SUPPORTING PAPERS: WORLD FOOD AND NUTRITION STUDY

VOLUME I

Study Team 1
Crop Productivity

Study Team 2
Animal Productivity

Study Team 3
Aquatic Food Sources

The National Research Council

INSTITUTE OF MEDICINE · NATIONAL ACADEMY OF ENGINEERING · NATIONAL ACADEMY OF SCIENCES

SUPPORTING PAPERS: WORLD FOOD AND NUTRITION STUDY

VOLUME I

Study Team 1
Crop Productivity

Study Team 2
Animal Productivity

Study Team 3
Aquatic Food Sources

Commission on International Relations
National Research Council

NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C.   1977

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

Library of Congress Catalog Card Number 77-087579

International Standard Book Number 0-309-02647-4

Available from:
Printing and Publishing Office
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America

This is Volume I of *Supporting Papers, World Food and Nutrition Study*. The other volumes are:

Volume II

Study Team 4	Resources for Agriculture
Study Team 5	Weather and Climate

Volume III

Study Team 6	Food Availability to Consumers
Study Team 7	Rural Institutions, Policies, and Social Science Research
Study Team 8	Information Systems
Study Team 10	Interdependencies

Volume IV

Study Team 9	Nutrition
Study Team 12	New Approaches to the Alleviation of Hunger

Volume V

Study Team 14	Agricultural Research Organization

PREFACE

Shortly after the World Food Conference held in Rome in 1974, the President of the United States wrote to the President of the National Academy of Sciences asking the Academy to make an assessment of the problem of hunger and malnutrition and "develop specific recommendations on how our research and development capabilities can best be applied to meeting this major challenge."

The study was begun in June 1975 by a Steering Committee appointed by the President of the Academy. It produced two reports for the President: an _Interim Report_, published by the Academy in November 1975, and a final report, _World Food and Nutrition Study: The Potential Contributions of Research_, published in June 1977. The Steering Committee was assisted by 14 study teams appointed by the Academy to analyze and make recommendations to the Committee on various portions of the study (Table 1).

This publication is one of five volumes containing the reports of Study Teams 1-10, 12, and 14. Study Team 11's report overlapped the other reports and has been integrated with them. Study Team 13's report of its ranking of research priorities was an integral part of the work of the Steering Committee. Consequently, it is not published here. Study Team 13's work is explained in detail in Appendix B of the Steering Committee's report.

The Steering Committee is deeply grateful to the chairmen and members of the study teams for their dedicated work, undertaken for the most part under heavy pressure of time. This work provided the greater part of the source materials for Chapters 2 and 3 of the Steering Committee's report, dealing respectively with "High Priority Research" and "How to Get the Work Done." The study teams are responsible for the content of their reports, which were reviewed by appropriate members of the Steering Committee.

Study Teams 1-12 were asked to identify areas of research and development that had outstanding prospects for helping to meet world food and nutrition problems

Table 1. Study teams, World Food and Nutrition Study

Study Team	Title		
1	Crop Productivity		
		Subgroup A	Pest Control
2	Animal Productivity		
		Subgroup A	Animal Health
3	Aquatic Food Sources		
4	Resources for Agriculture		
		Subgroup A	Farming Systems
		B	Land and Water
		C	Fertilizers
		D	Energy and Equipment
5	Weather and Climate		
6	Food Availability to Consumers		
		Subgroup A	Food Losses
		B	Food Processing and Preservation
		C	Food Marketing and Distribution
7	Rural Institutions, Policies, and Social Science Research		
		Subgroup A	Policies and Program Planning
		B	Research, Education and Training, and Extension
		C	Finance, Input Supplies, and Farmers' Organizations
8	Information Systems		
9	Nutrition		
10	Interdependencies		
		Subgroup A	Population and Health
		B	Energy, Resources, and Environment
		C	International Trade Policy and Comity Between Nations
		D	National Development Policies
11	New Approaches to Increasing Food Supplies		
12	New Approaches to the Alleviation of Hunger		
13	Research Priority Assessment		
14	Agricultural Research Organization		
		Subgroup A	Research Organization in the United States
		B	Global Agricultural Research Organization
		C	Development of Research Personnel

over the next several decades. For each such area, they were asked to respond to three questions:

-- What advances in knowledge will specific areas of research produce, and what is the scientific or technological significance of these advances?
-- If the research produces results, what effect would they likely have on reducing global hunger and malnutrition over the next several decades?
-- What supportive action will be required to conduct research for the accelerated activity recommended (e.g., more resources, policy changes, organizational changes)?

The study teams were asked to base their selection of research areas on their answers to the first two questions. Answers to the first and third questions provided insight on the feasibility of each research area. This information was used by Study Team 13 and the Steering Committee in the selection of research priorities. It also provided raw material for Study Team 14 and the Steering Committee when they considered steps to mobilize and organize resources to implement the proposed research.

Each study team's selection of high priority research areas involved two steps. In the first step, the study teams reviewed research recommendations and possibilities for research provided by existing reports, by the study team members themselves, and by hundreds of other people who were consulted, including many from other countries. From the hundreds of research possibilities, each team selected a limited set that would likely have the greatest global effect on hunger and nutrition. The second step narrowed this set to research areas whose potential was thought to stand out well beyond that of the rest of the group.

The Steering Committee hopes that these study team reports will provide rich source materials for those interested in pursuing the various subject areas in greater depth than could be done in the report of the Steering Committee.

Harrison Brown
CHAIRMAN
Steering Committee
World Food and Nutrition Study

Report of Study Team 1

CROP PRODUCTIVITY

STUDY TEAM 1

Richard H. Wellman, CHAIRMAN, Boyce Thompson Institute for Plant Research
Peter S. Carlson, LEAD ANALYST, Michigan State University
Samuel R. Aldrich, University of Illinois
Frederick Ausubel, Harvard University
John D. Axtell, Purdue University
Glenn W. Burton, U.S. Department of Agriculture
Ralph W. F. Hardy, du Pont Company
A. Colin McClung, The Rockefeller Foundation
Woodrow W. McPherson, University of Florida
T. Kelley White, Purdue University
Israel Zelitch, Connecticut Agricultural Experiment Station

SUBGROUP A PEST CONTROL

Ray F. Smith, CHAIRMAN, University of California, Berkeley
John H. Perkins, LEAD ANALYST, Miami University
Perry L. Adkisson, Texas A&M University
Boysie E. Day, University of California, Berkeley
John B. Siddall, Zoecon Corporation
H. David Thurston, Cornell University

ACKNOWLEDGMENTS

Study Team 1 would like to acknowledge the help of Nyle C. Brady who served as a consultant during the preparation of this report. We also would like to thank the great number of scientists who reviewed parts or all of our report at various stages of completion.

Subgroup A is appreciative to Waldemer Klaussen of the U.S. Department of Agriculture for providing them with an excellent paper on the autolethal method of pest control. They also wish to thank Carl Cox, Texas Natural Fibers and Protein Commission; K. F. Mattil, Texas A&M University; Janice V. Perino, Miami University; Hans D. Van Etten, Cornell University; and Olan C. Yoder, Cornell University for their assistance.

TABLE OF CONTENTS

SUBGROUP A PEST CONTROL

INTRODUCTION

RESTORING ERODED RESEARCH SUPPORT

Agricultural research efforts have led to an abundance of food in this country yet the number of agricultural research scientists has been allowed to decline, and their operating budgets have been reduced in terms of constant dollars. A study of the patterns of federal and state funding of agricultural research over the last decade shows a significant decline in constant-dollar levels of support.

We recommend restoring funding of the present problem-oriented research effort to levels lost to inflation over the last decade. The simple allocation of funds will not solve all of our agricultural needs, but a strong crop-oriented effort is essential to utilize effectively the results of basic research.

We strongly urge not only restoring but increasing funding of current research in areas that are crop oriented and problem oriented (e.g., extension of conventional breeding methods). In the next section, we identify several areas of more basic-type research that offer the most promise for meeting long-term food needs. These two types of research complement each other--basic research approaches provide new tools for problem-oriented researchers to apply to their immediate needs.

NEW SUPPORT FOR MISSION-ORIENTED BASIC RESEARCH

Initially we assembled areas of research that had been identified as having a high probability of increasing crop yields. From these areas, we selected eight as having a good chance of success: (1) nonconventional technologies for plant breeding, (2) photosynthetic carbon dioxide fixation, (3) biological nitrogen fixation, (4) plant adaptation to stress, (5) improvement of proteins in cereals, (6) roots and their interactions, (7) physiological components in crop yield, and (8) interactions of species. Successful research in each area could mean feeding at least 100 million additional people.

Table 1 shows each research area's chance of success and potential impact. Certainly some areas will not develop as anticipated, while others may exceed expectations. Research areas 1 through 5 have the greatest long-term potential, but all deserve support including area 8 because of its high chance of short-term success.

The initial funding recommendations adequately reflect the requirements outlined in our research profiles. The longer range funding recommendations are based on expectations of success and upon necessary developmental efforts. We are proposing that by the end of 10 years a total of $250 million annually in new funding may be needed.

EXPLORATORY PLANT BIOLOGY RESEARCH

A number of research areas warrant exploratory efforts but are not yet defined enough to justify an organized, mission-oriented approach. Mission-oriented efforts should be conducted only when there is enough background information to set a goal for technological development and to determine what the magnitude of the effort should be.

In addition, grant programs should be established to expand exploratory efforts in the plant sciences. As grant programs produce research results, mission-oriented research can be initiated to exploit defined areas of technological development, and funds for exploratory research can then be shifted to other areas.

While such research efforts will benefit the developing countries, and in fact all world agriculture, they will primarily benefit the United States where existing agricultural technology is the most thoroughly utilized. We propose an initial funding of $20 million per year, which within 10 years would be expected to expand to $100 million per year.

This exploratory research effort is intended to provide a knowledge base. Hence projects funded under this program need not demonstrate direct agronomic utilization. For example, in the 1960s the study of nitrogenase on bacteria such as Clostridia laid the groundwork for current developments in biological nitrogen fixation with Rhizobia and the discovery of nitrogen fixation associated with the roots of grain and grass species. Equivalent information could not have been obtained directly with Rhizobia even though these bacteria have direct agronomic usefulness.

Table 1. Chance of success, effect, and funding recommendations for eight mission-oriented research areas*

Research area	Short-term		Long-term		Funding recommendations ($ millions)	
	Chance of success (percent)	Potential effect (million tons of grain)	Chance of success (percent)	Potential effect (million tons of grain)	First year	Tenth year
1. Breeding	35	40	75	60	25	40
2. Photosynthesis	30	20	70	60	10	40
3. Nitrogen	25	20	75	60	15	40
4. Stress	50	40	75	60	5	20
5. Proteins	40	40	75	60	10	30
6. Roots	35	20	60	40	7.5	30
7. Yield factors	15	10	45	60	15	25
8. Interactions	80	20	85	40	5	25

*These areas were rated for chance of success, including implementation, both in the short term (within 15 years) and in the long term (15 to 30 years).

CROP PROTECTION

In spite of the many advances made in pest control, it is estimated that one-third of all potential production of food from crops is lost to pests between planting and harvesting. The chances are high that in one or more countries on one or more crops pests could completely eliminate any yield in a given year because of evolved resistance and adjustments in pest populations. In the developing countries, where food stock carryovers are low or nonexistent, such an occurrence on a major crop would be catastrophic. Any additional yield produced by other measures would pose still more problems of protection against pests. If an expanded program in integrated pest management is initiated, we estimate a 50 percent chance of cutting losses from pests in half within 15 years and a 75 percent chance within 25 years. Such a reduction would increase the world's food supply by 25 percent or roughly allow the minimum calories for an additional 500 million people.

For these reasons, we recommend that an additional $200 million be spent annually on research in crop protection as follows: integrated pest management systems, $45 million; cultural control, $22.5 million; breeding, $37.5 million; biological control, $22.5 million; pesticides, $22.5 million; and new areas (grant programs), $50 million.

OTHER RECOMMENDATIONS

Organization of Agricultural Research Grant Programs

Each grant program should fit the needs of its particular area and should contain the following general components:

- Grants should be made in research areas that will have a substantial effect on increasing world food supply.
- Grant applications should be reviewed and rated by peer review committees of scientists outside of the funding agency.
- Grant funds should be distributed according to the scientific merit of the proposal and productivity of the recipient.
- Grant funds should be viewed as having a training function, thereby increasing the number of individuals involved in agricultural research.
- In some cases, funding should be long term (i.e., 5 to 10 years) since it is difficult to establish a

research team and to make concrete advances on these long-term problems with less of a commitment.

Statements Regarding Genetic Manipulation

A consistent policy for genetic manipulation in higher plants is needed due to the development of new technologies that permit previously impossible recombinations between DNA molecules. This policy should govern U.S. Food and Drug Administration (FDA) regulations regarding permissible genetic alterations in new crop varieties. We propose the formation of a national committee to consider the consequences of genetic manipulation and to develop realistic guidelines for genetic evaluation, containment, and utilization in varietal improvement. Such a committee should be established along the lines of and work with the National Institutes of Health (NIH) committee that assesses research on recombinant DNA molecules.

Training Agriculturally-oriented Scientists

Presently there are not enough trained scientific or technical personnel to undertake expanded research. Funds allocated for increased or expanded research efforts should be used, when possible, to facilitate training or reorientation of scientific personnel.

Profile 1

NONCONVENTIONAL TECHNOLOGIES FOR PLANT BREEDING

Conventional breeding techniques have been successful in increasing yields of various crop species. However, in recent decades promising new technologies have been developed in the basic plant sciences, particularly in genetics, but they have yet to be applied. Plant improvement will progress more rapidly as these new approaches are used by plant breeders and other agronomically-oriented professionals. It must be kept in mind, however, that these nonconventional approaches will supplement rather than replace the efforts of conventional breeders.

RESEARCH NEEDS

Rapid Screening of Germ Plasm for Agronomically Important Characteristics

Plant breeders and plant pathologists have a long history of successful collaboration on developing new pathogen-resistant varieties. This is primarily due to the ease with which pathogen-resistant segregants in a population can be identified and to the relatively simple genetics of the resistance trait. Examples of increased productivity due to the combined efforts of plant biochemists and/or physiologists and plant breeders are more difficult to find. For the most part, plant improvement through breeding has been based upon empirical observations of whole plants without an understanding of the basic biochemical and/or physiological processes being manipulated. These processes are difficult to measure in the field on large numbers of plants, and, in most instances, these physiological and biochemical measurements have no direct economic meaning. Hence there is a need to develop rapid methods of screening germ plasm or of segregating populations for important biochemical and/or physiological processes that relate directly to productivity.

Impact

Rapid screening of germ plasm will permit the systematic search for genetic variation with unique biochemical and/or physiological characteristics. A range of possible traits and crop species would be involved. For example, if plants with an increased rate of nitrate accumulation could be identified and this germ plasm utilized, a variety of crop requiring less nitrate as fertilizer could result. Also, identifying an individual more efficient in carrying out photosynthesis could substantially boost yields. Similar alterations could be expected in using any biological process that underlies yield.

The chance of success using this approach is high (greater than 90 percent) given the range of crop species and possible biochemical and/or physiological processes that could be screened. The effect of this technology would be felt within 15 years.

Implementation

The screening methodology could be developed by a research institute at a major agricultural university, which would be staffed by approximately 30 scientists (both plant scientists and plant breeders). Once these methodologies are routine, efforts would then be turned toward selecting elite germ plasm. A fund of $4 million per year is suggested.

Preserving and Manipulating Genetic Variability

Modern cultivars are rapidly replacing indigenous land races of many crop species. These cultivars are usually superior in resistance to certain diseases, in yield, and in other agronomic characteristics. However, much of the existing genetic diversity in plants is found in the rapidly disappearing land races. Thus it may prove impossible to find resistance to new races of plant pests or certain superior agronomic qualities.

Examples of the importance of preserving indigenous germ plasm are the rice (Oryza sativa) varieties bred by the International Rice Research Institute (IRRI) which were found to be susceptible to the brown planthopper. The Green Revolution improvements in rice would have completely nullified the high yield had not one or two rice lines among thousands tested from the rice germ plasm bank been found to be resistant to the pest. The resistant line was hybridized with the high yielding cultivar, thereby combining insect resistance with the high yielding capability.

The primary need in this area is to collect, maintain, analyze, describe, and make available the genetic resources of the major crop species. Use of this material by plant breeders should be strongly encouraged.

A related necessity is genetic analysis and recombination within this germ plasm. Many important genes can only be expressed and, therefore, identified in very specific situations, and some will be expressed only in combination with certain other genes. Hence it is imperative to search for important genetic information in diverse environments and genetic backgrounds.

Impact

What will be the consequences if genetic resources are not collected, maintained, and made available for use? The long-term consequences would be the loss of certain crop species in some regions and perhaps a premature yield plateau in other crop species. Therefore, we must take germ plasm collection and maintenance seriously and expand current national and worldwide efforts. The chance of success is good (greater than 90 percent), and the results of this research should be evident within 15 years.

Implementation

We suggest quadrupling current U.S. support for the collection, analysis, storage, and distribution of germ plasm, and maintaining a research fund of $2 million per year at nonfederal installations. In addition, there is a need to more completely integrate U.S. efforts with those of international germ plasm collection centers, and to support research at those centers. An initial fund of $1 million per year is proposed.

Developing and Defining Methods of Mutation Breeding

Inducing mutations, primarily a method of generating genetic variation, can contribute to plant improvement when combined with selection, or recombination and selection, or other methods of manipulating genetic variation. Induced mutations supplement naturally occurring variation. A number of mutational events probably will have occurred in a selected genotype when specific mutants are selected following mutagenic treatment. Thus although most mutant varieties released so far have resulted from mutation and direct selection, the future trend must be to use mutations in constructing new varieties through further crossing and recombination. The primary roadblock to the more extensive use of induced mutations in crop improvement is not the production of mutations but the selection of those variants with potential agronomic usefulness.

Manipulating the environment from which mutations are selected holds the greatest promise for success. Therefore, there is a need for selective situations that encompass a wide range of agronomic characteristics and apply to a number of crop species.

Impact

Mutation breeding works best for single gene alterations in crop species and can be considered another way to obtain genetic variability. The examples of potential effects cited for germ plasm screening also would apply here. Since mutation breeding is successfully practiced and has led to the production of a number of new varieties, the chance of success of this approach is high (greater than 75 percent). An impact would be evident within 15 years.

Implementation

A grant program directed toward defining mutant selection methods of agronomically important characteristics would satisfy the needs of this area. Funding of $2 million per year is proposed.

Developing and Extending Methods of Producing Genetic Variability in vitro

Recent advances in the culture of plant cells and tissues in vitro have led to the application of certain methods developed for microbiology to higher plants. By employing populations of haploid and diploid cells as experimental material, it is possible to use the genetic, physiological, and biochemical procedures developed with microorganisms to analyze and genetically modify higher plants. The most striking manipulations include the hybridization of plant cells from diverse species and the rapid production of defined mutants.

Plant cells can be grown on agar indefinitely as masses of unorganized cells (callus) or in liquid suspension. When suspended and cultured under suitable conditions, cells of some species can be induced to differentiate, yielding complete plants. This process is called morphogenesis.

Cell and tissue culture methods should be developed for all economically important plant species, but these unconventional techniques will not replace conventional breeding methods of plant improvement. They provide only another tool with which to attack problems related to plant improvement and are complementary to conventional methods. Cell and tissue culture methods offer the possibility of unique experimental manipulations which will have an effect on all areas of crop improvement.

