared as potential production functions. To this effect, the experiments should include widely varying levels of the limiting factors, including levels that might be considered a priori to be either too low or too high for use in practice. The objective should be to evaluate the production functions throughout as wide a range of levels of the factors as possible, to insure the validity of the function to be finally selected and recommended. Since several production functions suggested so far include three or more constants, at least four and preferably six to seven levels of each of the factors under study should be included. There would be no need to include all possible combinations of the levels of the different factors, if the production functions under study are capable of accounting for the existence of interactions.

OPTIMUM ECONOMIC LEVEL OF THE YIELD-LIMITING FACTORS

Once a satisfactory production function is available, the optimum economic levels of the factors may be estimated by using procedures similar to the ones described by Spillman (14) and Capó (6), properly modified to estimate the optimum economic levels of the various limiting factors.

For these calculations, as mentioned in the introduction, it is necessary to know (1) the production function; (2) the actual levels of the yield-limiting factors in the site where the crop is to be grown; (3) the unit costs of changing the levels of the factors; (4) the cost of harvesting, handling, and marketing the crop; and (5) the selling price of the produce.

As regards such limiting factors as temperature and rainfall, the needed information may be gathered with relative ease. With regard to available levels of nutrients in the soil, the problem merits some analysis. This is done in the following section.

ACTUAL AVAILABLE LEVELS OF NUTRIENTS IN THE SOIL

Attention must be drawn to the fact that experimentation with plant nutrients is fundamentally different from experimentation with other yield-controlling factors, such as distance of planting and stable feeding of animals. The soil is able to provide the crop with a certain amount of each of the nutrients, and the response of the crop to the application of a certain nutrient is due to the change in level of that particular nutrient. The crop response to the application of a nutrient thus depends on how well the unfertilized soil may be able by itself to provide the crop with the given nutrient. There is, therefore, the need to measure or estimate how much of each nutrient the corresponding soils can provide to the crop in order to be able to transfer the information obtained in a certain site to another.

Soil chemists have dedicated a great deal of effort and time to evaluating the quantities of available nutrients in soils by analyzing soil samples. To date, however, such analyses, especially in the case of nitrogen, have not

Table 3. Fit of modified fertilizer-yield equation to Sudan grass yield data with varying applications of nitrogen, phosphorus, and potassium[1]

Cwts. NH_3 per acre	Cwts. P_2O_5 per acre	Cwts. K_2O per acre	Pounds of green matter per plot (21.75 ft by 14.5 ft)	
			Actual	Calculated
0.75	0.75	0.75	86.4	83.30
1.50	1.50	1.50	104.9	107.06
0.00	2.25	2.25	79.1	78.85
0.75	2.25	2.25	94.0	97.18
1.50	2.25	2.25	113.7	111.14
2.25	2.25	2.25	116.7	113.58
2.25	0.00	2.25	80.4	82.33
2.25	0.75	2.25	98.7	97.26
2.25	1.50	2.25	108.0	109.09
2.25	2.25	0.00	111.0	112.90
2.25	2.25	0.75	117.0	113.68
2.25	2.25	1.50	110.3	113.92

[1]Modified fertilizer-yield equation:

$$Y = \frac{114.67}{[1+0.11176(N-2.0066)^2][1+0.0758669(P-2.2369)^2][1+0.004434(K-1.4299)^2]}$$

Coefficient of determination (R^2) = 0.9637.
Data obtained by Capō (2).

Table 4. Fit of modified fertilizer-yield equation to Hegari sorghum yield data with varying applications of nitrogen, phosphorus, and potassium[1]

Grams of NH_3 applied per plot	Grams of P_2O_5 applied per plot	Grams of K_2O applied per plot	Dry-matter yield in grams per Mitscherlich pot	
			Actual	Calculated
0	0.1893	0.3654	10.3	18.26
0.3409	0.1893	0.3654	36.8	31.53
0.6818	0.1893	0.3654	42.5	46.77
1.0227	0.1893	0.3654	47.4	42.07
1.0227	0	0.3654	12.0	20.06
1.0227	0.0631	0.3654	25.3	25.06
1.0227	0.1262	0.3654	35.8	32.04
1.0227	0.1893	0	27.9	28.38
1.0227	0.1893	0.1218	34.8	36.30
1.0227	0.1893	0.2436	40.8	42.15
0.3409	0.0631	0.1218	21.5	16.21
0.6818	0.1263	0.2436	36.6	37.69

[1]Modified fertilizer-yield equation:

$$Y = \frac{226.16}{[1=2.6359(N-0.78821)^2][1+30.309(P-0.53371)^2][1+5.6082(K-0.30298)^2]}$$

Coefficient of determination (R^2) = 0.8356.
Data obtained by Capō (2).

proven accurate enough: none of the sampling procedures employed, the extracting solutions used, the soil extracting procedures utilized, or the precision of the chemical determinations have been able to duplicate properly the capacity of a plant to obtain its nutrients from a soil.

The problem of estimating the nutrient status of the soil has also been approached from the standpoint of biological tests, such as Mitscherlich's pot technique and the Neubauer tests. In these cases, there is need to use a plant that is of a different species from the one to be grown commercially. The data obtained in this type of work have also shown the great lack of precision that is attained by using a certain plant species to assess the nutrient status of a soil for the production of a different plant species. In fact, even different varieties of the same species differ both with respect to their capacities to absorb nutrients from the soil and with regard to their nutrient requirements for optimum growth and yield.

This problem has also been approached from the standpoint of leaf analysis. Mitchell and Chandler (9) used the Mitscherlich equation (10) to relate the nitrogen content in the leaves of forest trees with fertilizer nitrogen applications. Capō (5) used the logistics of Mitscherlich and his fertilizer-yield equations to relate the nitrogen, phosphorus, and potassium contents of the leaves of corn and sugarcane with their total available amounts in the soil, that is, the sum of what the soil could provide by itself and the quantities applied. The fits of all three equations to the corresponding fertilizer applications and to the respective nutrient leaf contents were very good. Hernandez-Medina (8) and Gonzalez-Tejera (7) conducted similar studies with pineapples. Table 5 is an example of the use of the Mitscherlich equation to estimate the quantity of available nitrogen in soil. Since a parameter in each of these equations is an estimate of the available quantity of the

Table 5. Use of Mitscherlich's equation to estimate the quantity of nitrogen available to pineapples[1]

Pounds of nitrogen applied per acre at time of planting	Nitrogen in percentage of dry-matter of leaves collected at 13 weeks of age	
	Actual	Calculated
0	1.21	1.20
50	1.52	1.52
100	1.68	1.73
150	1.86	1.87
200	2.01	1.96
250	2.09	2.02
300	2.10	2.05
350	1.94	2.08
400	2.12	2.09

[1]Mitscherlich's equation $L_N = 2.12282 - 0.92607\ (0.99135^N)$, where L_N is the percentage of leaf nitrogen. This equation may be converted to the form

$$L_N = 2.12282\ (1 - 0.99135^{95.56 + N})$$

which indicates that there were 95.56 pounds of nitrogen available to the pineapple crop in the unfertilized soil.

Coefficient of determination (r^2) = 0.9572.
Data obtained by Gonzalez-Tejera (7).

nutrient in the unfertilized soil, it seems that any one of these equations, or perhaps another, may be used to estimate with a high degree of precision the available nutrient contents of a soil from the chemical composition of a leaf sample of the crop growing in the given soil.

The amount thus estimated would be added to the amount applied as fertilizer to change the above-mentioned fertilizer-yield equation into a nutrient-yield equation representing the relation between total available nutrient in the soil and the yield. The equation might then be used to estimate the available soil nutrient level required for a maximum economic return.

Should this approach prove to be as useful as it promises, the analysis of a leaf sample taken at a commercial field might be used to determine how well the initial fertilizer application raised the available levels of the applied nutrients. For crops with long growth periods, these analyses might be used to determine whether the application of additional amounts of nutrients to the standing crop would be profitable. For crops with short growth periods, the analyses might provide information to modify the initial fertilizer applications for future plantings of the crop.

GENERAL YIELD-PRODUCTION FUNCTION

With regard to other yield-limiting factors, such as time of planting or harvesting throughout the year, attempts should be made to characterize with an acceptable precision the influence of the levels of such factors on crop yields. In Puerto Rico, the influence of time of planting as summarized by Samuels (13) has been found to alter severalfold the yields of such crops as corn, sweet potatoes, beans, soybeans, potatoes, sugarcane, and pineapples; in fact, in most cases, the yields are altered much more than by fertilizer applications.

This project should therefore endeavor to determine the possibility of including the influence of all pertinent yield-controlling factors in a general yield-production function for each of the crops to be studied. If success is attained in this effort, the optimum economic level of each factor for each crop studied might be determined.

ADDITIONAL CONSIDERATIONS

1. The soils and climate prevailing in the experimental sites should be representative of areas where the crops under study are grown for commercial purposes or for home consumption.
2. For the evaluation of the production functions to be compared, there is need to obtain the yields to be gained with perhaps up to seven levels of each of the yield-controlling factors. The experiments need not include all possible combinations of all the levels tested of the different factors.
3. It is more important to obtain information relative to the different levels than to use too many replicates. Perhaps no more than two replicates need be used.
4. The experimental designs used may be incomplete blocks with only a few plots per block, possibly not more than two or three plots per block.

5. The experiments for the evaluation of the production functions to be considered should be performed in sites with soils as uniform as possible. These experiments should be repeated by planting in at least two different times of the year.
6. Measurements of temperature, rainfall, water evaporation, and light intensity should be collected at each site, in addition to physical and chemical characteristics of the soils of the experimental sites.

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Economic Aspects of Production Functions for Soils

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Quantitative knowledge of the production surface for some common families of soils in the less-developed countries (LDC's) is a major step toward evaluation of the productivity of resources and relative efficiency of resource use throughout the tropical world. Even if the most optimistic conclusions are drawn from future global population estimates, resource productivity and efficiency of resource use in the tropics will play an increasingly vital role in the solution of world food problems. The present study will measure productivity differentials on a multi-LDC basis for important benchmark soils, and will focus attention on the response surface for selected management practices with potential for high payoff in terms of (a) increasing output from a given set of resources or (b) providing comparable output from a set of fewer inputs. Foremost in this regard, singular attention will be given to the response surface for fertilizer and water.