Impact

The effects of in vitro techniques could be felt in a number of ways. The possibilities of mutant production would allow a wide range of results, e.g., the production of crop varieties resistant to disease or to a herbicidal chemical. Cell hybridization could mean radical possibilities, e.g., the transfer of important germ plasm between sexually incompatible species or the development of new crop species. The success of this method depends upon the development of one critical technique, the regeneration of whole plants from single cells of the important crop species. (This has been achieved with certain crop species, such as carrots.) The chance of success of this technology is high (greater than 75 percent), and its effects should be evident within 15 to 30 years.

Implementation

A research institute should be established to overcome our inability to regenerate whole plants from single cells of important crop species which severely limits the use of in vitro techniques in crop improvement. Such an institute should be staffed by 20 to 25 biochemists, physiologists, developmental biologists, and geneticists with funding of approximately $3 million per year. Additional research on in vitro culture should be supported by a grant program of $5 million per year and undertaken by multidisciplinary teams concentrating on individual crop species.

Developing a Methodology for DNA Manipulation in Higher Plants

The direct manipulation of DNA in lower life forms has led to the development of some powerful tools of genetic manipulation applicable to both lower and higher organisms. With current technology we can isolate a gene, replicate its information, and introduce it into another organism. This technology permits organisms to be directly engineered. Genetic transformation and the production of hybrid plasmids containing DNA from widely different sources also hold potential for genetic engineering in higher plants and agriculturally important bacteria. It is important to take two steps in order to genetically modify higher plants. These steps include defining an adequate recombinant DNA technology and exploring a method for genetic transformation in higher plants.

Impact

Even though the techniques of DNA manipulation are still in an early stage of development, their long-term effects will be enormous. These techniques have a moderate chance of success in agriculturally important bacteria if not directly in higher plants. The effect will be felt within 15 to 30 years.

Implementation

We propose an exploratory grant of $1 million per year for 10 years to determine the feasibility of this approach. If research proves positive, increased support should be provided.

Profile 2

PHOTOSYNTHETIC CARBON DIOXIDE FIXATION

INTRODUCTION

Since about 90 percent of a crop's dry weight is derived from photosynthesis, there is probably no research that offers a greater opportunity for increasing crop productivity than that directed toward increasing the net fixation rate of carbon dioxide (CO_2) in photosynthesis.

Two of the most important components in the energy conversion of sunlight to food are sunlight and carbon dioxide. Both are delivered to field plants without cost, and we will not run short of either. Greater yields are often directly related to increases in solar radiation, when environmental factors such as temperature, water, mineral nutrition, and pests are controlled. Increasing the CO_2 concentration in the atmosphere in closed systems, as in greenhouses, increases photosynthesis and doubles the yields of vegetables and fruits.

The potential for improved fixation of carbon dioxide has been demonstrated. Yields of wheat, rice, and soybeans are increased 38 to 100 percent when plants in the field are enclosed in a plastic chamber to retain the CO_2 and the CO_2 concentration in the air is raised from the normal level of 300 parts per million (ppm) to 600 ppm. It is not economically feasible to use CO_2 enrichment to increase yields under field conditions--without a plastic cover almost all of the CO_2 added diffuses skyward. However, the dramatic results obtained by CO_2 enrichment in closed systems clearly demonstrate that huge increases in yields are possible if net photosynthesis is increased 50 percent or more at normal levels of CO_2. Some strategies for accomplishing this increase are discussed below.

Photorespiration

Photorespiration usually refers to the CO_2 produced in photosynthetic tissues in the light. The process is biochemically different from the more common form of respiration that occurs when a plant is placed in darkness, so-called dark respiration. Glycolic acid, an early product of photosynthesis, is the primary substance acted upon in photorespiration. The characteristics of photorespiration coincide rather precisely with those for the synthesis of glycolic acid and its further oxidation to CO_2.

Three different biochemical systems are known for reducing CO_2 in higher plants. C_3 species are those in which the first product of CO_2 assimilation is phosphoglyceric acid, which contains three carbon atoms. Examples of these species are legumes, most cereal grains, and fruits and vegetables. In C_4 species, malic or aspartic acids, each containing four carbon atoms per molecule, are the first stable products. Examples of C_4 species are maize, sorghum, sugarcane, and some prominent weeds. A third system, Crassulacean Acid Metabolism (CAM), is composed of aspects of C_3 and C_4 metabolism. CAM is restricted to plants that are adapted to arid climates and therefore occurs in few crop species.

Much of the difference in net CO_2 fixation between the different types of photosynthesis found in the C_4 and C_3 species results from the rapid photorespiration (three to five times faster than dark respiration) that is characteristic of only the C_3 species. The loss of carbon by photorespiration in C_3 species seems wasteful since at least 50 percent of the net CO_2 fixed during C_3 photosynthesis may be released by photorespiration at temperatures of 25°C or higher. The leaves of C_4 plants synthesize glycolic acid only about 10 percent as rapidly as C_3 species, and this undoubtedly accounts for the slow photorespiration in C_4 photosynthesis.

Laboratory experiments have shown that adding either biochemical inhibitors of glycolic acid synthesis or of glycolic acid oxidation to leaf tissue will slow photorespiration and increase net photosynthesis by at least 50 percent in C_3 species. Thus slowing photorespiration can greatly increase net photosynthesis and yield.

Slowing photorespiration by inhibiting the synthesis of glycolic acid seems a logical strategy. Some researchers are already seeking biochemicals that will slow photorespiration and thereby increase net photosynthesis. Others are attempting to grow complete plants with reduced photorespiration by obtaining biochemical mutants of plant cells. It is well known that the synthesis and metabolism of glycolic acid is oxygen-dependent. High levels of oxygen are accordingly toxic to plant cells because the higher oxygen concentrations enhance photorespiration. Some plant cells can now be grown in the light with CO_2 as a carbon source, and it might, for example, be possible to select mutant cells that are resistant to higher levels of oxygen and grow well because they have slower photorespiration.

Dark Respiration

All living cells respire and the respiration of photosynthetic tissues that is easily measured in darkness is known as "dark" respiration even though it also undoubtedly occurs in the light. The biochemistry of dark respiration in plants is similar to that in animals and microorganisms. This process provides energy in the form of adenosine triphosphate (ATP) in the course of oxidizing substances produced from photosynthesis (photosynthate) to CO_2. In microorganisms, ATP production often limits growth, and presumably this is also true in higher plants. Dark respiration is needed for plant growth, development, and mineral uptake, and in the synthesis of carbon compounds used in the many essential biosynthetic pathways that are found in plant cells.

The rate of dark respiration in photosynthetic tissues is usually about 5 to 10 percent of the CO_2 uptake in bright light. Lower, shaded leaves in a plant may carry out little photosynthesis and thus only consume photosynthate. Dark respiration also occurs in roots, stems, and fruits that fix little or no CO_2, and this respiration also consumes photosynthate. The process of "dark" respiration may even occur just as rapidly in the light in actively photosynthesizing tissues.

If part of the CO_2 lost by dark respiration was not needed for essential function, and was hence wasteful, eliminating that part would increase productivity in all species, including the C_4. An example of a variety of inbred maize that grew about 50 percent faster than another variety because of smaller losses of CO_2 by dark respiration has been described, showing that all of the dark respiration may not be needed. For example, wasteful dark respiration may result, in part, from a known alternate biochemical pathway in leaves that produces little ATP relative to the quantity of photosynthate respired. In some species 50 percent or more of the leaf respiration occurs by a less efficient biochemical pathway.

C_3 and C_4 Specie Differences

Leaves of C_4 species have rates of net photosynthesis two to three times greater than C_3 species at high light intensities. (See Tables 2 and 3 for a comparison of the growth rates of the two species.) The maximum and average yields of the C_4 species in the United States are also about twice as great as for the C_3 crops. For example, corn (C_4 species) has an average yield of 95 bushels per acre while soybeans (C_3 species) only yield 25 bushels per acre (NRC 1975a). The generally greater yields of the photosynthetically superior C_4 species provide an incentive for increasing net CO_2 fixation in the C_3 crops.

Leaves of C_4 species have a biochemical and morphological compartmentation not found in C_3 species. The arrangement of cells in C_4 species permits more rapid transport of photosynthate from leaves than in C_3 plants and also slows photorespiration. At normal concentrations of CO_2, photosynthesis is more rapid in C_4 plants than in C_3, while at saturating CO_2 levels (about 1,000 ppm CO_2) the C_4 species are only slightly superior. This indicates that photosynthetic capacity is not inherently more efficient in C_4 photosynthesis, but that in normal air, C_3 species have barriers that limit the rate of CO_2 assimilation.

The 21 percent oxygen concentration in our atmosphere inhibits photosynthesis about 35 percent in C_3 crops, but has no effect on C_4 photosynthesis. Most of this inhibition results from the rapid photorespiration of C_3 species since photorespiration is very oxygen-dependent. Oxygen also may inhibit the light reactions of photosynthesis as well as some of the enzymes of the photosynthetic carbon reduction cycle.

Plant Architecture and Photosynthesis

The total radiation available for photosynthesis and duration of photosynthesis are important factors affecting crop yields. Initially, a crop's canopy develops slowly. Maximum rates of crop photosynthesis are usually achieved when the ratio of leaf area to a given area of ground is about 4 to 5. This ratio is commonly called the leaf area index. The leaf area index of many annual crops exceeds 3 to 4 during only two to three months of the growing season. Hence yields can be increased by obtaining varieties with rapid rates of leaf area expansion, by using closer plant spacings to capture more sunlight, and by increasing the ratio of expanding to senescing leaves.

Table 2. Average crop growth rates in United States over entire season

	Grams of dry weight/square meter ground area/week
C_4 species	
Maize silage	47
Sorghum silage	43
Sugarcane (cane)	50
C_3 species	
Spinach	13
Tobacco (leaf plus stalk)	25
Hay	20

Source: Zelitch, I. (1971) Photosynthesis, Photorespiration, and Plant Productivity. New York: Academic Press.

Table 3. Maximal short-term growth rates

	Grams of dry weight/square meter ground area/day
C_4 species	
Millet	54
Sorghum	51
Maize	33, 42, 51, 52
Sugarcane	42
C_3 species	
Rice	29, 29, 36
Sugar beet	23, 28, 31, 32
Soybean	17, 18
Various crops (Netherlands)	20

Source: Zelitch, I. (1971) Photosynthesis, Photorespiration, and Plant Productivity. New York: Academic Press.

Many of the above characteristics can be obtained by conventional plant breeding. Plant breeders have manipulated leaf angle, leaf orientation, leaf anatomy, leaf stomatal frequency, and the proportion of the plant that is edible (the harvest index).

RESEARCH NEEDS

Slowing Photorespiration in C_3 Crop Species

The use of chemicals or genetic regulation could slow photorespiration. Chemicals that slow photorespiration during periods of grain development and filling, and that can be used on a number of species, would be especially useful. Genetic control would be a means of regulating the synthesis of glycolic acid in C_3 species. The biochemical reactions that account for the synthesis and regulation of glycolic acid formation and its further metabolism must be explored, and more reliable, simpler assays for photorespiration must be developed. Systems enabling genetic selection of plants with slower photorespiration also must be worked out, most likely by using techniques associated with selections made on plant cells. Methods of overcoming the inhibitory effects of oxygen on net photosynthesis must be devised. Greater insights on this might be gained by further investigations of how the C_4 species manage to accomplish this.

More Efficient Dark Respiration

More research is needed to determine how much dark respiration is essential for normal plant functions and how much could be eliminated without interfering with plant growth and development. Losses because of wasteful dark respiration might be reduced by chemical or genetic regulation. More information must be obtained about the proportion of dark respiration that occurs by the less efficient alternate pathway and the increased yields possible by eliminating this pathway. Chemicals that would slow dark respiration and inhibit the inefficient pathway are needed. Plant breeding systems must be developed for selecting and producing plants with slower rates or with more efficient biochemical systems of dark respiration.

Investigating C_3 and C_4 Specie Differences

Transforming C_3 species into C_4 species by conventional breeding methods does not seem likely because of many differences in leaf morphology and enzyme distribution in the two types of photosynthesis. However, if some of the advantageous CO_2-fixing mechanisms of the C_4 species were better understood, some of the restrictive photosynthetic features in C_3 species might be altered by the use of somatic cell genetics or biochemical control. Thus the regulation of carboxylation enzymes and further metabolism of carbon compounds associated with CO_2 fixation in C_3 and C_4 species should be investigated and compared.

The rapid transport of photosynthate in C_4 species should be studied in connection with its possible role in the regulation of CO_2 fixation by metabolites within the chloroplasts of leaves. The inhibitory effect of oxygen on photosynthesis in C_3 species (besides that caused by stimulation of photorespiration) should be studied, and comparisons made with C_4 species that are much less sensitive to oxygen. This knowledge could then be applied to increasing C_3 photosynthesis.

Improving Plant Architecture and Transport of Photosynthate

Improved canopy architecture is important for increasing yields. This was demonstrated by the larger rice yields of the IRRI dwarf varieties, and by the higher yields of dwarf wheat varieties that could tolerate greater than usual planting densities. Conventional breeding methods of improving light interception should provide increased yields in those crops where this has not yet been done. Plant breeders must continue to investigate means of improving the rate of leaf growth, leaf angle, stomatal diffusive resistance, root development, and control of leaf senescence since all of these influence net photosynthesis in the crop canopy.

Some products of photosynthesis have a feedback-type effect on slowing CO_2 fixation, but the biochemical nature of these inhibitions is not well understood. Plant hormones also can affect the transport of photosynthate, and research is needed to learn how the control of hormone levels might enhance the transport into edible plant parts. More research also could determine which photosynthetic products regulate photosynthesis and how this knowledge can be used to increase photosynthesis in all species.

IMPACT

The slowing of photorespiration by genetic or biochemical means should result in yield increases of about 50 percent in all C_3 species growing in climates where day temperatures are 25°C or higher. Applying chemicals to regulate photorespiration would be energy-intensive and would therefore be most useful in the high-income countries. Producing plants with slower photorespiration and greater net photosynthesis would be of greatest value in the labor-intensive agricultural systems of the developing countries.

The literature shows that 29 to 71 percent of the gross CO_2 fixed during photosynthesis may be lost by dark respiration. Since the alternate inefficient pathway of respiration often accounts for 50 percent of dark respiration, the elimination of this pathway alone would be expected to increase yields about 25 percent.

The C_4 crop species generally have yields twice as great as C_3 species. Thus slowing photorespiration and achieving oxygen resistance in the photosynthetic system of C_3 species would increase yields by 100 percent.

One hundred percent increases in yield can be expected in those crops where crop architecture has not yet been optimized, based on the experience of the Green Revolution. Where this has already been attempted, further improvements in crop architecture might increase yields about 10 percent.

The results of successful research in this field would be applicable on a worldwide basis, but the largest impact would occur in areas of relatively high temperatures where cereals are the major crops. The results should apply equally well to all sizes of farms. More purchased inputs would be required but certainly such increases would not be in proportion to increases in production. In the long run, the lower income consumers, who depend heavily on cereals for food, would benefit from more abundant food supplies at lower costs.

IMPLEMENTATION

There are probably no more than a dozen small laboratories engaged in research on photorespiration in the United States, and perhaps an equal number of agricultural chemical companies are working on the regulation of photorespiration. Even fewer investigators are working on the regulation of wasteful dark respiration.

Research on photosynthesis is being carried out in about 100 laboratories in the United States. This research requires chemists, biochemists, plant physiologists, crop physiologists, geneticists, plant breeders, and other scientific specialists. Thus most research will be done in the high-income countries. It seems reasonable that the effort be increased by about $10 million a year immediately, rising to $40 million a year in the next 10 years.

Profile 3

BIOLOGICAL NITROGEN FIXATION

INTRODUCTION

The 3 percent average annual increase in grain production during the past 25 years was largely dependent on the exponential increase in the use of nitrogen fertilizer. During the same period, the amount of agriculturally utilizable nitrogen contributed by biological fixation remained constant. If this trend continues, the worldwide demand for fertilizer nitrogen will grow to 160-200 million tons annually by the year 2000, four times the current usage.

Supplying the need for agricultural nitrogen over the next 25 years by fertilizer production alone will be extremely expensive, in terms of both cost of manufacture and consumption of limited energy supplies. At least 500 additional large-scale ammonia plants will have to be constructed at a cost of around $50 billion. This alone will ensure continued high prices for fertilizer nitrogen. The worldwide shortage of natural gas, the preferred energy and feedstock source for ammonia production, also will contribute to increased costs. Currently the cost of natural gas accounts for only 10 percent of manufacturing cost in the United States, but future price increases are expected to raise this figure to at least 50 percent. The absolute amount of natural gas consumed is also very high. Even if we make the unlikely assumption of a steady supply of natural gas at current levels, in the year 2000, 10 percent of the annual production of gas in the United States will be consumed by fertilizer factories (equivalent to 2 trillion cubic feet). Putting these facts together it is possible to predict an annual U.S. fertilizer bill of $30 billion or higher by the end of the century.

Nitrogen Requirement of Cereals and Legumes

It is easy to calculate the minimum nitrogen requirements of various crops. In the case of cereals with an average yield of 2,500 kilograms (kg) of grain per hectare (the current average yield in the high-income countries), approximately 100 kg of nitrogen per hectare are required. Cereals currently receive 40 to 50 kg of nitrogen per hectare (N/ha) in the high-income countries in the form of fertilizer nitrogen. Since only 50 percent of the applied nitrogen is actually used by cereal crops, the average cereal receives only 25 percent of its total nitrogen requirement from this source. This is surprising since increasing the total nitrogen input by 33 percent in the form of fertilizer nitrogen has been associated with the doubling of cereal yields during the past 20 years.

Legumes, whose seeds have a considerably higher protein content than cereal seeds, require approximately four times more nitrogen per kilogram of yield than cereals. Despite this high nitrogen requirement, grain legumes do not show any significant increase in yield in response to fertilizer nitrogen. Apparently this is related to the repressive effect of fixed nitrogen in the soil on nodulation and on the expression of nitrogen-fixing enzymes in the nodules. Since the amount of nitrogen fixed by legumes (84 kg N_2/ha for soybeans) is insufficient for high yield agriculture (5,000 kg per hectare of soybeans requires a total of 600 kg N/ha), yields of grain legumes are considerably less than cereal yields.

Although legumes fix their own nitrogen, the amount fixed is insufficient to supply the entire nitrogen requirement of the whole plant. In fact, as in the case of cereals fertilized with nitrogen, legumes obtain 75 percent of their nitrogen requirement from fixed nitrogen in the soil. Surprisingly, the 25 percent that is fixed in nodules appears to limit growth. There is now strong evidence that legume yields could be increased substantially if nitrogen fixation rates in the nodules could be increased. This has been achieved artificially by increasing the rate of photosynthesis since the supply of photosynthate to nodules appears to be one of the major factors limiting the amount of nitrogen fixed.

Impact of Increasing the Net Rate of Biological Nitrogen Fixation

The above statistics and observations lead to four important conclusions. First, cereal yields can be increased far out of proportion to the ratio, nitrogen applied as fertilizer/total nitrogen required for growth. This implies that if cereal crops in the high-income countries could be engineered to fix their own nitrogen at 30 percent the soybean rate (i.e., about 25 kg N_2/ha) the effect in terms of yield would be equivalent to the total increase in yield obtained by worldwide use of nitrogen fertilizer in 1975. This level of nitrogen fixation by cereals on a worldwide basis would supply them with 18 million tons of nitrogen equivalent to 36 million tons of fertilizer nitrogen. This is more than 1.5 times the current world usage and approximately 12 times the current usage in the developing countries. Extrapolating from current yield data in the developing countries, this amount of fixation could produce almost 200 million additional tons of grain, which is equivalent to about 50 percent of their current output. Looking into the future, the entire worldwide demand for fixed nitrogen in the year 2000 could be supplied by biological fixation if cereals could be induced to fix at the same rate as soybeans.