One of the major hypotheses to be tested in the proposed research is the proposition that input-output relationships for test variates throughout the tropical world may be expressed through a single production function. While there are theoretical objections to such an assumption--including heterogeneity of composition of soil even within the same soil families in different countries, temperature differentials, and rainfall variations--the approach is not without advantages for the choice of an experimental design that will provide both statistical and economic efficiency in development, collection, and analysis of data. Knowledge of some notion of the form of production functions corresponding to transnational soil families, however, is a prerequisite for the design of an experiment. Baum and Heady (1) state: "It is possible that work on fundamental design cannot progress far until more is known about the mathematical form of the biological data and specifications are made for the use of the data." In another paper in this workshop, Capó presents some interesting work he has undertaken to specify an equation conforming to the biological relationships involved in resource use. Knowledge of how the "Capó equation" may be manipulated to generate meaningful economic information may be found in several papers (2, 3, 4, 5) and is expanded below. A primary purpose of this paper will be to set forth interest of the economists and some specifications for drawing economic conclusions from soil research data.

USE OF PRODUCTION FUNCTIONS

Economic interest in biological production functions has led to a rich and somewhat voluminous literature describing cooperative work among agronomists and economists at various institutions. A partial listing of the use economists have found for biological functions in which soils, fertilizers, and water are involved follows:

1. Optimum inter- and intra-county resource allocations of fertilizer and other inputs.
2. Determination of economic optima for yields with respect to plant population and spacing, fertilizer, moisture, and so on.
3. Supply and demand functions for fertilizers.
4. Influence of fertilizers on profitability of various crops in different soils.
5. Optimum resource use under uncertainty conditions.
6. Estimation of isoquants, isoclines, and economic optima in crop fertilization with two or more variable nutrients.
7. Estimation of productivity levels with various soils.
8. Estimation of economic optima under price situations.
9. Derivation of crop supply functions.
10. Estimation of marginal rates of substitution of fertilizers for land, labor, and so on.
11. Determination of optimum crop stand and nutrient combinations.
12. Estimation of production elasticities.

Underlying all research is the need to make practical recommendations to farmers and policy makers, "practical" meaning that the important decision-making variates have been recognized (1). These variables include the price-cost relationship for each crop studied, levels of soil fertility, and crops suited for the farming area. With transnational research, differences in cultural practices, farm technology, sources of fertilizers, and labor costs also become important sources of heterogeneity. Most of the economic determinations listed above, however, may be derived from knowledge of the production response to the variables under study, knowledge of the opportunity costs of test inputs, and estimates of output prices.

DESIRABLE ATTRIBUTES OF PRODUCTION FUNCTIONS

There is a scientific principle--known as the "Law of Parsimony"--that seems to apply to the choice of production functions. This law, which emerged sometime in the 14th century, says that you should not explain a behavioral phenomenon by a higher, more complex process if a lower or simpler one will do. Translated to research terms, this means that we should select the simplest, least complex, and easiest to calculate equation that provides a tolerable approximation to the biological response surface for fertilizers, water, and so on, and that also contains attributes that are meaningful and desirable for economic interpretation. Some of these attributes are:

1. The functions should provide for diminishing marginal productivities and declining total product at higher input levels.
2. In cases where the nutrient content of the soil is relatively high, and soil-contained nutrients are not contained in the estimates, the production function must allow for isoclines to converge at the point of maximum yield, without intersecting the origin (6).

3. If soil-contained nutrients are determined prior to experimental treatment, a production function allowing for isocline origin on the axis rather than at the origin, but in which isoclines converge at the maximum, is appropriate (6).
4. If there are reasons to believe that constant elasticities of production do not prevail, then an algebraic function that provides for non-constant elasticities over the relevant range of input levels must be considered.
5. If returns to scale are of interest, a production function permitting increasing, decreasing, or constant returns may be desirable.

Methodological considerations of the economist thus become inextricably interlaced with choice of experimental design. Johnson (8) has provided an able statement of design considerations for attaining desirable characteristics for economic analysis. Paraphrasing Johnson, those design considerations that provide data in a form for making appropriate economic recommendations are attained by:

1. Ascertaining from known information the range of combinations of test variables for which marginal productivities are decreasing, and concentrating experimental observations on these combinations.
2. Securing observations for a sufficient number of combinations in the area for which marginal productivities are decreasing to give wide choice in selecting an appropriate equation for economic manipulation. While this may reduce the number of replications, the requirement insures that data on the interactions among inputs will be available.
3. Allocating experimental observations among the possible combinations of test variables in such a way as to minimize the linear correlations among terms whose coefficients are likely to be estimated. Minimizing intercorrelation among the terms whose coefficients are to be determined reduces the standard error of the estimated coefficients.
4. Allocating experimental observations among the possible combinations of test inputs in such a way as to increase the standard deviation of the variables whose coefficients are likely to be determined.
5. Maximizing, considering the resources available for testing, the number of observations made.

SOME ECONOMIC ASPECTS OF THE CAPŐ FUNCTION

Heady and Dillon (6) showed that there are numerous algebraic equation forms that may be used in deriving production functions, and they review a number of these, including the Cobb-Douglas, square root, hyperbolic, Spillman, and various polynomial equations. These functions have been amply used and described elsewhere and will not be expanded upon in this paper. Instead, some of the uses to which the Capő function may be put are presented, not because it is the best of all possible equations, but because it is less known and is an alternative that should be considered when fitting various equations to determine response surfaces for fertilizer and other input use. The rather simple illustration that follows summarizes the concepts that are needed to derive the optimum application of inputs of the Capő function.

Assuming that the quantity of output, Y, is a function of the quantities of variable inputs, X_1 and X_2, the production function may be stated:

$$Y = f\ (X_1,\ X_2) \qquad \ldots(1)$$

Profit, π, is the difference between total cost, C, and total value of output, Y. Total value is given by the yield, Y, multiplied by its price, P_y:

$$\pi = (P_y\ Y) - C \qquad \ldots(2)$$

Total cost, C, is given by the level of inputs, X_1 and X_2, multiplied by their respective prices, P_{x1} and P_{x2}:

$$C = P_{x1}\ X_1 + P_{x2}\ X_2 \qquad \ldots(3)$$

Substituting $Y = f\ (X_1,\ X_2)$ and $C = P_{x1}X_1 + P_{x2}\ X_2$:

$$\pi = P_y\ f(X_1,\ X_2) - P_{x1}\ X_1 - P_{x2}\ X_2 \qquad \ldots(4)$$

Setting the partial derivatives with respect to X_1 and X_2 equal to zero:

$$\frac{\partial y}{\partial X_1} = \frac{\partial Y}{\partial X_1}\ P_y - P_{x1} = 0 \qquad \ldots(5a)$$

and

$$\frac{\partial y}{\partial X_2} = \frac{\partial Y}{\partial X_2}\ P_y - P_{x2} = 0 \qquad \ldots(5b)$$

and moving the input price terms to the right:

$$\frac{\partial Y}{\partial X_1}\ P_y = P_{x1} \qquad \ldots(5c)$$

and

$$\frac{\partial Y}{\partial X_2}\ P_y = P_{x2} \qquad \ldots(5d)$$

The first-order conditions for profit maximization require that each input be utilized up to a point at which the value of its MP equals its price (7), as set forth in the above equations.

The form of production function suggested by Capō is

$$Y = \frac{T}{1 + D\ (X - C)^2} \qquad \ldots(6a)$$

where Y is the predicted crop yield, T is the maximum yield, X is the level of the yield-controlling factors, C is the level of the factors required for the maximum yield, and D is the coefficient that depends on the nature of the controlling factors. Substituting nitrogen (N) for X, the equation becomes

$$Y = \frac{T}{1 + D_n\ (N - C_n)^2} \qquad \ldots(6b)$$

As noted, the marginal productivity of N is the first derivative with respect to output:

$$\frac{dY}{dN} = \frac{-2\ A\ D_n\ (N - C_n)}{\{1 + D_n\ (N - C_n)^2\}^2} \qquad \ldots(7)$$

Maximum physical product is obtained when the marginal productivity above is set equal to zero. The profit-maximizing quantities of inputs, however, are found by introducing the price terms for inputs and output, and seeking that output at which the marginal value product of each input is equal to the price of the input. The following equation sets forth this relationship, with P_y representing the price of output and P_n the cost of nitrogen applied:

$$\frac{d\pi}{dN} = \frac{dY}{dN} P_y = P_n$$

$$= \frac{-2 A P_y D_n (N - C_n)}{[1 + D_n (N - C_n)^2]^2} \qquad \ldots(8)$$

THE DERIVATION OF YIELD AND PROFIT FUNCTIONS FOR SUGARCANE

The fertilizer experiments described in this paper were conducted in Puerto Rico with sugarcane to study the relationship between the nutrient content in the soil and the nutrient content in the leaves of the plants (5). In each experiment, nine levels of only one fertilizer material were used, and leaf samples were gathered and analyzed for total content of the corresponding nutrient under study. The relationship between nutrient status of the soil and nutrient leaf content was assumed to be of the diminishing-return type, the leaf content approaching a maximum value as an asymptote as the soil's available content of the nutrient increases indefinitely. A number of different curves were fitted to the data regarding fertilizer applications and respective leaf analysis, and the Mitscherlich equation was found to be as good as any tried. Leaf samples were taken from the plots that received the different fertilizer treatments when plants were 3 to 4 months of age.

After collection of leaf tissue observations, the Mitscherlich equation was used to estimate pretreatment nutrient content of the leaf blades and amounts of nutrients corresponding to different treatment levels of nitrogen, phosphorus, potassium, and magnesium. Predicted leaf content of the various nutrients, with statistics of the fitted equation, are shown in Table 1. The equation fit, as judged by their corresponding r^2 values, was relatively good with nitrogen and magnesium, and very good with phosphorus and potassium.