Second, we concluded that the impact of increasing the fixation rate in grain legumes on world nutrition probably would be contingent on increasing the yield of grain legumes so that on a yield per hectare basis their market value would compare favorably with cereal grains. This probably would necessitate at least a twofold increase in the total amount of N_2 fixed in nodules. Shifting 25 to 33 percent of total land use in the developing countries from cereals to high yielding legumes could easily double the agricultural production of protein and significantly improve the nutritional quality of diets.

The third conclusion is derived from the observation that both legume and cereal crops obtain most of their fixed nitrogen from the soil. Although it is generally agreed that free-living, nitrogen-fixing prokaryotes contribute negligible amounts of nitrogen to the soil, P. J. Dart (1974, unpublished data, Eighth Meeting, Consultative Group on International Agricultural Research, Technical Advisory Center, Washington, D.C.) concluded from results obtained in the Broadbalk experiment at Rothamsted that blue-green algal crusts growing on the surface of the soil can contribute as much as 34 kg N/ha/annum. In light of these observations, it may be important to reassess the contribution of free-living, photosynthetic nitrogen fixers. It seems unlikely that free-living, nonphotosynthetic, nitrogen-fixing bacteria could find a suitable energy source to make significant contributions of nitrogen to the soil. If it were found that free-living, photosynthetic, nitrogen fixers routinely add 30 kg N/ha/annum, then finding ways to double or triple this amount would result in a total nitrogen input approximately equal to the fertilizer nitrogen currently applied to cereal crops. The effect that this would have on agriculture could then be compared to the impact obtained by giving cereals 50 to 75 percent of the soybean-fixing capability.

The fourth conclusion concerns the effects of increasing biological nitrogen fixation in high-income compared to developing countries. Most likely, high-income countries can manufacture enough fertilizer nitrogen to supply agricultural demands. The cost will be high in both dollars and energy, unless a new industrial process is discovered that catalyzes the oxidation of N_2 under mild conditions. Increasing biological fixation should result in savings in dollars, energy, and environmental pollution. In many developing countries, lack of capital precludes the use of fertilizer nitrogen. This situation is likely to continue or worsen as fertilizer prices increase. Increasing biological fixation may be an appropriate way for the developing countries to increase legume and cereal yields to meet projected food requirements in the next 10 to 15 years.

Relationship of Nitrogen Fixation to Other Agricultural Technologies

Success in increasing biological nitrogen fixation will probably depend on two other technological advances: developing somatic cell breeding techniques and increasing the net rate of photosynthesis. The interdependency of these technologies must be recognized.

RESEARCH NEEDS

Here we describe research programs required to increase nitrogen fixation in legumes, cereals, and free-living prokaryotes. We will not discuss: (1) the development of new industrial catalysts designed to catalyze fixation under milder, less energy-intensive conditions; (2) methods designed to reduce nitrification and denitrification in the soil; (3) plant breeding schemes designed to increase uptake and utilization of fertilizer nitrogen; and (4) intercropping systems for legumes and cereals. All of these approaches are extremely important when considering total nitrogen input into plants, but are considered in other profiles.

Nitrogen Self-sufficiency of Cereals

Optimizing Nonnodular Root Microbe and Rhizosphere Associative Symbioses

In recent years, a number of examples of naturally occurring rhizosphere associations between free-living, nitrogen-fixing bacteria and grasses have been found in tropical areas. The most frequently cited example is that of *Spirillum* and *Zea*. It is not clear whether these associations can be used directly in agricultural situations or whether major modifications will have to be introduced at the plant breeding and molecular genetic levels. In the short term, the number and importance of associative symbioses should be determined by careful and extensive field studies which include in situ measurements using ^{15}N isotopes to determine the actual amount of nitrogen fixed. In the long term, molecular genetic modifications of both the plant and bacteria may be required. These modifications might include introducing highly efficient, nitrogen-fixing genes into the bacteria and breeding of plant varieties that excrete unusually large amounts of photosynthate into the rhizosphere.

The fact that fertilized cereals obtain as much as 75 percent of their fixed nitrogen from the soil indicates that unidentified, rhizosphere-associated bacteria may normally play a major role in supplying cereals with fixed nitrogen. When viewed in this light, the prospects of success in this experimental approach seem high. However, currently it is difficult to estimate the amount of time required to adapt or domesticate naturally occurring symbioses; these are long-run objectives. But once agriculturally useful symbioses have been developed, it seems likely that worldwide implementation could occur within 5 to 10 years.

Establishing Symbiotic Relationships between *Rhizobia* and Cereals

This long-term approach probably will require genetic information about cereals that we still do not have. We do know that several plant genes are involved in the nodulation process but there is no way at present to determine whether this is true of cereals. Undoubtedly some of these genes are involved in determining the specificity of bacterial-plant interactions. It is conceivable that nonlegumes might form nodules in response to a successful infection of their root hairs by *Rhizobia* if the species' specific barriers to infection were removed.

Success in this area will probably require a major effort directed at elucidating the basic molecular processes underlying the _Rhizobia_-legume symbiosis. Up to now, plant-bacterial symbiotic relationships have been studied almost exclusively by physiological and microscopic techniques. Thus, for example, the overall steps in the infection and nodulation process have been delineated but the molecular events are still obscure. The lack of detailed information is related to the complexity of the process, and it is likely that a detailed elucidation will take many years. Therefore, it is unrealistic to expect significant short-term progress leading to the establishment of new, agronomically viable, nitrogen-fixing symbiotic relationships between _Rhizobia_ and cereals. In the report of Study Team 4 (Profile 6, Subgroup B and Profile 1, Subgroup C) this topic is treated in more detail.

Transferring Functional Nitrogen-fixing Genes from Bacteria to Cereals

This approach depends on the availability of genetic vehicles capable of crossing the prokaryotic-eukaryotic barriers of DNA uptake, DNA replication, and gene expression. Success also will depend on finding a suitable anaerobic habitat inside plant cells in which nitrogen fixation can occur.

A number of reasons make the immediate pursuit of this approach attractive. First, there are no theoretical reasons to assume that prokaryotic genes could not function in plant cells. Second, by taking advantage of recent advances in molecular genetic engineering technology, it is easy to formulate an overall step-by-step strategy for using bacterial nitrogen-fixing genes to make plants fix nitrogen. At the same time, as it is possible to anticipate specific obstacles, experiments can be designed to test the seriousness of these potential obstacles or to circumvent them.

One such strategy, for example, is to clone nitrogen-fixing genes on a bacterial plasmid that contains, in addition to a bacterial replicon, the replicon from a cauliflower mosaic virus. Such a plasmid should be able to replicate in both plant and bacterial cells. The advantage of this type of strategy is that it is easy to predict the most likely major obstacles. Thus one might predict that prokaryotic DNA in general (or nitrogen-fixing genes in particular) may not be taken up, replicated, or expressed in eukaryotic cells. One particular problem may be that eukaryotic cells lack specific transcriptional or translational regulatory mechanisms required for correct initiation or termination of prokaryotic DNA and messages. Even if bacterial nitrogen-fixing enzymes are faithfully synthesized in eukaryotic cells, they might not find enough ATP, reducing power, molybdenum, or an appropriate anaerobic environment. Therefore, part of this type of strategy would be the inclusion of experiments designed to ask more general questions about the fate of prokaryotic DNA in eukaryotic cells. One would hope that this multipronged approach will determine relatively quickly whether there are any fundamental reasons why prokaryotic DNA cannot be stably maintained and expressed in eukaryotic plant cells. This will then pave the way for the introduction of specific bacterial genes such as nitrogen-fixing ones.

Recent progress indicates the viability of this approach. It has been possible to clone nitrogen-fixing genes from *Klebsiella pneumoniae* on a small amplifiable bacterial plasmid. This enables producing large quantities of DNA containing the nitrogen-fixing genes in a form in which they are likely to survive in a eukaryotic host. Furthermore, plant tissue culture cells will take up and preserve closed circular bacterial plasmid DNA for several hours.

Although it is easy to design strategies for experiments of this type, it is difficult to predict the probability of success. This is in contrast to the experimental approaches for optimizing nonnodular root microbe and rhizosphere associative symbioses where the chances of overall success seem good, but at the present time it is difficult to plan detailed strategies for elucidating the molecular processes underlying symbiotic relationships.

Increasing the Amount of Nitrogen Fixed by *Rhizobia* in Legume Root Nodules

Short-term and Long-term Research Programs

A detailed survey of legumes in present agricultural systems is required to assess factors such as: degree of nodulation; amount of nitrogen fixed and amount of nitrogen transferred to subsequent crops for a variety of legume-*Rhizobium* systems; effects of trace elements, fixed nitrogen, temperature, and water stress on fixation; and the effectiveness of various *Rhizobium* strains. National and international centers must be set up to collect and distribute *Rhizobium* strains, to design effective inoculation procedures, to prepare high quality inoculants, and to optimize the matching of *Rhizobium* strains and legume varieties for effective nodulation and efficiency of nitrogen fixation.

Enlarging the Supply of Photosynthate to Nodules

Study Team 4 (Profile 6, Subgroup B) deals with the interaction between nitrogen fixation and photosynthesis. Research should be undertaken to develop legume cultivars capable of effectively partitioning photosynthate between developing seeds and nodules. This research must be coordinated with research designed to increase the net rate of CO_2 fixation (see Profile 2 on photosynthesis).

Two reports lead to optimism about the long-term potential for success of this approach: experiments discussed above that show that nitrogen fixation rates can be increased severalfold by increasing the net rate of CO_2 fixation, and experiments that show that increased rates of photosynthesis can be obtained by chemically blocking photorespiration. Clearly these are long-term goals, but by the year 2000 it is reasonable to expect at least a twofold increase in the net rate of nitrogen fixation.

Increasing Nitrogen Fixation in Nodules

This research goal would require designing and constructing special legume and *Rhizobium* strains in which nitrogen fixation is not repressed by fixed nitrogen, and developing superior *Rhizobium* strains for specific legume crops and specific soil and environmental conditions.

Recent advances in elucidating the molecular genetic control of nitrogen-fixing genes in *Klebsiella* and inducing *Rhizobia* to fix nitrogen in a free-living state indicate that it will soon be possible to construct *Rhizobium* strains that express nitrogenase in the presence of fixed nitrogen sources. The factors involved in regulating the nodulation process itself, however, are poorly understood. Some progress has recently been made in identifying specific lectins present in host root hairs that play a major role in the plant bacterial recognition process. This latter work opens the possibility of specifically designing special promiscuous strains capable of infecting a wide range of legumes. New *Rhizobium* strains constructed in the laboratory must be able to compete effectively with the native *Rhizobia* and other microflora of the rhizosphere so as to be able to establish the dominant symbioses with the host. Any genetic manipulation of

Rhizobium strains will have to be closely coupled with ecological studies.

The chance of these lines of research succeeding is close to 100 percent. Constitutive genotypes have been constructed frequently in prokaryotes and there is no reason to assume that "constitutive" legume-*Rhizobium* symbioses could not be developed. It is likely that such plants will be responsive to fertilizer nitrogen.

Increasing the Amount of Nitrogen Contributed by Free-living, Photosynthetic, Nitrogen-fixing Prokaryotes

A new determination should be made of the amount of nitrogen fixed by blue-green algae in rice paddies and in "crusts" growing on the soil surface. The amount fixed probably could be increased substantially by introducing highly efficient nitrogen-fixing genes.

IMPACT

Biological nitrogen fixation would have major effects in all countries. In the high-income countries, it would increase the yields of legumes and reduce costs in that it would substitute for chemical nitrogen in the production of cereals and pasture grasses. It also could mean reducing the number of adverse environmental effects.

In the developing countries, where less chemical nitrogen is used and legumes are not so widely grown, the yields of cereals and grasses would be increased. Technically, the effects of biological nitrogen fixation should apply to all sizes of farms; however, a more intensive technical educational program will be required in the case of small farms. There also would be savings in energy and a reduction in purchased inputs on farms where less chemical nitrogen is used. The greatest increases in food supply would occur in the developing countries. As output is increased on more and more farms, consumers would benefit with the largest share going to the lowest income consumers who depend heavily on cereals.

IMPLEMENTATION

Approximately $5 million a year is now being spent on exploratory nitrogen fixation research. This amount should be doubled within three years to expand existing research and then gradually increased to at least $20 to $30 million annually as new researchers are trained.

The following areas of exploratory research should be funded on an individual grant basis during the next 25 years:

- Molecular genetic control of nitrogen-fixing genes in Rhizobia, Klebsiella, Azotobacter, etc.
- Prokaryotic and eukaryotic contributions to nitrogen-fixing symbiotic relationships. Detailed molecular mechanism of initiation and maintenance of symbiosis.
- Ecology of nitrogen-fixing prokaryotes in the soil.
- Replication and expression of prokaryotic DNA in plant cells.
- Physiology of photosynthate transport to legume root nodules.
- Ways of increasing net CO_2 fixation to provide energy for nitrogen fixation.

In addition to exploratory work on nitrogen fixation, a federally sponsored center for agricultural nitrogen fixation research should be established. This center would be responsible for collecting, evaluating, storing, and distributing Rhizobium strains and other naturally occurring, nitrogen-fixing bacteria that form associations with nonlegume crops. The center would concentrate on application problems such as those described under the first two research needs. In addition, the center would monitor the quality of commercial Rhizobium inoculums. The center should be staffed by 30 to 50 full-time scientists and may cost $10 to $20 million annually. It should have the flexibility of forming short-term (2 to 5 years), multidisciplinary research teams to solve specific application problems as they arise. By the time the center is constructed (five years), a sufficient number of personnel should have been trained in nitrogen fixation research. It is not recommended that this center become the key domestic center for basic nitrogen fixation research since this activity would dilute its concentration on application problems.

Profile 4

PLANT ADAPTATION TO STRESS

INTRODUCTION

The development of plants with greater tolerance to adverse environmental conditions offers considerable promise for increasing crop production in the developing countries. The more direct approaches of altering stress conditions through engineering procedures, by the use of soil amendments, or by similar means often are not economically feasible in the developing countries. Small farmers and those on marginal or remote lands are particularly vulnerable to environmental factors that may affect production. Crop varieties more resistant to adverse conditions would be of great value to this group of farmers. Such improvements would be particularly useful if accompanied by modifications in cropping systems that also would reduce risk.

Relatively few crop improvement programs have aimed directly at environmental stress factors. Some exceptions have been efforts to develop frost or cold resistance in some crops and heat tolerance in others. Some programs have been spectacularly successful in opening up new production possibilities for a particular species, but their effect on total production has not been as impressive either because of the relatively minor importance of the crop or the breakthrough has tended to substitute one crop for another.

Two crop characteristics in particular would be of value in the developing countries. They are tolerance of crops to high levels of aluminum in soils, and resistance to drought. These same characteristics also could be of value to U.S. farmers.

In this report, we concentrate on these two possibilities, but there are excellent ones in other areas. For example, IRRI's work to improve rice production under intermittent or continuous flooding shows excellent potential. The International Maize and

Wheat Improvement Center (CIMMYT) has promising lines of cold-tolerant sorghum, and the International Potato Center (CIP) is working with cultivars of potatoes capable of withstanding several degrees of frost at any point in their life cycle and others that will produce tubers under high temperatures. Iron toxicity and problems of salinity are important. These and other lines of research deserve continuing and increased attention. But, in terms of broad concern, high soil aluminum and drought stand out as the environmental stress factors most needing attention at present. See Study Team 4's report (Profile 5, Subgroup B) for additional material on stress.

Specific Stress Factors

Soil Aluminum

High levels of soluble aluminum are characteristic of acid mineral soils. Aluminum solubility in soils is determined almost entirely by the pH of the system. Soils at pH6 contain little available aluminum while at pH5 and below the problem is so severe that crop failures of many important species are common. Deficiencies of phosphorus, calcium, magnesium, or potassium also are common in acid soils.

Liming is widely practiced in the high-income countries to reduce soil acidity. Often up to 10 tons of lime per hectare are required to raise the pH of the top 15 to 25 centimeters of soil surface above six. Doubling of yields under these conditions is quite possible. Liming can be a costly practice, however. In the United States, costs between $100 and $200 per hectare are not unusual and depend on the distance of the quarry.

In many developing countries lime is not readily available, and costs may be prohibitive. Even if lime is used, results may be less than satisfactory because root penetration into the subsoil is restricted and water utilization is limited. In rainfed areas, this may severely limit crop yields if frequency or amount of rainfall is less than optimum. This situation has been noted particularly in the campo cerrado areas of Brazil. The surface soil may be limed to a point where aluminum is not a problem, and spectacularly better growth may be obtained. However, the plant root system may be superficial so that the crop succumbs in drought periods of relatively short duration.

The development of aluminum-tolerant cultivars will not eliminate the need for liming. Modest applications of lime to the surface soil will be needed to supply calcium and magnesium and to adjust the pH to the point where plant nutrients from native soil sources and from applied fertilizers will have an optimum availability to the plant.

Drought

Drought, which has been a scourge throughout history, made its most recent mark on the world consciousness in 1974. The World Food Conference of 1974 and this report grew out of food shortages that followed two years of drought in major grain-producing areas.

It is difficult to get agreement on a definition of drought, much less on a standard method of measuring it. For our purposes, drought is identified as an abnormal dryness. Farmers in any particular region usually know what they can expect in terms of total rainfall and in rainfall distribution. The cropping procedures and farming systems adopted take those expectations into account. If rainfall is sufficiently below these expected averages and causes seriously reduced crop yields, a drought has occurred. If farming systems are oriented toward high rainfall, a drought may occur at a level of rainfall that would be deemed entirely adequate in a system aimed at semiarid conditions.

Here we do not look at one of the most obvious ways of dealing with drought--irrigation--nor at one of the more exotic possibilities--climate modification. Instead we look into approaches in the area of crop improvement fitted to particular cropping systems, which are less demanding in terms of capital investment and which may be used individually by small holders.

Crop varieties with a shorter growing season are one obvious means of reducing the risks presented by drought. Such varieties may be geared toward the principal rainy season when the probability of drought is lower. The faster maturing type may be brought to harvest before the end of the rainy season and thus avoid the higher variability in rainfall and losses that may be associated with the rainy season. The same types may grow faster in the seedling stage and thus more rapidly establish a root system which makes the planting better able to come through periods of low rainfall. If an early planting fails because of drought, it may be possible to replant if a suitable short-season variety is available. In the tropics, temperature conditions usually permit plantings over long periods of time. The traditional farmer makes use of this possibility by planting part of a crop with the first rains and part of it on a series of subsequent dates. This spreads out the farmer's risks from drought as well as the workload. The farmer knows that this procedure means a lesser chance of losses from drought and a lesser chance of a complete crop failure if plantings are in several stages of growth when drought comes. Some plantings may be hard hit while others are unscathed. The traditional subsistence farmer usually finds stability of results more desirable than chances for exceptionally high yields. Good short-season varieties can be very useful in this kind of numbers game.

A deeper, more extensive root system can reduce losses from drought. Many species vary significantly in this regard. Although the more extensive rooting pattern may not be combined with better plant type or other desirable characteristics, there is no reason to believe that it could not be recombined to produce varieties with drought advantages along with other desirable characteristics. If one looks more broadly at a range of species within a given genus, it seems clear that some major differences in rooting habits occur. In addition to extent and distribution of roots, there may be useful differences in the internal anatomy of the root, such as in the numbers of primary xylem elements through which water is conducted. As mentioned in the section on aluminum tolerance, toxic factors in the soil may prevent a crop from fully developing the root system of which it is genetically capable. This can increase susceptibility to drought. Procedures that reduce the effect of toxic factors are advantageous and, if they are achieved by genetic modification, they will be particularly useful to the small farmer.

Among species, differences in leaf pubescence, stomatal reaction, cutical surface, and similar features impart drought resistance. Similar differences exist within crop species, although little has been done to identify them clearly and make use of them in varietal improvement.

Drought tolerance or resistance is essential to survival, but the crop's ability to resume rapid growth following the period of stress may be even more important in determining final yield. Such differences are well recognized among species, and farmers have traditionally selected the more resilient species for use in drought-prone situations. Much less is known about the recovery potential of different strains within a species, although differences are generally considered to exist within many if not all species.

RESEARCH NEEDS

Aluminum Stress

Prospects are excellent for breeding varieties with a greater tolerance to aluminum. Wide genetic diversity in this characteristic has been identified in or is suspected in wheat, rye, corn, barley, potatoes, soybeans, and rice. Unfortunately, the newer, higher yielding varieties of many species are generally in the more sensitive categories, probably because most breeding programs do not emphasize aluminum stress when segregating germ plasm. Consequently, much of the tolerance is found in indigenous, low yielding varieties. There has been no systematic effort to identify tolerance to aluminum in this germ plasm.

A major effort should be undertaken to incorporate aluminum tolerance into the principal food crops. Much of the actual breeding work might best be carried out at the international centers having responsibility for each crop and in the national programs in the developing countries. Some work is already underway for certain crops, but progress is slow because of the lack of adequate techniques for screening for aluminum tolerance.

In the initial stages, research on screening techniques can best be done at U.S. laboratories where screening methods are developed. The risk of losing valuable germ plasm is real, and a major effort should be undertaken as soon as possible to identify and preserve aluminum-tolerant germ plasm.

Once a rapid screening method is available, it can accelerate the breeding of tolerant varieties. Screening of germ plasm from various parts of the world can quickly identify sources of maximum tolerance, and this information or germ plasm can be made available so breeders can include it in crossing programs.

Basic research is needed to determine the number of genes involved, their linkages, their chromosomal location, and the mode of inheritance. Investigations into inducing mutations in this character should be undertaken where sufficient natural variation is lacking. This information would be as useful to breeders as similar information on disease resistance has been. As superior tolerance becomes available in various species, it could be introduced into breeding programs overseas.

Impact

About 40 percent of the world's potentially arable soils contain enough soluble and exchangeable aluminum to affect crop yields adversely. More importantly, probably up to three-fourths of the world's new lands that could be brought under cultivation are acid and thus have an aluminum toxicity problem. Extensive areas of acid soils are found in the warm temperate zones, the subtropics, and the humid tropics. Although aluminum toxicity is not the only problem associated with these soils, it is a major limiting factor in crop production.

The high aluminum soils of the world are found mostly in humid areas. In fact, as noted, high aluminum is a consequence of low pH which in turn results from leaching out of bases as rainwater percolates through the soil. Thus if aluminum toxicity is removed or alleviated through crop improvement, substantial increases in production are possible. Crops will respond to modest applications of lime, phosphorus fertilizer, and other inputs, and they will be less subject to drought losses.

The estimate of benefits in cost savings or increased production that could result from crops being able to tolerate high levels of aluminum is subject to wide error. However, the area possibly affected is very large and the potential benefit proportionately so. There may be as much as 500 million hectares of land in the tropics and subtropics of Latin America, Africa, and Asia where significant benefits could be obtained. Much of this land is presently unoccupied and/or unused and much of it is not very accessible. Also, benefits from aluminum tolerance alone would be modest and short-lived. Fertilizers and other inputs would be needed to achieve the principal benefits of aluminum tolerance. But, with other practices being adequate, it would not be unreasonable to estimate savings of 1 or 2 tons of lime per hectare as a result of crop tolerance of high aluminum or to obtain production increases on the order of a ton per hectare if aluminum toxicity were eliminated. The area in question is so large that billions of dollars could be saved in the purchase of lime or potential increases in production could be calculated in hundreds of millions of tons of grain. These are gross estimates, but success in this line of research would be of great value.

Implementation

Twenty-five scientists, with appropriate support staff, are needed for these studies. The cost of this level of input is currently estimated to be $2.5 million, including funds for equipment and supplies, travel, and similar items. This research effort for the aluminum stress problem should be programmed for at least 10 years.

Initial capital costs for this effort might be on the order of $1 to $3 million. This would be used to expand existing facilities and to provide controlled environment chambers and related items.

Drought Tolerance

Development of drought-tolerant crop varieties and farming systems should be a goal of the world agricultural research system. The prospects of a reasonable amount of success are good for several possible routes of attacking the problem and excellent for a few. Major breakthroughs are unlikely to mean major improvements. Instead, incremental improvements within a crop species and a farming system are probable. One exception might be through wide crossing programs involving interspecific and intergenetic hybridization. Scientists working on such programs should be encouraged to include drought tolerance among the characteristics being sought. This is one route whereby a breakthrough rather than an incremental result might be forthcoming.

All breeding programs should take into account the moisture stress risks that the crop concerned will face. IRRI points out that about three-fourths of all rice planted in the tropics is subject to some incidence of drought. Essentially all of the corn crop in the tropics is unirrigated and hence partially exposed to drought. CIMMYT will measure the performance of all of its nurseries under enough different conditions to assure that drought-tolerant strains can be picked out. These are important steps, although some reorientation of thinking and economic input will be needed to assure that more drought-stable, but perhaps lower yielding, lines will not be passed over in favor of more drought-susceptible but otherwise attractive ones.

IMPACT

The benefits from developing crop varieties better able to avoid or withstand drought periods would be great. It is extremely difficult to put any precise measurement on what the economic losses are, partly because of the difficulty in defining drought. For our purposes, a useful although extremely rough estimate might be found from India's experience during the drought years of 1965-67. Other factors were at work that would have tended to increase production over this period, but yields during these two years appear to have fallen below the trend line by perhaps 15 percent. This figure could serve as a rough estimate of what the aggregate losses could be over a large tropical area having a broad range of farming systems oriented toward a range of expected climatic conditions from very humid to semiarid.

Total production losses because of drought are not, however, a fully satisfactory measure of the importance that the development of drought-resistant crop varieties could have, for losses can amount to crop failures in some areas. Invariably losses fall more heavily on the most disadvantaged: farmers on the poorest soils and those with the least economic reserves to replant or otherwise moderate the effects of the drought. For a nation as a whole, reserve stocks of grains should serve as a precaution against drought. For the individual farmer, drought-tolerant crops and farming systems are the first line of defense.

IMPLEMENTATION

Support of modest levels at a large number of points is indicated for work on drought hardiness and drought avoidance. The work should be shared by advanced centers in the United States, the international centers, and the national programs of the developing countries. The importance of the subject would justify an added input equivalent to 25 scientist-years per year. Including the costs of support staff, equipment, and so forth, the costs of this input are currently estimated at $2.5 million per year.

Support should be given to some centers to encourage more basic work on the physiological and anatomical bases for drought tolerance. Means of placing particular types of drought stress on the crop and of measuring their effects on specific phases of plant behavior should be developed. Better ways of measuring the size and characteristics of the root system are needed. This is a situation in which many research units should be encouraged to assign innovative talent to different aspects of the problem. Grant support of specific project proposals should be provided as well as sustained long-term support to centers that develop special expertise on the subject.

Profile 5

PROTEIN QUALITY AND QUANTITY OF CEREALS

Cereals provide most of the world population's calories and are the principal source of protein, particularly in the developing countries. Four grains--rice, wheat, corn, and sorghum--provide over two-fifths of the protein consumed in the developing countries and in large areas they provide more than half. Dependence on grain is highest among the lowest income groups. In a world in which animal protein will cost more and more, plant proteins will have to provide a greater share of our protein intake.

Cereal protein is not fully usable by humans because of imbalances in the amino acids of the protein. A shortage of one or more amino acids prevents full use of the others. This qualitative defect is greatest for sorghum and almost as great for corn. It is necessary to eat about twice as much protein from sorghum or corn as from animal protein in order to get the same protein value.

Sorghum is the most important food staple for the poorest group of developing countries. Corn is the most important food crop of Latin America and Africa and is important in parts of Asia. It also is grown and eaten principally by poor people. Thus in much of the world the poorest groups that typically are shortest of calories and protein also receive a low quality protein.

The physical characteristics of a grain are equally as important as the chemical (nutrient) composition in determining the ultimate utility of seeds. The sum total of these properties is referred to rather nebulously as "grain quality." Little is known about the basic biology of the various components that determine good grain quality. Cereal technologists have developed some very useful functional tests that successfully measure grain quality, but little is known about the underlying biochemistry that determines these traits. It is reasonably certain, however, that the physical characteristics of grain (including endosperm hardness or density) are a function of the kinds of proteins and carbohydrates present and the matrices that they form in combination.

The question we must ask is: To what extent do we base our selection of a cereal species for a particular environment on grain quality (including nutritional quality) of the species rather than on the potential productivity of a species defined by environmental parameters? For example, would we not achieve greater overall cereal productivity if sorghum grains with physical characteristics and protein quality similar to rice were grown in place of upland rice which is relatively drought susceptible? Our diversity of options for cropping systems would be significantly enhanced if we could remove the restrictions placed on the use of our C_4 cereal species by poor grain and nutritional quality. This would allow the agronomist greater flexibility in selecting cereal species that optimize production potential under any given set of environmental parameters. In the long run, this would lead to more food as well as to better quality food for people in all areas of the world, but especially for people in the tropics where C_4 species have their greatest potential for feeding humankind.

The biological value of a seed protein is the ultimate measure of its worth in human and animal diets. An evaluation of protein availability in these systems must be an integral part of any plant breeding program designed to affect nutritional quality. In many of our food grains, protein is often not fully available, and the reasons for this are not understood in most cases.

RESEARCH NEEDS

Improving Protein Quality in Cereals

Seeds contain a considerable portion of their protein as reserve or storage proteins that serve as a source of nitrogen for the germinating embryo. Since a plant can synthesize all the amino acids, given a source of nitrogen, there is no need for storage proteins to have any particular amino acid composition.

T. B. Osborne initiated systematic studies of seed proteins in 1891. His classification of seed proteins according to their solubility is still used since no functional criteria can be applied. Seed proteins are classified as albumins (water soluble), globulins (insoluble in water but soluble in saline solutions), prolamines (soluble in relatively strong alcohol), and glutelins (soluble in dilute alkaline solutions but not in water, saline, or alcohol solutions). The prolamine fractions from all cereals are relatively rich in proline and gluamine, but are all low in lysine. It has been known for many years that rats of all ages go into rapid decline and eventually die if placed on a diet in which zein (the prolamine extracted from maize) is the sole source of protein. These early chemical and nutritional experiments with zein exemplify the problems of protein quality in cereals. The prolamine contents of the major cereals fall into three rather distinct groups: 5 to 10 percent, rice and oats (avenin); 30 to 40 perent, barley (hordein) and wheat (gliadin); and 50 to 60 percent, maize (zein) and sorghum (kafirin).

Since the protein quality of cereals in general is inversely related to their prolamine content, these cereal groups increase in protein quality as they decrease in prolamine content. In view of this distinction among the major species of cereal, continuing research designed to identify gene mutations in sorghum and maize that reduce prolamine concentration to the levels characteristic of other more traditional food grains such as rice should be supported.

Research geared toward improving protein quality in rice and/or oats by adopting the above strategy would probably be fruitless, since the prolamine content of these species is already minimal. The protein content of rice, however, which averages only about 7 percent, should be increased to the extent that this can be accomplished without loss of yield.

Appreciation of the possibility that the prolamine content might be reduced in corn led to the discovery of the opaque-2 mutant. This mutant has an amino acid profile differing from that of common maize, being significantly higher in lysine and tryptophan. Involved is a drastic reduction in the zein protein fraction and an increase in the water-soluble and salt-soluble proteins. Similar changes account for nutritional differences found in certain barley and sorghum mutants where higher lysine levels occur with a reduction in prolamine levels (see Figure 1).

Mutations in maize and sorghum have reduced the content of the alcohol-soluble proteins to about the content found in normal barley. The mutation in barley has reduced the content of prolamine to about that found in normal varieties of rice or oats. It is possible that rice has already incorporated mutations homologous to those that have been detected in maize, sorghum, and barley.

These changes from higher to lower prolamine content appear to occur in two steps. This suggests that the regulation of prolamine synthesis may be controlled by two major genes in these cereals. If

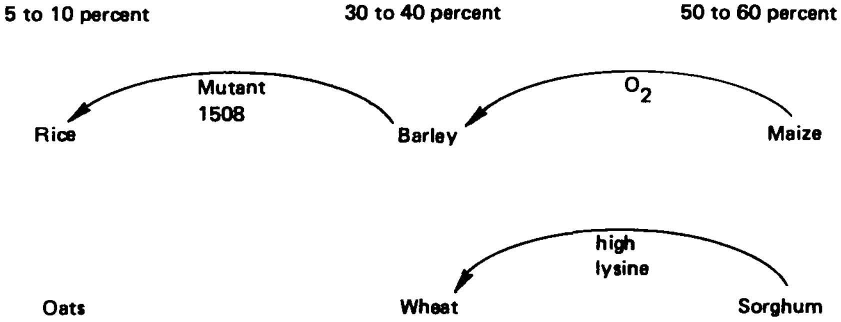

FIGURE 1 Prolamine content of major cereals.

this interpretation is correct, it should be possible to find a "second step" mutation in sorghum (or corn) that will reduce the prolamine content to approximately 10 percent, with further increases in overall protein quality. This would provide us with a cereal grain species, for example, that combines the photosynthetic efficiency and stress tolerance of sorghum with the protein and nutritional quality of oats or rice.

A second distinction among major cereal species is also relevant. Plant physiologists have determined that of the six cereal species only maize and sorghum currently have the "C_4 pathway" with the more efficient CO_2 fixation package that leads to greater productivity under tropical conditions. The paradox facing plant scientists and nutritionists, therefore, is that none of the currently available cereal species combine both the nutritional advantages of low endosperm prolamine content and the high productivity characteristic of C_4 species. Two approaches to the solution of this problem should be followed. First, the advantages of efficient CO_2 fixation should be incorporated into those cereal species that lack this characteristic, namely, rice, oats, wheat, and barley. Second, the improved protein quality characteristics of rice and/or wheat could be incorporated into the maize and sorghum genomes by manipulating the genes that regulate storage protein biosynthesis. This manipulation could be in favor of enhanced production of albumin, globulin, and glutelin protein with reduced prolamine protein production in the endosperm tissue.

Will it be easier to select for increased photosynthetic efficiency in rice or oats, or to take the alternative approach and breed for enhanced nutritional quality in sorghum and corn which already have the genetic machinery for a more efficient photosynthetic pathway? The answer depends on which biochemical process is easiest to manipulate genetically, which in turn can only be decided when we understand the genetic control of these important biochemical pathways in cereal grains. Obviously, each cereal species has advantages and limitations, and the greatest overall efficiency will be achieved by directing research within each species toward the optimal combination of characteristics that best meets a human's nutritional needs for both carbohydrate and high quality protein.

Improving Protein Availability

Significant progress has been made recently in improving the protein content of wheat and oats. Nebraska has released the wheat variety Lancota, which reportedly produces 5 percent more grain and 1 percent more grain protein than the check varieties. The Dal, Goodland, and Wright varieties of oats developed in Wisconsin have increased oat protein content without significantly reducing grain yield. An important area for future research is the relationship between energy and protein production and storage by the cereal species.

It is generally assumed that most of the protein from grain legumes is readily available for monogastric digestion, although in many species this assumption has not been critically documented. We are only now beginning to recognize that tannins and other compounds, which may have important survival value for plant species producing seed in the tropics, may also seriously reduce nutrient availability in grain when consumed by humans. The net effect is a waste of protein and other nutrients which the consuming population cannot generally afford. The biological efficiency of a food-producing system must be measured in terms of the net utilization of nutrients by human and animal systems, and not only by the yield of nutrients produced. It is difficult to quantify the potential benefits at this time because we have only recently recognized the problem. The loss of nutrients produced could be substantial, and a greater research effort should be initiated immediately to identify the magnitude of the problem.

Current results from several feeding studies suggest that tannins are interfering with the maximal use of the nutrients (including protein) in high-tannin sorghum. Tannins and other phenolic compounds are capable of interacting with proteins in many different ways. These interactions may be classified as reversible and noncovalent, and covalent.

Recent preliminary evidence from nitrogen balance studies suggests that only 50 percent of the protein in some red and black bean varieties (Phaseolus) may be available for monogastric utilization because of tannins present and because of other unknown factors. Additional research is needed to document and resolve this problem since the high protein and lysine content of grain legumes are important nutritional components that complement cereal-based diets. Further complications arise from the fact that many people prefer red and black beans to varieties with a white seed coat and from the fact that colored seed coat varieties are often higher yielding and more frequently resistant to disease than white seeded counterparts.

IMPACT

The chance of success of the research efforts we recommend would be: improving protein quality in cereals, 75 percent within 15 years and 95 percent after 15 years; improving protein availability (tannin problem), 80 percent within 15 years and 90 percent after 15 years; and learning more about the biology of seed proteins, 40 percent within 15 years and 80 percent after 15 years.

A tremendous impact can be expected from these efforts, including: (1) improved nutrition, health, and vitality for those around the world who are barely at or somewhat below minimum caloric requirements and who do not receive enough supplemental protein from noncereal sources; (2) valuable gains in the developing countries for pregnant and nursing women, and for children being weaned and at postweaning growth stages who are most in need of additional protein; and (3) lower costs of livestock feed per pound of meat products through the use of high quality protein corn and sorghum, including some substitution for other higher cost feeds.

Some advances in the research area we describe have been made already. The biological significance of the opaque-2 maize work is not only that the protein quality has been remarkably improved (since similar protein quality also is available in other cereal grain species), but that we now have a cereal grain in a C_4 cereal species with very good nutritional quality and with high photosynthetic efficiency. Likewise, the biologically significant advance represented by the low prolamine (i.e., high lysine) sorghum mutants is not simply the improvement in overall protein quality, but that we now have a cereal grain in a C_4 species with good protein quality and with high photosynthetic efficiency, drought tolerance, and similar grain size to that of wheat and rice. This is important for easy adaptation to various human food preparation systems. In short, the combination of desirable characteristics needed, high grain yield potential and good grain nutritional quality, are now available in a single species for the first time.

IMPLEMENTATION

Successful genetic modification of protein quality and/or quantity must be an interdisciplinary effort involving plant genetics, biochemistry, human and animal physiology, human and animal nutrition, and cereal technology and agronomic production. Integrated research in this area can be undertaken by establishing funded core projects that will, in turn, fund research in supporting project areas. Each project area will participate in evaluating the overall project.

These core projects should be linked with similar research at the international centers, which must in the final analysis provide the adaptive research and delivery systems for the use of improved germ plasm by the developing countries. Two core projects are required with annual budgets of $2 million per year for 10 years to accomplish this objective. Additional funding at two international centers, including CIMMYT and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), with annual budgets of $2 million per year for each center over 10 to 15 years, also is required to use successfully research results.