Table 2 presents sugarcane yields predicted from the bell-shaped fertilizer-yield curve

$$Y = \frac{T}{1 + D (X - C)^2} \qquad \ldots(9)$$

where Y is the predicted sugarcane yield expressed as tons cane per acre (TC/A), X is the units of fertilizer applied, and other symbols denote values already expressed. In this case, the production surfaces represent those predicted yields after fitting the equation to represent the relation between applied nutrients and the cane yield. Analysis of regression showed the coefficient of determination was significant only for the nitrogen experiment wherein the maximum yield exceeded the zero-level treatment by about 50 percent.

To express the relation between the total available quantities of a nutrient in the soil and the cane yield, there is need to determine the pretreatment nutrient content of the soil. In the case of the nitrogen experiment,

this was estimated to be 6.895 units[1]. Substituting N for X in the equation, and adding the amount of pretreatment nutrients, 6.895, to the value E = 1.291, the relation between total available quantity of N in the soil and the cane tonnage, Y, is

$$Y = \frac{56.50}{1 + 0.1715\ (N - 8.186)^2} \qquad \ldots(10)$$

Since profit is the difference between gross income and expenditure, if: π = profit per acre; Y = cane tonnage per acre; N = units of nutrient per acre; P_n = cost of one unit of nutrient applied; and P_y = farm value of one ton of cane ready for harvest, then the gross income per acre is P_y Y and the expenditures per acre are $P_n N$. Thus, the profit equation is:

$$\pi = P_y\ Y - P_n\ N$$

$$= \frac{P_y\ T}{1 + D\ (N - C_n)^2} - P_n\ N \qquad \ldots(11)$$

The optimum economic level of the nutrient in the soil is the value of N, which will make the first derivative of π with respect to N equal to zero, and its second derivative positive in value. The first derivative of π, equated to zero is:

$$\frac{d\pi}{dN} = D^2 P_n\ (N - C_n)^4 + 2DP_n\ (N - C_n)^2 + 2P_y TD\ (N - C_n) + P_n = 0 \qquad \ldots(12)$$

which, if one defines $Z = N - C_n$, becomes:

$$\frac{d\pi}{dn} = D^2 P_n Z^4 + 2DP_n Z^2 + 2P_y TDZ + P_n = 0 \qquad \ldots(13)$$

If P = \$125 per unit of nitrogen and P_y = \$10 per ton of cane, the relation between nitrogen and cane tonnage is:

$$\frac{d\pi}{dn} = (0.1715)^2\ (125)\ Z^4 + 2\ (0.1715)\ (125)\ Z^2 + 2\ (10)\ (56.50)\ (0.1715)\ Z$$

$$= 125 - 3.6765\ Z^4 + 42.8750\ Z^2 + 193.7950\ Z + 125 = 0 \qquad \ldots(14)$$

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[1]The fitted Mitscherlich equations of Table 1 represent the relations between the quantity applied of a given nutrient and the leaf content of the nutrient. The relations between the total available content of a nutrient may be derived from these equations by transforming them into the more common form of expressing the Mitscherlich equation: $L = A\ (1 - C^{S + X})$, where S = available nutrient content of the unfertilized soil. The transformation is carried out by stating that $B = AC^S$, whereupon $L = A - BC^X = A - AC^S C^X = A\ (1 - C^{S + X})$.

If one now defines N = S + X, the relation between the soil's available and leaf nutrient contents is $L = A\ (1 - C^N)$. That is, $N = \frac{\log\ (A - L) - \log A}{\log C}$.

This, then, is the relation proposed to be used in estimating the content of a nutrient by the soil of a commercial field in a form available to the sugarcane plant.

Since $B = A\ C^S$, $S = \frac{\log B - \text{Log } A}{\log C}$. Thus, the nitrogen content of the unfertilized soil of the nitrogen experiment of Table 1 was $S = \frac{\log 0.9917}{\log 0.8708}$ log 2.574 = 6.895 units of nitrogen.

The value of Z that makes the first derivative equal to zero and the second derivative positive is - 0.791. Since $Z = N - C_n$ but $C_n + S = 8.186$, $N = C_n + S + Z = 8.186 - 0.791 = 7.395$. As the nutrient content of the unfertilized soil was 6.895, the optimum economic quantity of nitrogen to apply is 7.395 - 6.895 = 0.500 unit.

The estimated cane yield with 0.500 unit of nitrogen would be:

$$Y_{0.500} = \frac{56.50}{1 + 0.1715\ (0.500 - 1.291)^2} = 51.02 \text{ tons} \qquad \ldots(15)$$

More work with this function is needed to study other economic applications and derivations, including isocline characteristics, isoquant equations, extension to more than one variable, and other manipulations of economic consequence.