We also recommend that grant funds of $500,000 per year be used to develop rapid, accurate crop screening procedures for protein and nutritional quality so that plant breeders are able to select superior lines. Such research requires a review of bioassay procedures and their pertinence to human requirements. An interdisciplinary effort by nutritionists, plant breeders, and biochemists is needed to accomplish this objective. Support should be made available for a critical nutritional evaluation of grain sorghum as well as *Phaseolus* spp. and other tropical grain legumes at the Institute of Nutrition for Central America and Panama (INCAP) in Guatemala City, ICRISAT, the

International Institute of Tropical Agriculture (IITA), and other international centers to determine the extent of the problem.

Back-up research to identify the polyphenolic compounds involved and the mechanism of their biochemical effects should be developed in university laboratories. An understanding of the tannin-protein interaction could lead to simple processing methods to alleviate the problem. Alternatively, plant breeders could select for cultivars with reduced concentrations of undesirable compounds once these have been identified and when suitable chemical assays have been developed.

It is recommended that $1 million a year be allocated for five years to carry out the initial stages of the objective. Longer term funding will be necessary to resolve the problem, but the magnitude needed will be determined at the end of the first five-year period.

Profile 6

ROOTS AND THEIR INTERACTIONS

Here we deal briefly with only three of the many interactions of roots in the complex rhizosphere of a plant. The rhizosphere is the soil that surrounds and is influenced by the roots of a plant, and it supplies the water and plant nutrients for crop production. Little is known about the rhizosphere of crop plants because it is extremely difficult to study. Likewise, little is known about the three root interactions that we shall emphasize (see the report of Study Team 4).

RESEARCH NEEDS

Penetrating Soil Hardpans

Hardpans that are found in many soils impede root penetration below the 6- to 9-inch plow zone and restrict plant growth by limiting available water and nutrients. Breaking this hardpan mechanically by subsoiling (an expensive, power-consuming operation) has often doubled crop yields in dry years, but the effect is usually good for only one or two years.

Elkins, Lowry, and Langford (1973) found that a well-established sod of Pensacola Bahia grass opened up the dense subsoil for at least a four-year period and doubled yields of seed cotton grown continuously during that period. A study of the rhizosphere revealed that the coarse roots of this grass were able to penetrate the hardpan. Cotton roots then followed the channels left by the Bahia grass roots permitting at least 20 percent of the cotton plant roots to extend below the plow zone to depths of up to six feet. More than 99 percent of the cotton roots had been confined to the 9-inch plow zone on the check plots. Apparently, the tiny channels left by the Bahia grass roots were more stable than the irregular fractures following mechanical subsoiling. There is good reason to believe that this effect could work with other sods and other crops throughout the world.

The effects of Pensacola Bahia grass sod on other important crops in the same area in which this sod is adapted must be evaluated. Other deep-rooted, well-adapted perennials and annuals should be planted on hardpan soils in their areas of adaptation to study their ability to penetrate hardpans. The performance, root development, and yield of food crops following species capable of penetrating the hardpans also must be studied. Rhizatrons and other ingenious devices should be used to monitor root activity in these studies.

Impact

Successful penetration of soil hardpans with grass sods such as the one described above could double crop yields wherever such hardpans occur, especially in dry years. The energy required and cost of the treatment would be low compared with mechanical subsoiling, particularly if the sod crop could be used at the same time to supply feed for livestock. Sod rotations have been widely recognized as being beneficial without knowing why. Their ability to penetrate the hardpan may be a major reason.

The chance of success of this research would be 90 percent within 10 years and 95 percent within 25 years.

Implementation

A joint effort by teams of crop and soil scientists is required for this research. Three well-supported centers--one at Auburn, Alabama, where the original work is being continued; one in the northern United States; and one in the semiarid United States or at a center such as ICRISAT in India--can determine in 10 years the potential of further effort in this area. Three five-scientist teams, each receiving $500,000 in annual support, will be required.

Mycorrhizae

Mycorrhizae are a group of fungal species that live in close association with plant roots and assist the root in accumulating certain nutrients. Ectotrophic mycorrhizae of forest trees have been long known and thoroughly studied, but it was not until the 1950s that an organism involved in the vesicular-arbuscular (VA) mycorrhizae type was isolated, identified, and shown to be capable of mycorrhizae formation. Recently, it has been shown that VA mycorrhizae are in a wide variety of plants almost to the point of being ubiquitous, including such important cereals as maize, wheat, and upland rice.

The fungus obtains carbohydrates and growth factors from the host plant and supplies it with an enlarged root system. (The root system of the plant is actually reduced but the combined system of roots and fungus is enlarged.) It has been shown that the presence of the fungus increases the ability of plants to absorb nutrients, particularly phosphates, magnesium, calcium, trace elements, and water.

VA mycorrhizae can stimulate growth and nitrogen fixation by legumes. This ability is particularly noticeable in phosophorus-deficient soils. Tropical legumes are much more dependent upon mycorrhizae for growth than the temperate species. Thus mycorrhizae might be very effective in establishing legumes on high aluminum ion soils such as the campo cerrado soils of Brazil.

Study of the advantages, if any, of mycorrhizal associations to host plants has been difficult simply because of the complexity of the interrelationships among host, soil, water, other microflora, and fertility. However, in a series of 71 field trials in southern Australia, Ridge and Rovira (1968) found an average increase in grain yield of 5.5 percent and a maximum increase of 37 percent from plots inoculated with mycorrhizal fungi over the uninoculated plots. Since species of Endogone occur almost universally, it should not be expected that tremendous yield increases would occur upon inoculation. However, selecting the proper strain of the fungus and matching it with the proper cultivar (assuming that it could be introduced and would persist in the soil) could result in yield increases of 25 percent, particularly in soils deficient in phosphorus. The poorer soils of the tropics should benefit most by inoculation with proper strains of the fungus, but there is reason to believe mycorrhizae might prove useful to U.S. agriculture.

Impact

The discovery of strains of mycorrhizae specific for certain crops, which could be introduced into the soil and which could continue to compete with other soil organisms, may increase yields up to 25 percent. The findings could then be applied throughout the world wherever the crops are adapted and wherever the rhizosphere permits introducing the selected strain.

The chance of success of this research effort would be 15 percent within 10 years and 30 percent within 25 years.

The chances of success in using mycorrhizae to improve crop yields are low because it has yet to be demonstrated that improved strains of the fungus can persist in the field in competition with existing soil microflora. Testing of this ability to persist in the soil should be initiated early in the exploration of mycorrhizae. If the fungus cannot persist, the project should be an exploratory one until more knowledge is accumulated. If the fungus can persist, the chances of success should be improved to 25 percent within 10 years and 60 percent within 25 years.

Implementation

We recommend that multidisciplinary teams, including those from the disciplines of plant physiology, biochemistry, soil science, agronomy, microbiology, plant pathology, entomology, nematology, electron microscopy, genetics, and statistics be formed for work on corn, wheat, sorghum, upland rice, and soybeans. This research should be located in both tropical and temperate locations. A special investigation should be started on high aluminum ion soils. We also recommend that research be coordinated so that scientists in each field are aware of what others are learning. Such a program could be instituted for about $5 million a year and should be funded for the first five years before it is decided whether to proceed.

Breeding Cultivars with Deeper, More Efficient Root Systems

Burton, et al. (1954, 1957) have demonstrated that the rate of penetration, depth, and efficiency of nutrient and water uptake of roots can be improved by breeding the forage species Bermuda grass. When compared with the common Bermuda grass check, Coastal Bermuda (1) produced roots that penetrated nearly twice as fast and recovered nearly three times as much phosphorus placed at various depths under the sod, (2) developed twice as many roots by weight in the 2- to 8-foot root zone, and (3) yielded six times as much in a very dry year (twice as much in a wet year). Coastal Bermuda required less water per pound of dry matter produced in the very dry year than in the wet year, while Common Bermuda and all other species tested required much more water. Experience since this research indicates that breeders could select for a more extensive root system by growing segregating populations in deep (8-foot plus) sand soils and assessing their above ground growth.

Impact

Success in breeding cultivars with deeper, more efficient root systems could have a tremendous effect on world agriculture. The examples described earlier suggest that yields might be doubled. It must be realized that the higher yielding cultivars that have been bred probably had superior root systems for the rhizosphere in which they were bred. Generally these rhizospheres have not put the stresses on root development that may be encountered in much of the world.

The chance of success of this research is 75 percent within 10 years and 85 percent within 25 years.

Implementation

The germ plasm of the world's major food crops should be screened for those plants with deeper, more efficient root systems. This could be done by growing these crops in deep sand soils in a semiarid environment and in an environment where rainfall is usually favorable but soil fertility is low, such as the southeastern United States. Above ground yields and concentration of soil nutrients (particularly nitrogen, potassium, phosphorus, calcium, magnesium, and sulfur) should be determined. Lines showing promise above ground should be studied below ground and should be intermated in an effort to accumulate genes responsible for the desired traits. Teams including a crop agronomist, a soil scientist, a geneticist, and a plant physiologist with access to limited help from other disciplines should be able to ascertain in 10 years the potential of continued and expanded research in this area. A minimum of two centers, each requiring annual support of $500,000, will be required for the first 10 years. If the effort proves as promising as the examples suggest, it could be expanded in less than 10 years.

Profile 7

SELECTED YIELD FACTORS

Solutions for increasing crop productivity will come from genetic, chemical, or cultural and possibly physical approaches. Developing these solutions has been and continues to be severely restricted by the necessity of relying for the most part on empirical approaches. For example, plant breeding selection systems are based almost exclusively on an ideotype that permits visual scoring. More knowledge about the physiological and biochemical components of major crop yields should mean a more effective approach to increasing yields.

We have selected three areas--improving the harvest index, controlling the conversion of vegetative to reproductive growth, and controlling senescence--which are promising candidates for immediate increased exploratory research. Success in these three areas will provide the basis for increasing crop production in the long term (15 to 25 years). We also recommend expanding broad exploratory research programs on the physiology and biochemistry of crop plants in order to discover totally unrecognized limitations of crop production. These studies will provide the basis for increasing crop productivity in the next 25 years and beyond.

Three types of information are needed to improve yield through the physiological and biochemical route. These are outlined with the area of photorespiration used to illustrate each:

-- The specific physiological and biochemical component(s) limiting yield. This area has received almost all of the attention of plant physiologists and biochemists, but in the three areas we will describe the specific identifications have not been made. In the case of photosynthesis, the photorespiratory limitation at the physiological level and the oxygen-carbon dioxide promiscuity of the CO_2-fixing enzyme at the biochemical level are examples of such specific identifications. Similar identifications must be made for other possible physiological and/or biochemical components of yield.

-- The quantitative significance of the yield limitation of the specific physiological or biochemical component. Research in this area has been negligible and must be expanded since quantitative information is essential to assess the potential and problems of a specific area. Evaluations should be made on the major crops in each of the major cropping areas under normal field conditions. Even in the case of photorespiration where CO_2 enrichment provides a single approach, information is available for only field-grown rice, wheat, and soybeans from single locations for each crop.

-- Develop rapid but specific assays to use for selecting the desired genetic or chemical solution. There are few examples of where this need has been met. The plant breeder or chemist must evaluate thousands of plants or chemicals to find a desirable cultivar or plant growth regulator. On the average, a new pesticide may be found in every 10,000 chemicals while a plant growth regulator that specifically perturbs rather than kills will occur even less frequently. An example of such an assay may be that for decreased photorespiration using delayed plant death under reduced CO_2 where large numbers can be visually evaluated.

RESEARCH NEEDS

Improving the Harvest Index

Successful manipulation of the translocation and partitioning of dry matter would increase the economic yield, or harvest index. The plant breeder uses an empirical approach to select for increased harvest index. Major U.S. crops have harvest indices of 50 to 70 percent but some of the food legumes have indices of only 20 percent. Therefore, food legumes could produce larger yields by increasing the harvest index. Even a 25 percent yield increase is possible by increasing the harvest index from 60 to 75 percent.

The primary process or reaction regulating the partitioning of assimilate has not been identified. The process or reaction may occur either in the sink, in the source, or in the conducting tissue. A recently discovered process or reaction regulated by oxygen concentration alters the partitioning between reproductive and vegetative growth in all crops with partitioning to seed favored by higher oxygen concentrations. Sugar accumulation in cane appears to be influenced by the distribution of acid and neutral invertases. The cross-sectional area of the phloem in wheat plants that span the evolutionary scale is correlated with seed yield. The translocation rate is greater for C_4 species than for C_3 species. Regulating the amount of assimilate converted to sucrose versus starch in the source leaf may be a key. A nutritional component is suggested by the inhibition of starch synthesis by a high phosphate. The role of hormones on the sink, translocation, and source system is unclear. There are many leads but no answers.

Although the significance of modifying assimilate partitioning can be calculated on a theoretical basis, few field measurements have been made. Manipulation of the oxygen concentration may be a useful experimental tool. Environmental effects such as low temperature have been used with sugar beets.

There are no simple assays to select genetic material or chemicals for an improved harvest index outside of the laborious and time-consuming empirical growth approach, and simple assays may not be developed until a better understanding of the primary factors is obtained.

Controlling Conversion of Vegetative to Reproductive Growth

We must control the conversion of vegetative to reproductive growth by genetic, chemical, cultural, or physical means to allow an increase in productivity. Converting plants to reproductive growth earlier might increase yields through a longer period of seedfilling or might decrease the total time per crop, thereby enabling more crops per year and increasing total productivity. Later conversion may increase yields by providing a larger vegetative source to support reproductive growth. Instantaneous versus gradual conversion of vegetative to reproductive growth also may mean yield increases. Being able to control conversion would expand the potential geographic applications of photoperiod-sensitive crops such as soybeans. Eliminating conversion to reproductive growth is desirable in forage and tuber crops.

The primary process or reaction controlling the conversion of vegetative to reproductive growth in crop plants is unknown. However, it is possible to manipulate the phytochrome system to control flowering in Xanthium and chrysanthemums by light treatments. Manipulation of phytochrome is used in the commercial production of chrysanthemums. The flowering system in crop plants is more complex. In several instances it has been suggested that a flowering hormone exists but it has never been isolated and identified. The carbon-nitrogen ratio has been associated with flowering. Environmental factors such as temperature as well as light quality and quantity influence conversion to reproductive growth. Some varieties undergo an instantaneous conversion, i.e., determinate, while others undergo a gradual conversion, i.e., indeterminate. These seemingly unrelated observations document the need for exploratory research to identify the primary process or reaction controlling this key conversion.

Only very preliminary data are available on the significance of controlling conversion of vegetative to reproductive growth. Using laser beams to manipulate the phytochrome system has produced beneficial effects, but no major crop plants were examined. A one-week delay in the flowering of beans by field illumination increased yields by 70 percent. The potential may be large but much more experimentation is necessary.

A simple assay system outside of phytochrome has not been developed. Such an assay does not appear possible until more is learned about the primary process or reaction.

Controlling Senescence

We must learn to manipulate senescence by genetic, chemical, or cultural means to increase yield per total cropping time and/or decrease costs. The type of control, i.e., delay or promotion, will vary with the crop, geographic area, and type of cropping. In some crops it might be desirable to delay senescence of source leaves and reproductive structures. An example is wheat where each day of delay may produce a 3 percent increase in yield. In other crops it would be desirable to promote senescence to facilitate multiple cropping or to promote in-field drying and eliminate fossil fuel drying. Examples of the latter might include soybeans or corn. In another type of control it may be desirable to produce a more graduated senescence. For example, senescence of the lower leaves with transfer of assimilate to the reproductive structures might precede the senescence of upper leaves in wheat and rice. In still another case, it may be desirable to decrease the sink activity and thereby decrease the rate of senescence of source leaves and expand the total accumulation of assimilate.

The primary process or reaction regulating senescence in crop plants is unknown, which is not surprising since there have been few investigations of senescence in whole plants. Cytokinins are thought to play a negative role in senescence but few data are available for their effect on other than plant parts. A naturally occurring senescence factor has been suggested but has not been isolated. Environmental factors such as excess nitrogen fertilization or CO_2 enrichment delay senescence. The photosynthetically efficient C_4 plants may revert to a photosynthetically inefficient C_3 type as they senesce. The development of reproductive structures promote senescence. The removal of reproductive structures or the exposure of plants to subambient oxygen concentrations that arrest reproductive growth delays senescence. The strong sink activity of reproductive structures of soybeans may lead to a self-destruction from senescence of leaves. The above diverse observations indicate the failure to identify the primary regulator of senescence.

Little information is available on the significance of modifying senescence. Some work suggests that delay of senescence of a flag leaf of wheat by environmental manipulation--water or nutrients--may increase yield by 20 percent.

No simple specific assays are available outside of possibly the green color of chlorophyll, but this effect may be remote from the primary effect of senescence in a mature crop plant.

IMPACT

Our understanding of each of these areas is minimal, and we lack data on the significance of modifying each area. Therefore, any impact statements are of very low reliability. The short-term effect of this research probably will be greater scientific knowledge with a negligible effect on food production, while the long-term effects could be major increases in food production.

The chances of success defined as increasing crop production by 25 percent or greater in the short term is unfavorable, 0 to 10 percent. In the long term it is favorable, 75 percent. However, this long-term expectation is only valid if exploratory research programs are initiated immediately. Each of the three areas appears to have an equal chance of success.

Success in the research areas described above would:

-- Accelerate the rate of selection of chemicals or genetic material for increased crop productivity.
-- Increase yield a minimum of 20 to 30 percent for each of the three areas.

-- Apply to most of the major crops--grains, legumes, root and tuber crops, forage crops, and sugar crops. It would apply to food legumes as well as cereal grains so that the declining food legume/cereal grain ratio should not be worsened and could be improved.

-- Not alter the nutritional quality of crops.

-- Apply broadly geographically to the agriculture of both the high-income and developing countries. The technology would be most readily adopted in the high-income countries which have the existing infrastructure to support the production and distribution of required new inputs. In the developing countries, this technology would be adopted more rapidly by the larger, more commercial farmers. Thus total food production would be increased, but the direct effect on the poorest farmers and countries might be limited--the limitation possibly greater for chemical than genetic solutions.

-- Increase the requirements for seed, chemicals, fertilizer, and water similar to those experienced in the Green Revolution. An improved harvest index is a favorable exception since it would increase food production with minimal requirements for additional inputs. However, to the extent that the proportion of plant growth utilized is increased, the removal of soil nutrients also would increase and therefore fertilization would be required. Labor and machinery costs per hectare per year also would be increased for the expanded number of crops grown per year.

-- Enable chemical regulators (plant growth regulators) to be broadly applicable across crops, if a common primary reaction is being regulated. However, genetic manipulation will require much longer to implement, and physical solutions will require applying new types of inputs.

Controlling senescence and the conversion of vegetative to reproductive growth would (1) stabilize food production in regions with a shortened growing season due to frost or lack of rainfall, e.g., U.S.S.R., Canada, and the semiarid tropics; (2) facilitate multiple cropping in those areas having longer growing seasons; and (3) extend the land area suitable for crop production.

IMPLEMENTATION

Two phases of research are proposed. The initial or exploratory phase would be performed for the most part in the public sector or by contract in the private sector. The second or technology development phase would be performed in both the public and private sectors--the private sector presumably providing chemical solutions and the public sector presumably providing genetic solutions, unless the solutions are coupled to the exclusivity provided by hybrids. A change in the Plant Protection Act would permit the private sector to participate more in genetic solutions.

The essential exploratory phase could be completed within 5 to 15 years. It would cost $1.5 million per year to support 15 scientists for each research area plus a one-time facilities cost of $3 million for expanding laboratories and greenhouse facilities. These 15 scientists should include physical chemists, organic chemists, analytical chemists, biochemists, physiologists, agronomists, and soil scientists.

In addition, expanded exploratory research on plant biology and biochemistry outside of the three indicated areas is needed and 100 annual grants of $100,000 per year are recommended at a cost of $10 million per year. Most of this work would be done at universities. Adequate funding is needed to attract creative scientists into the crop production area.

The technology development phase would be initiated when promising leads are found. The number of scientists could vary from a minimum of 15 to a maximum of 50, representing annual costs of $1.5 to $5 million for each area.

Profile 8

INTERACTIONS OF SPECIES

INTRODUCTION

The interactions of plant species have received little attention in temperate zone research programs located in the technologically developed countries. Most crops--annuals, perennials, tree crops--are grown in single cultures, that is, a single crop occupies the area and with minor exceptions it is the only crop grown during the year.

The situation is dramatically different in some parts of the world, especially in the tropics, where there is an incredible variety of sequential cropping, relay cropping, intercropping, and mixed cropping involving grains, root crops, vegetables, and, in many cases, tree crops. It is not uncommon for the area adjacent to a home to support an additional 50 to 60 species of food crops of nutritional importance.

In some countries, these types of cropping systems have evolved over hundreds or thousands of years; in others they have been introduced recently or are still only under consideration. In systems of long standing, there is a reservoir of practical knowledge in the art of culture, but the scientific underpinning is minimal or absent.

Successful research on crop interactions could substantially increase food yields. We will briefly examine some of the research potential for representative systems, recognizing that there is great variety within them. There are colloquial terms for the systems, but we use only descriptive terms. Subgroup D, Study Team 4 deals specifically with many aspects of cropping systems. Systems are described here only as a basis for considering possible interactions of species.

Sequential Cropping

With this cropping system two to five crops are planted in sequence at varying intervals of time and with varying amounts of interim tillage. Some interactions are: effects on soil moisture, depletion of plant nutrients, effects of residual nitrogen from leguminous crops, effects on soil structure, and effects of decaying residues.

The chief purpose of sequential cropping is to increase the period of time during which crops are capturing solar energy and/or to more efficiently utilize available water. Additional goals include better distribution of labor, greater stability of total yield, and better distribution of food throughout the year.

Relay Cropping

In relay cropping two or more crops are grown in sequence but with some overlap in occupancy of the land. According to Richard R. Harwood (1976, personal communication, International Agricultural Development Service): "For the sake of clarity we have been stating that the second crop is planted after the beginning of the reproductive stage of the first, so that at flowering the crops are alone." In addition to the purposes listed for sequential cropping, a single major tillage operation may suffice for several crops and soil erosion could be reduced. Corn-rice-cassava represents this system. Corn is harvested before rice heads. Rice is harvested later but before cassava begins to spread. Finally, cassava is harvested after 9 to 10 months. Tillage is performed only when the cassava is harvested.

In systems where crops overlap, they interact in respect to light, water, and plant nutrients. There are both above- and below-ground interactions. Potential sources of interaction are: (1) the relative time at which each crop is started, whether from seed or as transplants; (2) the above-ground architecture including height, leaf area index, and perhaps leaf angle; (3) the depth, lateral extension, degree of branching, possible exudates, and, in some cases, nitrogen-fixing capability of roots; and (4) the enhancing or inhibitory factors from decomposing plant residues.

Intercropping

We shall limit intercropping to systems in which single rows or sets of rows of two crops are planted alternately across the land area.

Traditional research in the United States has usually shown that the total yield is less than where the higher yielding crop occupies the entire space. But recent research by IRRI in the Philippines (Harwood 1976, personal communication) and ICRISAT in India (B. A. Krantz 1976, personal communication, Farming Systems Program, IÇRISAT) reveals that some combinations are considerably more productive than the higher yielding crop in single culture. Some very interesting interactions occur in the forms of less disease (downy mildew in the corn-soybean intercrop in Indonesia), fewer weeds (corn-mung bean intercrop in the Philippines), and fewer insects (corn borer in several intercropping systems). In IRRI trials, rice and corn produced about 30 percent greater value of grain from 180 kg/ha nitrogen fertilizer than did corn alone (Harwood, forthcoming publication of an INCAP Symposium in Guatemala, 1974). Krantz (1976, personal communication) reports that the yield effects of intercropping were different on black and on red soils.

Most potential interactions discussed under relay cropping also apply to some extent to intercropping.

Mixed Cropping

We shall apply this term only to situations in which two or more crops are intermingled on the same area. There are two distinct systems and several intergrades.

The first system is a mixture of annual crops, frequently hand-tended vegetables throughout East, South, and Southeast Asia (China, Taiwan, Japan, Indonesia, Thailand, Vietnam). In these areas, the plants are commonly grown in narrow beds separated by channels from which water is hand-dipped onto the beds for irrigation. This method prevents salt accumulation in the surface soil. Several species at approximately the same stage of growth occupy the beds, and a succession of plantings takes place throughout the year, often greatly telescoped in time by transplanting rather than by starting from seed. Some species occupy the site for 30 days or less, notably those grown only for consumption of the vegetative rather than the reproductive parts (seeds, fruits, etc.). J. R. Harlan reported (1976, personal communication, Crop Evolution Laboratory, University of Illinois) that a U.S. plant pathologist was amazed to find some vegetables infected by several diseases but damage to yield appeared to be minimal, perhaps because of the short interval from planting to harvest. Harwood reports that "highly productive systems on low-cash flow farms of Java and Nepal include 20 to 30 annual food crops and 20 to 30 perennials (Paper presented at an U.S. Agency for International Development Staff Seminar, Manila, The Philippines, January 16, 1976)."

The second system is a mixture of tree crops with an understory of annuals or short-term perennials. The main areas of interaction are light, nutrients, and water. Upland rice and cassava, for example, tolerate the partial shading under banana, rubber, and coconut trees. In some cases, the problem of light competition is solved by planting the annuals shortly before the time of normal leaf fall of the trees. The decaying leaves supply nutrients for the shallow-rooted annuals thus minimizing or eliminating the need for fertilizer.

The maximum potential for research on crop interactions is in the area of mixed cropping systems. The possibilities seem almost endless for improving quantity and/or quality of foods by elucidating principles of interactions of indigenous species, for introducing species from other areas, for developing superior suitability to intercropping through genetic change in both native and introduced species, and for manipulating species through management, fertilization, etc., to modify interactions.

Homestead Area Cropping

In tropical areas it is not uncommon to find 20 to 50 species of food plants in close proximity to homes. There may be annuals and perennials, fruits, nuts, vegetables, bushes, and vines. They interact in all the ways previously listed. The homestead area involves recycling human, animal, and plant wastes. Through long periods of trial and error local people have learned which combinations of crops are workable and which best fit their family resources and food needs. But scientific research on the interactions among species is almost nonexistent. Experienced observers can draw many inferences that could lead to productive research. (Homestead area cropping is relatively new to soil and plant scientists who visit the tropics.)

Near the homesteads in some areas rural families harvest a wide variety of wild species. A graduate student from Nigeria reported 60 species of food plants (Harlan 1976, personal communication) being used to supplement diets.

RESEARCH NEEDS

First, an inventory of the types of cropping systems currently in use should be prepared. Each type of cropping system should be classified and analyzed as to why it is productive or unproductive. Special insect, disease, weed, or other pest problems or lack of problems should be described. And each system's contribution to the nutritional status of people should be evaluated. This step can only be accomplished through on-site visits by a team of scientists with broad knowledge in soils, plant growth, plant pathology, entomology, and human nutrition. The proficiency of such teams will grow with experience.

Second, each cropping system should be followed throughout a complete growth cycle in order to understand its strengths and weaknesses. Introducing modifications into the traditional system may help to gain insight on these points.

Third, Krantz (1976, personal communication) suggests that simulation models be developed to analyze climatic and soil data and the seasonal requirements of plant species as a means of synthesizing promising new systems for trial.

Fourth, research should be initiated on response to light intensity (tolerance to shading), root system compatibility, root exudates, and effects of decomposing residues. This research can be conducted in greenhouses or in any region with a similar climate. The final evaluation must, however, be done locally because the entire ecological complex of soil, climate, and pests cannot be duplicated elsewhere.

Finally, we must determine how systems match human resources and nutritional needs.

IMPACT

The SAT (Semi-Arid Tropics) area of the world involves parts of 48 countries, including parts of the Indian sub-continent, Burma and northeast Thailand, two belts of Africa, above and below the equatorial humid tropics and parts of South and Central America. It is estimated that this area contains about 500,000,000 people about half of which live in the SAT of India (Krantz 1976, personal communication).

If we could grow an additional crop on these 18.2 million hectares of the Indian semi-arid tropics (includes only land which is fallowed in the karif and fallowed by a single rabi

> crop) with a foodgrain yield of 1000 kg./ha., which is not an infeasible figure, this could increase India's foodgrain production by about 16 percent on present day production figures (J. G. Ryan 1976, personal communication, ICRISAT).
>
> ...the semi-arid tropics is the most under-researched area, and it is also the area in which the greatest amount of food aid has been provided during the reoccurring drouths and floods in recent years (Krantz 1976, personal communication).

Similar potential exists for research on crop interactions in Central and South America and other areas of the humid tropics where large populations occur:

> In my judgment, improvements in cropping systems probably provide as great a potential for increased crop production in Asia as any other single factor (N. C. Brady 1976, personal communication, IRRI).
>
> A farmer will include in his system a portion of his farm devoted to intensive sequential cropping, a portion to field vegetables, and perhaps a portion to tree-fruit, crops...when viewed as a whole, these combinations tend to make more efficient use of his labor, power and cash resources, and give him far greater diversity and quality in his diet.... We must remember, however, that this model pertains to the "small" farmer whose limited resources preclude his entering a powerbased, capital-intensive, service-oriented economy (R.R. Harwood 1976, unpublished data, Cropping Systems Program, IRRI).

In summary, knowledgeable scientists say that improvements in mixed, multiple, sequential, intercropping, and homestead cropping would be of great benefit. Increases of 20 to 25 percent are possible for the entire semiarid tropics where one-eighth of the world's population lives, and for sizable portions of the humid tropics. Some of the results will have special significance for small farms which have, to date, participated very little in the fruits of research.

While some yield increases in individual crops may result from interactions among species in multiple cropping systems, the main effect on total output results from more fully using land resources. Thus total output per unit of land per year is increased, having the same effect on output as an increase in land area cropped. The wider variety of crops grown reduces the probability of complete crop failure.

Multiple cropping systems tend to increase the number of different crops grown and the number of months during the year that production takes place. Thus the effect on the labor requirement may be quite different than would result from increasing the land area used for crops. The seasonality of labor use is reduced and the proportion of the year that labor can be employed productively in farming activities is increased. Thus while more labor is required, the number of people employed does not necessarily increase, and may even decline as seasonal peaks are reduced. The expected result is increased output and income per person.

Additional purchased inputs may or may not be required depending on the combination of species grown and the effect of multiple cropping on disease and insect infestation and on soil nutrient removal. Supplemental water may be necessary to extend the production season in some areas.

With the possible exception of sequential cropping, these systems are not well suited to mechanization. They have their greatest potential use in situations in which land is scarce relative to labor, and the labor force has few opportunities for seasonal off-farm employment. This describes the situation of the small, low-income farmer in most of the developing countries. Therefore, this technology is likely to have its greatest effect on the rural poor of the poor countries.

The adoption of new multiple cropping systems by this group may be limited by the following factors. First, these farmers produce primarily for their own consumption and local markets. Systems that involve introducing new crops may encounter resistance because of the lack of either a place in the farmer's consumption habits or a market. Second, many of the crops already produced are for local consumption and no market structure exists for excess production. Third, these farmers are poorly educated and have a high aversion to risk. Thus an intensive demonstration program may be required to convince them to adopt new cropping systems.

Except for sequential cropping these systems would seem to have little relevance to agriculture in the high-income countries such as the United States.

IMPLEMENTATION

During the past decade a cadre of scientists extremely knowledgeable in tropical cropping systems, in socioeconomic matters, and in the understanding of life-styles has developed, especially in the international research centers, within the Rockefeller Foundation, and in the U.S. land-grant colleges that have contract programs in the developing countries.

We believe there could be a great payoff for training and deploying teams of three to five scientists each to travel extensively in the developing countries. These teams would observe, inventory, and analyze existing systems; suggest the transfer of systems from region to region; and outline needed research on crop interactions. The resources required for such a program would be similar in support staff, operating cost, and salary for scientists performing research at a site in a developing country and only slightly in excess of those needed for a U.S. agriculture scientist in an experiment station or in the Agricultural Research Service of the U.S. Department of Agriculture (USDA).

An accelerated training program should be instituted soon, but since the program will be phased in over time, the number of additional scientists that can be efficiently used need not be decided now. Training would be conducted mainly in the United States but would involve both domestic and foreign students.

Report of Subgroup A, Study Team 1

PEST CONTROL

INTRODUCTION

Pests are biological organisms that interfere with people's needs and desires. They are biologically diverse and include insects, other arthropods and invertebrates, vertebrates, plants (weeds), fungi, bacteria, and viruses. Whether a particular species is determined to be a pest or not depends upon its habits, the time and place of its occurrence, and the numbers in which it appears. This report concentrates on preharvest losses caused by pests. Postharvest losses are covered by Study Team 6.

The magnitude of losses from pests is not known precisely. Cramer (1967) has compiled the only global estimates on losses available, and he acknowledges that the data may be inaccurate. The United States has the most comprehensive data; estimates of losses in the developing countries are considerably less complete. In the absence of better estimates, we will use Cramer's work as an approximation of global losses.

Table 4 summarizes losses in the world's major crops from insects, diseases, and weeds. Losses from vertebrates such as rats and birds also occur, but comprehensive estimates of these losses are not available. The production that would be possible if losses did not occur also is calculated. Unfortunately, rice, the world's most important crop, suffers the highest losses from pests (46.4 percent). In 1974, nearly 280 million tons of rice were lost to pests. All crops suffer losses of over 20 percent.

Data in Table 4 must be regarded as conservative for several reasons. First, Cramer always selected conservative estimates if more than one estimate was available. Second, the data are average losses over many years, thus catastrophic losses in one year are hidden in long-term averages. Such losses, however, are likely to have disastrous consequences, especially in the developing countries with low or no food reserves. Third, Cramer's estimates do not account for losses that are consistently so high that particular

Table 4. Losses from pests in the world's major crops

Crop	Losses (percent)*				1974 production (million tons)	
	Insects	Diseases	Weeds	Total	Actual	Potential
<u>Cereals and grains</u>						
Rice, paddy	26.7	8.9	10.8	46.4	323.0	603.0
Wheat	5.0	9.1	9.8	23.9	360.0	473.0
Maize	12.4	9.4	13.0	34.8	293.0	449.0
Millet/sorghum	9.6	10.6	17.8	38.0	93.0	150.0
<u>Vegetables</u>						
Potatoes	6.5	21.8	4.0	32.3	294.0	434.0
Cassava	7.7	16.6	9.2	33.5	104.0	158.0
Sweet potatoes	8.9	5.0	11.7	25.5	134.0	180.0
Tomatoes	7.5	11.6	5.4	24.5	36.0	48.0
<u>Oilseeds</u>						
Soybeans	4.5	11.1	13.5	29.1	57.0	80.0
Ground nuts (shell)	17.1	11.5	11.8	40.4	18.0	30.0
Palm kernels	11.6	7.4	9.6	28.6	1.3	1.9
Copra	14.7	19.3	10.0	44.0	3.6	6.4
Cottonseed	11.0	9.1	4.5	24.6	26.0	34.0
<u>Fruits</u>						
Bananas	5.2	23.0	3.0	31.3	36.0	52.0
Citrus	8.3	9.5	3.8	21.6	29.0	37.0

*Does not include losses from other types of pests.

Sources: Cramer (1967) and FAO (1975a).

crops are no longer grown in certain areas. Such losses should be considered when planning research on pest problems.

It has been found that existing pest control practices can lose their effectiveness. For example, resistance to pesticides has seriously eroded the effectiveness of chemicals, especially in the control of insects. Furthermore, the replacement of one weed pest that is sensitive to a herbicide by one that is not is a well-recognized occurrence. The evolution of new biotypes of disease organisms can render a resistant cultivar sensitive to severe infestation. There is, therefore, a continuous need for research on pest control. The biological plasticity of the target organisms necessitates a never-ending search for new practices just to "stay even" with our current position.

As the world's population continues to grow, it will become increasingly necessary to reduce losses from pests if people are to be well nourished. In general, there are two major ways that pest control can improve world nutrition: by improving crop yields and by protecting harvested crops from postharvest destruction and/or rotting (see the report of Study Team 6). Larger yields of cereals, legumes, and starch roots and fruits can increase the availability of calories (except for the starch roots and fruits) and protein. In most areas where endemic malnutrition is prevalent, increases in yields offer the most promise for alleviating calorie-protein malnutrition. Increased yields of leafy green vegetables and some fruits could be quite useful in combating certain vitamin deficiencies such as vitamin A deficiency with associated xerophthalmia. Protecting vegetables and fruits from postharvest rot should be an important objective of pest control research in most tropical areas because as much as 50 percent of fruits and vegetables may rot before they can be consumed.

Improved pest control technologies also might increase the option of growing a particular crop where it is not grown now because of severe pest problems. For example, the tomato is not grown in parts of the Philippines because Pseudomonas solanacearum prevents its growth.

Pest control problems, like many agricultural production problems, are highly dependent upon their location. The physical and biological environment, social customs, political events, and the economic millieu can all interact in order to create the problem and to constrain feasible solutions. Research may need to be location-specific for many of the following reasons.

Pest problems always involve the interaction of at least two biological organisms, the pest and the host. Each organism may show genetic variation from location to location. For this reason, a solution generated in one area may not be useful in another.

Solutions to pest problems are by no means permanent additions to agricultural technologies because of the genetic plasticity of pest organisms. For example, fungal diseases of many cereals continually evolve new races that are virulent on formerly resistant strains of hosts. New pest strains evolve in a specific location. Likewise, the resistance of insects to insecticides varies from place to place.

Worldwide patterns of commerce have introduced alien species into new locations. This situation will continue to generate new problems.

Climate patterns may be roughly similar in two locations and yet show subtle differences that are crucial to establishing efficient pest control practices. Successful biological control depends upon the use of parasites adapted to specific locations (DeBach 1974). For example, attempts were made to control the walnut-aphid in California with Trioxys pallidus imported from southern France. The latter organism became established along the coastal plain of southern California, but not in northern and central California. Only when Trioxys pallidus was introduced from the hot, dry portion of central Iran was it successfully established in all areas of California. Subtle differences between the strains from France and Iran probably reflect adaptations to different climates.

Specific crops grown in an area are associated with specific key pests. Developing and introducing a practice to control one key pest on a specific crop may have little relation to control practices for other key pests on other crops in the same area or to practices that are useful on the same crop grown in a different location.

Political organization may make some control practices feasible in some areas but not in others. For example, in Kwantung Province of the People's Republic of China the Big Sand Commune uses thousands of ducklings as biological control agents for insect pests on early rice (NRC 1976). Only societies with careful planning and sophisticated worker organizations could implement such practices.

The above examples are by no means exhaustive of the location-specific nature of pest control problems, nor are they meant to imply that other agricultural problems are not also location-specific. They do imply, however, that there are limits to general recommendations that can be made for pest control research.