Table 1. Results obtained on fitting Mitscherlich equations leaf-blade data of sugarcane variety P.R. 980 grown in Cialitos clay at Corozal, Puerto Rico[a]

	N		P		K		Mg	
Treatment no.	Units applied[b]	Yield content (%)	Units applied[a]	Yield content (%)	Units applied	Yield content (%)	Units applied	Yield content (%)
1	0.00	1.620	0.00	0.125	0.00	1.285	0.00	0.075
2	0.05	1.545	0.05	0.140	0.05	1.300	0.12	0.085
3	0.10	1.575	0.10	0.145	0.10	1.395	0.24	0.115
4	0.15	1.550	0.15	0.140	0.15	1.370	0.36	0.130
5	0.20	1.685	0.20	0.145	0.20	1.765	0.48	0.150
6	0.30	1.605	0.50	0.170	0.50	1.865	0.60	0.100
7	0.60	1.665	0.75	0.160	2.00	2.110	0.72	0.145
8	1.20	1.780	1.00	0.185	5.00	2.195	0.96	0.170
9	2.00	1.790	1.50	0.205	10.00	2.445	1.20	0.175
Statistics of the fitted equations[c]								
A		2.574		1.123		2.263		1.076
B		0.9917		0.9889		0.1013		0.9915
C		0.8708		0.9514		0.1486		0.9180
r^2		0.766*		0.926**		0.925**		0.764*

[a]Experiments planted on May 9, 1963; leaf-blade samples at 4 months of age, on September 9, 1963.

[b]One fertilizer unit = 1000 pounds of the element per acre: nitrogen as ammonium sulfate, phosphorus as calcium superphosphate, potassium as muriate of potash, and magnesium as magnesium sulfate. Soil pH = 4.72.

[c]Form of Mitscherlich equations fitted: $L = A - BC^X$, where L = percentage content of the leaf blades; X = units of fertilizer applied; and A, B, and C = estimates of parameters. r^2 = coefficient of determination. * = significant at the 5% level, ** = significant at the 1% level.

Table 2. Results obtained on fitting fertilizer-yield equations to cane production data of sugarcane variety P.R. 980 grown in Cialitos clay at Corozal, Puerto Rico[a]

Treatment no.	N		P		K		Mg	
	Units applied[b]	Predicted yield (TC/A)[c]	Units applied	Predicted yield (TC/A)	Units applied	Predicted yield (TC/A)	Units applied	Predicted yield (TC/A)
1	0.00	38.7	0.00	46.0	0.00	52.3	0.00	58.3
2	0.05	43.3	0.05	43.0	0.05	56.0	0.12	53.7
3	0.10	48.7	0.10	48.3	0.10	59.0	0.24	58.2
4	0.15	49.5	0.15	59.5	0.15	51.2	0.36	53.8
5	0.20	47.7	0.20	44.0	0.20	58.3	0.48	55.2
6	0.30	49.5	0.50	54.8	0.50	55.8	0.60	60.2
7	0.60	50.2	0.75	57.2	2.00	55.2	0.72	52.7
8	1.20	56.3	1.00	46.7	5.00	61.3	0.96	56.0
9	2.00	52.2	1.50	51.5	10.00	55.8	1.20	57.5
Statistics of the fitted equations[d]								
T		56.50		53.69		59.99		55.56
D		0.1715		0.1992		0.0032		-0.0776
E		1.291		0.8362		5.365		0.5754
r^2		0.719		0.175		0.282		0.062

[a]Experiments planted on May 9, 1963; harvested at the age of 13 months, on June 8, 1964.

[b]Tons cane per acre.

[c]One fertilizer unit = 1000 pounds of the element per acre: nitrogen as ammonium sulfate, phosphorus as calcium superphosphate, potassium as muriate of potash, and magnesium as magnesium sulfate. Soil pH = 4.72.

[d]Form of Mitscherlich equations fitted: $L = A - BC^X$, where L = percentage content of the leaf blades; X = units of fertilizer applied; and A, B, and C = estimates of parameters; r^2 = coefficient of determination.

GENERAL CONSIDERATIONS

The contractual objective of this project is to assess the transferability of soils research information on the basis of soil classification within tropical countries. Extending the project scope to include economic aspects will permit inference from the production functions of what would be the most economical and optimum way to maximize the net returns from fertilizer and other management variables in the LDC's. These conclusions will be drawn from the marginal productivities of the different resource inputs considered in the project, knowledge of the extent of the kinds of soils used in the experiments, and importance of the test crops in the LDC's. Inasmuch as testing for extrapolatability of soils knowledge is a central objective of the project, experimental design and subsequent statistical evaluation must anticipate testing for differences among and within countries. Assuming that some form of block design is used, significantly different yields for blocks on the same soil at a particular site or among different countries would suggest that the production function be first fitted for each block (6). Statistical tests to determine differences between corresponding coefficients in the production function would then be made. If there is no evidence that the blocks had different response surfaces, regressions using pooled data could then be computed (6), and extrapolation could be provided through coefficients denoting nonsoil variables, such as latitude, rainfall, and temperature.