RESEARCH NEEDS

We recommend below different types of research that should be pursued to reduce losses from pests. This research includes: basic laboratory and field studies; applied, mission-oriented research; and implementation studies to help put the scientific findings into practice. All three types of research are important in developing and successfully adopting useful innovations. The last category, implementation studies, has been slighted in the past despite the fact that without adequate extension activities, innovations remain theoretical or of laboratory interest only. Efforts to increase basic or applied research should not cause a reduction in extension activity. If they do, it is unlikely that the resulting innovations will have a positive effect on worldwide hunger and malnutrition.

Integrated Pest Management Systems

Crop yields often vary when crops are protected by a single method of pest control. Stable yields are more likely if a variety of control tactics, systematically combined, are used. Integrated control practices rely on cultural, biological, pesticidal, and autolethal methods, and the use of pest-resistant plant varieties. Moreover, approaches to crop protection must be adapted to changes in production technology, must be economically and environmentally sound, and must be socially acceptable. Integrated pest management systems of crop protection are needed for farming systems that range from the large-scale, heavily capitalized operations to the small-scale, labor-intensive operations of the developing countries.

The term "integrated pest control" was coined by entomologists to emphasize the importance of combining several tactics in order to manage insect populations. However, the fundamental ecological principles involved, i.e., concepts of interactions within an ecosystem and population regulation, have been widely advocated by plant protection scientists for more than a century, although not clearly articulated into a strategy. Certain pest control tactics seem to have had wider applicability for particular categories of pests, e.g., classical biological control for insects and host plant resistance for plant pathogens. However, it is difficult in most instances to distinguish between the real potential of a tactic and the level of effort to apply it. Some of the specifics of integrated control developed for insects may be less applicable for other kinds of pests, but the ecological approach is one that should be utilized in all pest control. Furthermore, the same basic ecological approach used in integrated pest management for specific insects also is needed when attempts are made to combine management of all categories of pests into a single pest management system for a crop.

Practical experience in integrated pest management to date suggests several lines of research that would be required to develop integrated pest management systems. Some lines of research are applicable to certain classes of pests and not to others.

Characterizing Significant Pests

It is not necessary or practical to eliminate all pests at all times from a crop production system. Consequently, it is important to identify which key pests cause significant damage to the yield and quality of the crop, and when this damage occurs. In some instances, a key pest may not be a single species but a group of similar pests, e.g., lepidopterous borers, annual weeds, fruit rots. For key pests it is important to establish quantitatively and qualitatively: (1) the relationships between them and their natural enemies; (2) the influence of variations in soil, water, weather, and crop production practices on their population size; and (3) the relative economic features of alternative control practices.

Establishing Criteria for Control Actions

There is no justification for initiating a control practice if the cost of the damage by the pest is below the cost of control. In general, the "economic threshold" is the level of a pest population that justifies control activity. The criteria for taking action is the level of economic damage done by the pest. "Action thresholds" also are made with respect to a certain growth stage, phenological period, or physiological state of the crop plant. Research should be done to identify more carefully the most appropriate action threshold.

Maximizing the Benefits of Natural Enemies, Pest-resistant Varieties, and Cultural Practices

Natural enemies, resistant varieties of plants, and cultural practices are used by many farmers although they often do not necessarily understand the technological basis for their actions. The fact that these pest control methods often require low capital input makes them particularly attractive. Later we will describe specific kinds of research for this area.

Developing Measures for Selectively Controlling Pests

It is frequently desirable to suppress an outbreak of a particular species without disrupting the equilibrium of other pests. Species-specific control measures are useful in such cases. Broad spectrum insecticides that destroy beneficial insects are the antithesis of selective controls. In weed control the selective control of one pest may be of little value because the eliminated pest is replaced by its ecological counterparts. In such cases selective resistance of a crop plant to herbicides is important.

Developing Modeling and Systems Analysis for Selection of Control Tactics

For effective integrated pest management, control tactics must be combined so that they reinforce each other. Mathematical modeling and systems analysis have proven to be effective procedures for interpreting large amounts of data gathered while monitoring pests in agro-ecosystems. Modeling also can assist in understanding agro-ecosystem processes, such as crop growth and the population dynamics of pests. Thus it can provide guidance for the necessary research and support procedures.

Developing Implementation Studies for Integrated Pest Management Systems

Pest management systems must be incorporated within the food production process if they are to help improve the world food and nutrition situation. Moreover, the development of useful pest control practices requires close cooperation between scientist and farmer. Implementation studies identify the processes by which farmers and researchers can give mutual feedback to each other on changes that are needed in experimental design.

Cultural Control

Cultural control involves manipulating the environment (1) to make it unfavorable for pests and favorable for crops, (2) to reduce the rate of pest increase or damage, or (3) to provide suitable conditions for the use of other control methods. Cultural methods of pest control depend primarily on knowing what factors favor a proliferation of pest species, and on a thorough knowledge of the crop and the agronomic practices used for its production. With this knowledge the pest manager modifies a habitat using irrigation, drainage, fertility practices, seedbed preparation, change in planting and harvesting dates, fallowing, intercropping, crop residue destruction, changes in crop variety, and crop rotations.

It has been estimated that more than one-half of the people in the world depend upon a subsistence type of agriculture, and that 40 percent of the land under cultivation worldwide is in the hands of the subsistence farmer (Wellhausen 1970). Subsistence farmers generally use traditional methods of pest control as opposed to "modern" methods that depend heavily on machinery and chemicals. Many of our modern cultural methods of pest control have evolved from traditional ones, and there is no sharp line dividing the two.

Most traditional methods have developed empirically through the centuries and have resulted in sound farming systems. Scientists, working with anthropologists, economic botanists, sociologists, and economists, should analyze and gather the information and techniques used in traditional farming. Such analysis should provide new information or suggest new lines of research to the plant protectionists, and should identify aspects of traditional systems that restrict increased production and that are susceptible to change based on scientific knowledge.

Knowledge gained from research on traditional agriculture will help explain why the traditional farmer often rejects information generated by "modern" agricultural science. A study of existing traditional methods of pest control will provide a sound base on which to initiate improvements in systems of subsistence agriculture.

Breeding for Resistance to Plant Pests

Establishing Germ Plasm Programs

The best sources of plants resistant to pests are often found in the centers of origin of a given crop. Plant explorers have made these sources available in current international and national germ plasm collections for many of the major food and fiber crops of the world. The genes available in these collections are the primary resource in breeding for pest resistance. However, collection is still needed to maintain the widest possible range of genetic materials of cultivated crops (Harlan 1975).

The germ plasm in banks only represent a fraction of the diversity of species in nature. The maintenance of collections, especially living collections, is time-consuming and expensive, but it is essential if efforts to breed varieties with multiple resistance to pests are to succeed. Living collections should be maintained near or in their region of origin in order to prevent the inadvertent loss of valuable genes.

It is paradoxical that as improved, high yielding varieties are more widely used around the world, the old, native varieties are disappearing. The introduction of new and improved varieties, more intensive land use, and a reduction in the total number of crops grown have resulted in serious losses of genetic resources.

Little evidence exists that induced variation will add significantly to pest resistance already available in nature. Thus it is essential that germ plasm be systematically collected, evaluated, and maintained for pest resistance. Priorities for collection of germ plasm should be established. Data banks on resistance to pests should be established from the results of evaluating each collection.

Long-term storage of germ plasm of vegetatively propagated plants under liquid nitrogen is now feasible and should greatly reduce the costs of maintaining living collections of vegetatively propagated crop plants. Nevertheless, more work is needed before the method will come into general use.

The specific needs in the area of germ plasm programs include: (1) expanding efforts to collect, maintain, and evaluate germ plasm resources for pest resistance; (2) maintaining "living collections" of the wild ancestors of the major food crops in their native state in internationally protected "natural reserves"; (3) establishing data banks on resistance to pests from the results of evaluating germ plasm collections; and (4) supporting research on long-term storage of germ plasm.

Developing Techniques for Plant Cell and Organ Culture

Having the ability to culture cells and organs and to regenerate complete new plants from their parts could improve two pest control techniques long in use, plant quarantines and the selection of resistant varieties. Such techniques also open up the possibility of selecting new interspecific hybrids that may have highly desirable pest-resistant properties. The general research needed to develop tissue culture techniques more fully is described in a later section.

Plant Quarantines. The danger of pests and pathogens moving among countries and continents is becoming more serious in today's jet age. Great quantities of improved crop seeds are moved from continent to continent, and true seed and vegetatively propagated plant parts of a variety of crop plants are tested in international nurseries. There is a serious potential hazard of introducing new pests when germ plasm is moved, especially that of vegetatively propagated plants. Thus quarantines are often justified.

Recent advances in plant tissue culture methods, which have resulted in pathogen-free stocks, now make it feasible to ship plants free of disease, insects, weeds, and nematodes anywhere in the world. Unfortunately, investigators in most developing countries seldom have the facilities or the training to carry out these procedures. With adequate research, stocks of the major food crops that are vegetatively reproduced could be maintained, free of pathogens and other pests, and shipped elsewhere in the world. There is even danger when distributing some crops multiplied by true seed. Developing such tissue culture methods would speed the transfer of technology to the developing countries by making available germ plasm that now cannot be imported or can be imported only with great difficulty and danger. It also should be noted that such research is complementary to that recommended on tissue culture as a means for increasing options in plant breeding.

The research required for this area would include:

-- developing practical methods of meristematic tip culture for the major food crops that are vegetatively reproduced (eventually tissue culture also may be useful for crops with true seed which occasionally harbor pests);

-- establishing reliable methods of indexing for freedom from the important pests of the material from meristematic tip culture;

-- developing and evaluating methods for the rapid multiplication, maintenance, and dissemination of such clean stocks in a pest-free state.

Selecting Pest-resistant Varieties. If cell and organ culture methods were improved, it would be possible (1) to assess large populations for pest resistance in a short time and in a small space, (2) to transfer genetic material between species more easily than by using whole plants, and (3) to assemble new forms of resistance more easily than by using whole plants. However, pests themselves do not relate to cells in culture as they do to whole plants and therefore do not discriminate between susceptible and resistant genotypes. Since most pests exhibit some degree of host specificity, it is important to determine the chemical basis of this specificity in the hopes that a chemical isolated from the pest can be used to identify accurately susceptible or resistant cells in vitro. This approach has been used successfully with several fungal plant pathogens. Host-specific, fungus-produced toxins have been isolated and used in plant breeding programs to efficiently eliminate all susceptible plants or cells in a segregating population. A limitation to this approach is that host-specific chemicals have not been identified for most of the important diseases of crop plants; we are continuing to search for such materials. When or if the use of host-specific chemicals becomes common, the high level of screening efficiency they provide will allow for detection of rare and/or highly effective types of resistance and transfer of such resistance into desirable crop plants. It also will provide a tool for screening mutagenized populations of cells.

Naturally occurring chemicals produced by the pest that are not host-specific also may be useful in screening for resistance in vitro, but they are more difficult to use because resistance to the chemical may not be equivalent to resistance to the pest itself. Plant cell cultures also are potentially useful in screening for herbicides including toxins derived from fungi and other biological sources as well as synthetic chemicals.

Three areas of research are necessary for selecting pest-resistant varieties. First, we must identify host-selective chemicals for important pests of crop plants. This is necessary to eliminate accurately all susceptible cells from mixed populations, while permitting recovery of all resistant cells. Second, we must determine the principles behind molecular control of specificity in the host-parasite interaction in order to identify host-selective chemicals produced by plant pests. This will provide a rational rather than empirical approach to disease control. Third, we must improve techniques for manipulating cells of crop plants in vitro. This involves culturing of tissues and cells, genetic modification by asexual means, and regeneration of intact plants from genetically modified cells. The latter is difficult, but is absolutely necessary before cell biology techniques can influence food production.

Selecting Interspecific Hybrids with Improved Pest Resistance. The dwindling genetic variation of many major crop species makes it imperative that new approaches be developed to extend the range of plant hybridization beyond the present bounds of sexual compatibility. At present, relatively few interspecific crosses have been successful.

Triticale, a hybrid between wheat and rye, illustrates the potential value of interspecific crosses. It combines the high protein content and high yielding capacity of wheat with the high lysine content and ruggedness of rye and it is resistant to races of rust to which wheat is susceptible. Triticale is presently grown on 400,000 hectares in 52 countries and is rapidly becoming an important world food crop (Hulse and Spurgeon 1974).

If techniques for achieving similar interspecific crosses of diverse germ plasm could be developed, the implications for pest protection would be far reaching. Some cultivated species are not resistant to many pests, but wild species often contain such resistance. The wild species related to our crop plants have scarcely been tapped as sources of resistance to pests. Occasionally, interspecific crosses occur in nature as chance outcrosses or as the result of using conventional breeding techniques, but dramatic breakthroughs in achieving interspecific hybridization are unlikely with these traditional methods. Plant cell culture techniques hold the greatest promise in achieving success with interspecific crosses of higher plants. Viable protoplasts that undergo proliferation by cell division have been isolated successfully for several plant genera. These protoplasts also have been induced to fuse, but lack of selective markers for recognizing hybrids and the inability to regenerate hybrid cells into entire plants still present major problems (Carlson and Polacco 1975). Research on tissue culture techniques recommended elsewhere should include investigations designed to select new interspecific hybrids with improved resistance to pests.

Selection and Breeding for Pest Resistance

National and International Collections of Pests. The need for germ plasm collections of plants is obvious, but evaluating plants for pest resistance call for pest collections as well. Maintaining collections of insects that attack plants is difficult and expensive. Thus few collections are maintained, even in the United States.

Cultures of plant pathogens such as fungi, bacteria, and viruses often can be maintained. The American Type Culture Collections, USDA, and other agencies maintain cultures of many parasites. These activities should be expanded and given more support. Many pests cannot be maintained in vitro and can only be maintained in vivo with great difficulty and at great expense. Care must be exercised to prevent pest collections from being a source of infestation for commercially-grown crops.

In order to maintain national and international pest collections, we must (1) develop better methods of long-term storage of pests, (2) support national and international entities that collect and maintain pests for dispersal to breeding programs for pest resistance, (3) catalog existing national and international pest collections so they can be more easily accessible to all scientists breeding for pest resistance, and (4) establish "living-gene parks" where coevolution in host and pathogen can continue in the center of origin of the major food and fiber crops.

Communication among Plant Resistance Programs. An index of breeding programs found worldwide is in the World List of Plant Breeders which FAO published over 10 years ago (Mao 1965). Language problems, constraints on travel, inadequate library facilities, and lack of organized exchange of information have resulted in considerable duplication in plant breeding programs for pest resistance. Present communication networks among breeders of wheat, maize, and rice may serve as a model for facilitating communication, but an immense task remains to be done in this area for most crops. The United States could help by coordinating and facilitating increased communication among those breeding for pest resistance in cooperation with other national and international agencies. In particular there is an immediate need to collect and disseminate a compendium of standard screening procedures used in plant breeding. Such a collection would aid the evaluation that occurs prior to the release of newly selected varieties.

Monitoring the Spread of Pests. Pests move among continents with great ease. The problem is especially acute with tropical plant pests. Accurate data with which to evaluate the potential of pests to cause serious losses are generally lacking, and without such information it is extremely difficult for plant protectionists and governments to determine which pests are truly important. FAO is working in this area; however, much more research is needed to determine the ability of pests to spread, and especially the ability to cause disastrous losses once established in a new locality.

A worldwide cooperative effort is needed for this research. Obviously, with the large number of pests attacking crops only selected pests could be monitored. Pests that attack the basic food crops that feed 90 percent of humanity--rice, wheat, maize, sorghum, millet, rye, barley, sweet potatoes, cassava, coconuts, and bananas--should be emphasized.

The need for monitoring pests is exemplified by the downy mildews of maize, the most destructive pathogens of maize in tropical Asia. Eight different species of fungi cause downy mildew of maize.

One species, *Sclerospora sorghi*, was found in Texas in 1961 and since has spread to 13 American states and Mexico. It rapidly spread to the Atlantic coast of Mexico where it caused serious losses, and was recently reported in El Salvador, Guatemala, Honduras, Venezuela, and Brazil. In 1969, it caused an estimated $2.5 million loss in sorghum and corn in Texas, and losses were again heavy in 1973, with 80 percent of the plants infected in many fields. The broom corn industry was eliminated in Texas because of *S. sorghi*.

If *S. sorghi* or the other destructive species now confined to Asia spread throughout the tropics, the effect would be devastating since losses from the downy mildews in Asia often reach 30 to 40 percent. The maize presently grown in the Americas and Africa has little resistance to these pathogens. Monitoring the international spread of the downy mildews on a crop of such worldwide importance as maize would be an invaluable service to the developing countries of the tropics. Many national, international, and tropical developing country entities might participate in this monitoring effort.

To set up networks that would monitor pests, we must: (1) determine the most efficient methods of monitoring the geographical spread of crop pests; (2) identify the national, international, and developing country organizations that could participate in the monitoring effort; and (3) communicate the results of monitoring efforts to the concerned national and international agencies.

Preserving Genetic Diversity in Crop Populations. The narrow germ plasm base of many food and fiber crops has led to increased genetic vulnerability to pests

(NRC 1972). The southern corn leaf blight epidemic on maize in the United States in 1970 and the tungro epidemics on rice in Asia which also occurred in the 1970s are recent examples of this increased vulnerability. Vulnerability arises from genetic uniformity that has been encouraged in the United States by the demands of the market, by the mechanization of agriculture, and by government regulations.

Genetic diversity in crops is the best protection against genetic vulnerability. Unfortunately, most modern agricultural practices encourage greater uniformity. Many vegetatively propagated crops such as varieties of potatoes, cassava, and apples are completely uniform. Clones of these crops are identical genetically and equally susceptible to pests. Self-pollinated crops such as wheat and beans are highly uniform in comparison to cross-pollinated crops. Corn, although cross-pollinated, is, by the production of pure line and inbreeding, highly uniform when grown as hybrids.

The use of cytoplasmic genes such as the Texas male-sterile cytoplasm also introduced, with tragic results (i.e., the epidemic of southern leaf blight), cytoplasmic uniformity into the many maize varieties grown in the United States. Similar cytoplasmic uniformity also is found in sorghum, millet, sugar beets, onions, and cotton.

All of the high yielding varieties of rice and wheat contain the same genes for the dwarfing characteristic that enables them to be heavily fertilized. High yielding varieties do, of course, show other differences. Monocultures of many crops with little genetic diversity are important in many developing countries, such as rubber, cocoa, coffee, and bananas.

The research needs in this area include: (1) increasing the availability of germ plasm to breeders so as to increase diversity in crop populations, (2) developing and evaluating multiline varieties for pest resistance, (3) searching for general resistance in breeding programs, and (4) determining the value of combining general and specific resistance to pests.

Studies on the Biology of Pests

Mechanisms of Resistance. Historically, two different types of approaches have been followed in attempting to identify resistant "mechanisms" in higher plants. One approach has concentrated on analyzing plants for a preformed factor that makes them an unsuitable environment for most pests. Generally such studies have concentrated on a search for specific compounds such as alkaloids and phenols or for a specific type of physical barrier such as thickness of cuticle. Almost all of these studies have failed to find any one specific preformed factor responsible for the resistance of a plant to most pests.