Capó focused attention on the inherent nutrient-providing capability of soil, such that crop response due to nutrient treatments is a function of (a) the amount of pretreatment nutrients available, (b) the change in the level of test nutrient, and (c) the response surface. It is a basic assumption of this project that the taxonomic classification provides a semi-qualitative assessment of the nutrient status of the soil. If soil classification can be used to determine pretreatment fertility level, then the basic production function can be used to transfer soil knowledge--that is, to predict crop response and optimum nutrient application on a given kind of soil in any location. If soil classification does not provide a sufficiently rigorous data system, then soil testing and tissue analysis will be used to determine the amount of nontreatment nutrients. The basis for extrapolation will be the pretreatment nutrient status of the soil, and the treatment response from such fertility base as predicted by the production function.

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Experimental Design for Predicting Crop Productivity with Environmental and Economic Inputs

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PURPOSE

It is the purpose of this proposal to test the hypothesis that agricultural technology manifested through crop productivity can be exchanged between diverse geographical tropical regions, provided the technology developed at one site is transferred and practiced on soil of the same or similar family at the other site.

To test the validity of the hypothesis, an experimental design is suggested, which might serve as a preliminary effort requiring minimum expenditures of AID resources for maximum gains.

The design implicitly tests the suitability of the soil family (U.S. Soil Taxonomy) to serve as a vehicle for the transfer of agrotechnology among tropical regions.

RATIONALE FOR EXPERIMENTAL DESIGN

The preliminary effort should not seek to isolate and measure those specific soil properties that could strongly influence crop responses. Rather, the research design should view the soil family as a pedological unit operating on crop responses. The same consideration should be extended to the environment external to the soil. The separate factors of climate, plant physiology, biotic population, and so on, and their interactions have varying effects on plant responses, and testing these parameters becomes an awesome and unmanageable task. Taken as a whole, the influence of the normal external environment at a site can be considered as constant in the experimental design. It is proposed, therefore, that a soil management innovation become the independent variable that will operate on crop productivity through the design described below.

A tropical agronomic crop is selected as an indicator plant from several crops important to the economy of the agricultural sector in LDC's. The crop might be cultured at four different geographical testing sites (the replicates) on similar benchmark soils employing practices unique for each site and presently reliable enough to produce satisfactory yields under normal environmental conditions.

The relative crop responses (the dependent variables) to a soil management innovation (the independent variable) are compared between sites. A soil innovation would include those factors of the soil which strongly influence yields on upland soils of the tropics--as, for example, the levels of soil nitrogen and phosphorus, which are serious constraints to crop production in the tropics.

If a statistical variance of response between treatments is detected and an interaction between site and treatment is not, the null hypothesis is accepted and the influence of treatment on an identical soil family among diverse sites is manifest. In essence, by measuring plant responses to a soil innovation at all sites, the experiment will test the "predictability" of a relative response to a soil management innovation. If the transfer of agrotechnology can be accomplished with reliability, then the economics of the innovation can be ascertained.

ASSUMPTIONS AND RESTRICTIONS INHERENT IN THE DESIGN

1. The benchmark soil at each site is correctly classified at the family level.
2. A comparable soil family is available at each site.
3. The varieties of the indicator crop used at a specific site are responsive to soil treatments.
4. The normal external environment of the benchmark soils prevails during the test period, or abnormal situations can be assessed.
5. The technical innovation is soil-oriented or an operation on the physical and chemical properties of the soil.

EXPERIMENTAL DESIGN

Four sites will be selected within the tropical world at different locations. In each case the site should be associated with an agricultural institution. To test the interaction of the site and treatment on crop productivity, a factorial experiment is suggested. As an example, the following treatments are proposed.

At each site, a soil management innovation is introduced, involving the preplant addition of a slow-release nitrogen compound and phosphorus from rock phosphate applied to groundnut at three respective rates. The design is a randomized block of treatments replicated three times. Yield data are plotted against level of treatments for each site. Divergence of the plotted parallel lines between sites is indicative of a site or soil interaction with the innovation. If it is subsequently determined that the divergence is soil related, then the hypothesis that agrotechnology transfer is feasible at the soil family level is weakened and the soil property(ies) contributing to the divergence should be ascertained (Tables 1 and 2).

The statistics employing the same treatment per site and between sites for two families are depicted in Tables 3 and 4.

Table 1. Analysis of variance of yield at each site for a single soil family

Source of variation	Degrees of freedom
Total	26
Block (Replications)	2
Treatments	(8)
N	2
P	2
N X P	4
Error	16

Table 2. Analysis of variance of yield between diverse sites and treatment for a single soil family

Source of variation	Degrees of freedom
Total	107
Sites [diverse locale (S)]	3
Replicates/site	8
Treatments (T)	(8)
N	2
P	2
N X P	4
S X T	(24)
S X N	6
S X P	6
S X N X P	12
Error	64

Table 3. Analysis of variance of yield at each site for two soil families

Source of variation	Degrees of freedom
Total	53
Soils (So)	1
Replicates/soil	4
Treatments (T)	(8)
N	2
P	2
N X P	4
So X T	(8)
So X N	2
So X P	2
So X N X P	4
Error	32

Table 4. Analysis of variance of yield between diverse sites and treatment for two soil families

Source of variation	Degrees of freedom
Total	215
Soils (So)	1
Sites/soil (S/So)	6
Replicates/site/soil	16
Treatments (T)	(8)
N	2
P	2
N X P	4
So X T	(8)
So X N	2
So X P	2
So X N X P	4
S/So X T	(48)
S/So X N	12
S/So X P	12
S/So X N X P	24
Error	128

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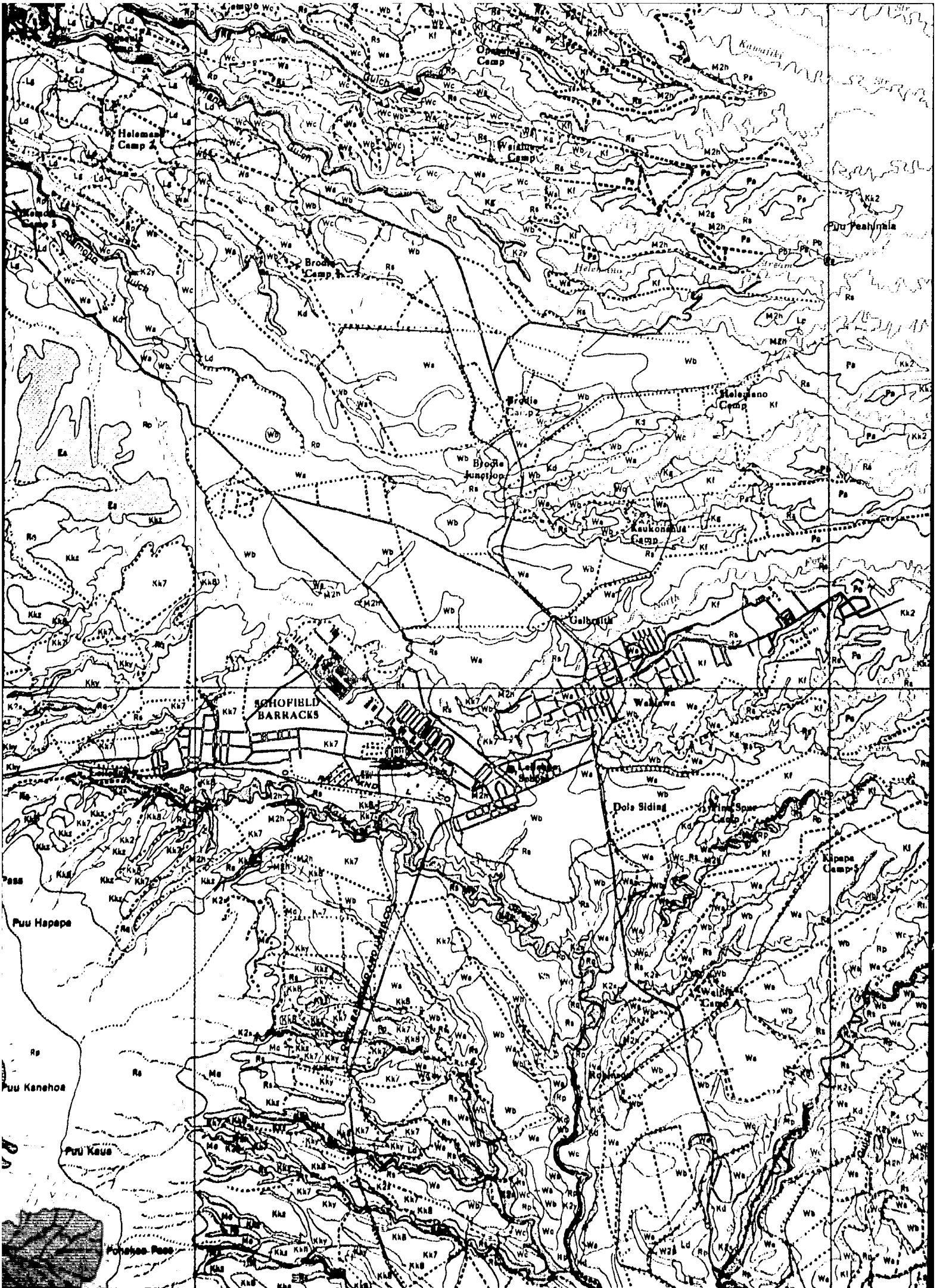
Helemano Camp 2
Helemano Camp 5
Brodie Camp 3
Brodie Camp 2
Brodie Junction
Helemano Camp
Kaukonahua Camp
Galbraith
SCHOFIELD BARRACKS
Wahiawa
Dole Siding
Kipapa Camps
Puu Hapapa
Puu Kanehoa
Puu Kaua
Puu Peahinala

NOTE: As part of a structural reorganization, the Hawaii Agricultural Experiment Station and the Hawaii Cooperative Extension Service have been merged administratively under the name HAWAII INSTITUTE OF TROPICAL AGRICULTURE AND HUMAN RESOURCES, College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa.

Hawaii Institute of Tropical Agriculture and Human Resources
College of Tropical Agriculture and Human Resources
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