The other approach assumes that the plant is normally a suitable habitat for most pests but that the plant responds to challenging organisms by producing an unsuitable environment in the plant tissue. Most of the effort in this area has concentrated on either identifying specific compounds (e.g., phytoalexins) or a specific physical barrier (e.g., papilla) that is produced in response to infection that renders the plants resistant. However, most detailed studies of these systems have failed to demonstrate that any one specific factor is responsible for the resistance of plants to most pests.

A current concept gaining more attention is that rather than one specific factor being responsible for plant resistance to most microorganisms, it is the summation of many factors present before and/or after infection that renders a plant resistant. Since only a few pests are able to infect or attack any given plant, it is envisioned that the specific factor responsible for making an organism a successful pest will be found by analyzing that particular organism and the <u>susceptible</u> reaction it causes in the plant. One example of the success of this approach is the identification of toxins from pathogens that affect only hosts of the pathogen. In this case, the "resistant factor" in a nonhost is a lack of a receptor site for the toxin. Such a plant would be insensitive to the toxin, and the many other factors that normally make a plant resistant to most pests also would be operative. Another example is the idea that the successful pest prevents the host from recognizing it as a "foreign" entity by specifically repressing the normal general resistance responses. Again, the nonhost is resistant because it lacks a specific "receptor" for the repressor of the general resistance response. If these examples are found to be universal in plant-pest interactions, then resistance to a given pest would not result from the presence of any one specific resistance factor but from the lack of a specific "susceptibility" factor. Thus it is imperative to identify specific gene products that confer pest status to specific plants. Once such gene products are identified, there would be the possibility of manipulating the plant in a manner that either nullifies the specific pathogenic factors or breeds specific "susceptibility" factors out of the host.

Genetic Plasticity of Pest Species. Genetic variation in pests is an almost universal phenomenon and leads to a loss of resistance to the pest. Examples could be cited for insects, fungi, bacteria, viruses, and nematodes. *Puccinia graminis tritici* (stem rust of wheat) and *Phytophthora infestans* (late blight of potatoes) are classic cases. Some pests frequently produce new biotypes or races and others are relatively stable in comparison. New biotypes or races may arise by genetic changes resulting from mutations, sexual recombinations, or heterokaryosis. Little can be done to keep pests from varying, but much can be done to see that their genetic variation does not result in food or fiber losses.

Breeders can use both general (horizontal) and specific (vertical) resistance to combat variation in pests, but to use specific resistance the potential genetic plasticity of pests must be understood. Examples abound illustrating the loss of specific resistance due to one or more genes in a new pest biotype. General and specific resistance often can be combined to form one variety, with even greater protection from pest variation. Multiline varieties, mechanical mixtures of lines that appear phenotypically alike but genotypically contain diverse genes for specific resistance, are being successfully used commercially. The concept is useful but the speed with which pests can overcome multiline resistance needs careful evaluation.

Heterogeneity among Populations of Pests. Brown, et al. (1975:285) found that studies on fungal pathogens indicate that pest populations may show significant differences in fitness. They further found that:

> Research techniques are becoming available to measure changes within a species of its survival characteristics, ability to spread, infection capabilities, and pest densities. These techniques should also be applied to detect and measure changes in a given population over time (e.g., from year to year). Studies on the underlying genetical factors for these characteristics then become essential to reveal the manner in which this phenomenon of population genetics is determined and modulated. With insect pests, the finding that European corn borer populations in Iowa differ from those in New York State in the pheromone mixtures to which they are sensitive illustrates the importance of population characteristics in devising control strategies for a given area. Problems

in weed control have scarcely been directed to such research channels at the present time.

How Pests Survive. Brown, et al. (1975:285-286) also state that pest species must be studied "at the points in their life-cycle which are weakest or at which they are most in jeopardy." Furthermore:

> The carryover of the pest from one growing season to the next depends upon its resistance to the stress applied, whether it be low temperature, drought, flood, or the drastic tillage or removal of all food and shelter which may occur in normal agronomic practice. Therefore full assessment should be made of the survival characteristics and mechanisms of the pest species to these various stress factors; particularly relevant are the phenomena of diapause and dormancy. These will serve as a guide to improving the existing plant protection practices, as well as to devising new ones.

Biological Control

Biological control is "the action of parasites, predators and pathogens in maintaining another organism's density at a lower average than would occur in their absence (DeBach 1964)." Biological control is a part of the natural controls that limit the numbers of all organisms. In the context of pest control, biological control is a natural ecological phenomenon that may be used to suppress and maintain pest populations at satisfactory levels.

Classic examples of biological control are found in agriculture, for example, cottony cushion scale in California, prickly pear cactus in Australia, various mealybugs and scale insects on citrus in California, and Klamath weed in several countries. In these cases, biological control has involved introducing biological control agents from an exotic area against an introduced pest (in fact, most cases have been the reassociation of a pest and its natural enemies).

Biological control of plant pathogens is rarely of the type described above for insects and weeds. Most often it involves manipulating the indigenous microflora so that it will be antagonistic toward the target pest pathogen. Further work in the biological control of plant pathogens should be encouraged. The section above on developing techniques of plant cell and organ culture describes some promising pathways.

The term "biological control" also has been used to embrace the use of host plant resistance, competitive displacement, autocidal techniques, genetic manipulation, habitat management, behavior modification, chemical compounds, and the like, in fact, any technique that involves a biological phenomenon. This unreasonably dilutes the term "biological control." For the purposes of this report, we will use it in its more restricted sense (i.e., the use of natural enemies in pest control) and deal with the other biologically-based technologies in other sections.

Biological control and breeding of resistant crops have little applicability in cropland weed control. We cannot expect to breed a crop plant that has enough competitive vigor to suppress adequately the whole complex of other plants (weeds), nor can we expect to apply a biological control agent that will suppress a whole complex of weeds and leave only the crop. Biological control might prove useful in controlling some singularly dominant weed species but not a complex and changing weed flora. Breeding of vigorous varieties and specific biological control of key weeds are both beneficial, but their use against particularly noxious weeds is more likely to be beneficial in ranges and pastures than in cropland monocultures.

Biological control agents often, if not commonly, fail to give satisfactory levels of control in all situations. For this reason, biological control agents are used most effectively when supplemented by other management tactics.

Although biological control agents have been dramatically effective in many instances, the tactic has been used only in a limited way. Many major insect pests and weeds introduced into the United States commonly have natural enemies in their countries of origin that also could be introduced for biological control. In the developing countries, biological control has a special appeal. Biological control agents can be introduced and established with a low capital investment and without sophisticated management problems, and can provide a relatively permanent means of control.

Biological Control Agents

We must make a worldwide effort to obtain biological control agents (parasites, predators, and pathogens). This should be done in a logical series of steps as part of a long-range program. It would require: (1) establishing a candidate list of pests, (2) perfecting a methodology for determining the most probable areas to search (including considerations of origins and suitable biotypes), (3) exploring these areas persistently, and (4) introducing biological control agents with proper safeguards against hyperparasites and accidental pest introductions.

Long lists of natural enemies of important insect pest species have been prepared. However, the fact that new natural enemies are usually discovered when the search is intensified suggests that many undiscovered natural enemies probably could still be found by a systematic effort. To date the search for natural enemies of weeds has been even more limited than that for insects. Yet the potential for such discovery may be equally great, particularly for the control of noxious perennial weeds.

Only a few specialists have been successful in their search for natural enemies. These explorations have been based on the biogeography of the pest, its host plants, and the climate of the area involved. The methodology for determining the most likely areas for search should be improved, using the talents of ecologists, biogeographers, and experienced biological explorers.

Any introduction of a new biological agent should be made cautiously and with proper quarantine procedures to eliminate hyperparasites and other undesirable organisms that may be associated with the biological control agent. In some instances, there may be disagreement about desirability of introducing the natural enemy; for example, a weed species also may be a valuable honey plant, or a natural enemy may not be specific to the target pest species.

Regional Collection Centers for Insect Pathogenic Viruses

Insect pathogenic viruses have great potential as pesticidal agents in the integrated control of insect pests, particularly those affecting tropical crops. However, such viruses must be used responsibly, which requires background knowledge on their physical and chemical properties and specificity in the natural environment. A serious limitation to producing such data in tropical countries is the difficulty in organizing meaningful surveys of crop pests for insect virus diseases and in arranging for subsequent virological diagnosis. Often material of potential value is lost because either the material was prepared improperly or it was delayed in shipment to virological laboratories. Such material is frequently so mishandled that it is completely useless for virological study. Further, if the pest under investigation cannot be reared in virological laboratories, tests of pathogenicity or efficacy cannot be made. Frequently, there are no trained personnel in the country of origin to carry out such tests, even if specific, highly purified preparations are supplied.

There is an urgent need for regional stations where properly trained personnel can collect diseased material. The virus or viruses could then be isolated and partially purified with fairly modest equipment. If the samples are freeze-dried, they could be sent to virological laboratories in a viable condition. The staff of such regional centers could carry out the essential efficacy tests in the country of origin. Such centers should work closely with local authorities and organizations and could provide valuable training facilities for indigenous personnel.

Release and Establishment Procedures for Biological Control Agents

For many biological control agents the release and establishment process is a simple matter; for others it is extremely difficult. Special methods of importing, maintaining, increasing, and colonizing the agents are required. Even after establishing a biological control agent it may be necessary to facilitate its spread in the area and to assist in maintaining the population in critical periods. For these reasons, all aspects of release and establishment should be studied, including an analysis of the factors involved in successful establishment. When appropriate, inexpensive mass culture technology such as fractious hosts or artificial media may be developed.

Effectiveness of Biological Control Agents

Quite often the introduction and establishment of a biological control agent may not control the pest population satisfactorily. In some instances, the biological control agent can be used in combination with other tactics to produce a satisfactory level of control. In other cases, technology can be developed to enhance its effectiveness.

The factors that influence the effectiveness of biological control agents and the periods of their effective natural enemy-prey ratios as related to crop phenology should be evaluated. Limitations to their effectiveness can often be overcome by: supplemental feeding (including host-pest release) at a critical time, annual or periodic colonization, modification of the environment by cultural methods (e.g., strip planting, fertilization, irrigation, dust control), overwintering shelters, and the establishment of secondary hosts.

Management Principles for the Use of Biological Control Agents

It is important to develop overall crop management principles for the maximum utilization of biological control. If biological control agents can only partially control a pest, supplemental tactics must be provided. If biological control is available for only a few of the pests in a crop production system, other tactics must be used to manage the other pest populations. All of these operations must be developed and integrated into the total crop production system. This requires evaluating the local ongoing effectiveness of biological control agents (both indigenous and introduced) to determine what supplemental or additional tactics should be used. In some cases, it may be appropriate to use combinations of biological control agents. Where chemical control is used as one of the additional tactics, it is critical to understand the compatibility of the two tactics. For this reason, the compatibility of biological control agents and conventional pesticides should be studied. These studies should take into consideration the fact that in some instances the behavioral characteristics of the biological control agents can be exploited to prevent a severe effect from the pesticide.

Pesticide Research

Pesticides play an important and often critical role in crop and commodity production. In some cases, there are no practical alternatives to pesticides for preventing losses of major crops and commodities. In other situations, pesticides only play a minor role in production systems that primarily depend on cultural, biological, or other management techniques for plant protection. The usefulness of pesticides is restricted by their undesirable effect on nontarget organisms, their limited effectiveness because of evolved resistance, adjustments in pest populations, and other technical imperfections, as well as by a variety of economic, environmental, and legal restraints.

Selective insecticides could play a vital role in schemes for integrated pest management. Such materials are probably being discovered at a faster rate in the private sector than are broad spectrum compounds. The problem is how to promote the development, registration, and use of these compounds that are considered uneconomical by their discoverers and therefore rarely released from company files. Analyses of and solutions to the problem have been proposed by the National Academy of Sciences (NRC 1975b), Djerassi, et al. (1974), and Arthur D. Little Co. (1975) in a study for the Environmental Protection Agency's Office of Pesticide Programs. Possible solutions include direct government participation and changes in regulatory procedures, among others, but few of them have been adopted. Some are still under study by government agencies; thus it would be inappropriate for us to make recommendations at this time.

Zectran and RE-11,775 of the Dow Chemical Co. and the Chevron Chemical Co., respectively, are two examples of insecticides that were discarded before they could be marketed. Zectran was intended for the forest pest control market, and RE-11,775 was meant for the mosquito control market. The former was actually carried to the point of registration, but the latter was dropped before that stage was reached. In both cases, the companies decided that the size of the potential market was not sufficient to warrant continued manufacture of the compound. The case history of RE-11,775 is described in more detail by Kohn (1975).

There is no evidence that the shortcomings of currently available pesticides represent some ultimate limit inherent in chemical methods. On the contrary, it is widely recognized that chemical control technology is far from perfected and has potential. Current research yields highly useful new chemicals and important new technology, including new uses for older materials. The private sector will continue to discover and exploit new pesticides as long as the industry feels it has adequate incentives to do so.

Research Requirements

Improving the Use of Existing Pesticides. As a first step, existing pesticides must be adapted to local agricultural conditions worldwide. Most modern pesticides are developed for large-scale use with major crops such as corn, cotton, and rice. Their small-scale use with food crops and specialty crops has been neglected and indeed is often restricted as a matter of policy. There is an urgent need to adapt available chemicals to the small-scale, labor-intensive farming operations especially prevalent in the developing countries.

Second, more efficient, safer formulations must be developed that have the greatest effect on pests and the least side effects. Particular needs exist for formulations that can be applied manually by small farmers and for formulations that limit drift.

Third, improved equipment for applying pesticides must be developed to reduce the hazard to nontarget organisms and to deliver the pesticide more precisely to the pest. There is a need to improve application and to adapt pest control technology to local conditions. Improved hand-operated sprayers and other means of application are needed for low-drift treatments in small-scale, labor-intensive agriculture. Major research efforts should be undertaken to devise an inexpensive, safe replacement for the cannister sprayers and the high drift nozzles now used throughout the world for the small-scale application of pesticides. Practical protective clothing or shielding for persons engaged in hand application should be developed, particularly for tropical conditions.

Fourth, appropriate antidotes to protect personnel and livestock must be devised.

Fifth, synergists must be developed to recapture the useful properties of pesticides that have lost effectiveness because of evolved resistance and to enhance the value of currently used materials. This research can be approached only through a fundamental understanding of why effectiveness was lost in each case. Then, suitable synergists and other methods often can be devised to block the detoxification systems.

Finally, new individual and combinational uses of pesticides with one another and with other technology must be explored. We must examine new and radical systems of crop culture--particularly nontillage and reduced tillage systems--which are based on the enhanced capacity of pesticides to protect crops. Pesticides originally developed to fit into existing crop production systems often provide a basis for the major restructuring of agronomic systems. Crops that formerly could not be grown in an area can, with proper pest control, be grown there. Herbicides, in particular, have led to the virtual elimination of cultivation in some crop production systems. With little loss of time for land preparation between crops, multiple cropping becomes possible in areas where the seasons are too short for multiple cropping under normal circumstances. Such systems may greatly reduce soil erosion and save the energy formerly expended on plowing.

Developing New Pesticides with Novel and Diverse Modes of Action. This research would aim at developing new and more fundamental rationales for the discovery of efficient, safe pesticides less subject to obsolescence from evolved resistance. This would require expanding the disciplinary study of comparative metabolism and toxicology as a basis for the synthesis and screening of potential pesticides. Systematic searches would have to be undertaken for naturally occurring biological chemicals concerned with resistance to pests, diseases, (phytoalexins), and chemical competition among plants (allelopathic chemicals). These chemicals could be used as starting points in the synthesis of pesticidal homologues and analogues with improved properties, particularly ones to which pests do not so readily become resistant.

Institutional Factors

The discovery and exploitation of new pesticides have fallen traditionally within the realm of private industrial research. Governments and public agency researchers have not generally undertaken such research with public funds. For this and other reasons, attempts by governments, universities, and public institutes to establish screening programs for the discovery of new pesticides have not yet been productive. Deliberate changes in public policy would be necessary if nonprofit agencies are to search seriously for new pesticides.

There is, nevertheless, a major place for public research relating to the discovery and exploitation of new pesticides. The field of natural products chemistry offers a wealth of opportunities for investigating the chemical interaction between organisms which can lead to new rationales for industry screening programs and can provide basic molecules that serve as starting points in the synthesis of potential pesticides. Public agency research, particularly university research in physiology, toxicology, natural products chemistry, and chemical interactions between organisms can be highly supportive of practical industry research.

Autolethal Control

All autolethal methods of pest control rely on the fact that if one or both of the sexes of a pest species can be rendered sterile, then matings between sexes will not produce offspring. The most dramatic success with this method is the suppression of the screwworm, Cochliomyia hominivorax, in the southern United States. This technique also has been judged useful in managing the Mexican fruit fly, Anastrepha ludens, in northwestern Mexico, in eliminating incipient infestations of the Mediterranean fruit fly, *Ceratitis capitata*, in Los Angeles County in 1975, and in preventing the entry of pink bollworm to the San Joaquin Valley in California. Successes with this technique have been largely confined to the Dipteran insects, but it may also succeed with other insects (such as the *Lepidoptera*), and there is no theoretical reason why it could not succeed with any sexually reproducing pest, including rats, bats, birds, and others.

Successes to date have been based on the induction of dominant lethal mutations with radiation. Other genetic mechanisms, such as ones involving meiotic drive, translocations, and hybrid sterility, are now the subject of active research. The successes to date are sufficient grounds for urging continued research on the autolethal method of pest control. The fact that this technique is highly specific for a particular species renders it comparatively safe environmentally.

We must note that the autolethal method has some limitations. First, the method may continue to show its greatest promise when applied to insects and other invertebrate animals. Second, this technique must be applied on an areawide basis for the best chance of success. Areas that cross national boundaries may be difficult to treat for institutional reasons. Third, in most cases the autolethal technique requires the mass rearing and releasing of sterile individuals, and the costs of such practices will remain a problem for some species.

The specific research needs for this area include: (1) developing procedures for identifying suitable candidates for management with genetic methods, (2) developing rationales for determining which genetic method should be attempted on different species, (3) investigating the ecology and population dynamics of species judged susceptible to genetic control methods, (4) improving the ability to rear insects in large numbers for sterilization and release, and (5) developing techniques for comparing laboratory-reared organisms with wild organisms.

"Blue Sky" Research

Much of the research on crop protection is simply the straightforward application of known principles to the solution of practical problems. Pests are identified, diseases diagnosed, and damage assessed. The process merges research, development, and practice. The work is complex and places high demands on the experience, technical competence, skill, and creativity of research personnel. It is the very substance of practical progress in crop protection and production.

There also is a need for basic research of a more speculative nature aimed at generating new knowledge and new principles potentially useful in plant protection. We cannot forecast what these findings might be. New means of applying energy in the form of heat or radiation; new kinds of genetic manipulation; new discoveries in toxicology, parasitology, or predation; or a better understanding of the comparative biochemistry of living things--all these may provide breakthroughs applicable to pest control. Weak links in the life cycles of pests should be studied, defined, and exploited. The nature of the egg, seed, and spore should be better understood. How pests defend themselves against control measures should be studied with an eye toward devising countermeasures. Ideas and viewpoints should be sought not only from the agriculturalists and biologists but also from physicists, engineers, and anthropologists.

THE EFFECT OF IMPROVED PEST CONTROL ON WORLD HUNGER

Enormous amounts of major crops are lost because of pests (see Table 4). Aggregate losses from pests in world food production are conservatively estimated to be about 35 percent of potential production (i.e., were the pests not present). It is not unreasonable to think that improved pest control practices could eliminate 50 percent of the current losses so that the total world food production could reach about 82 percent of its potential rather than its current 65 percent. The increased production would be about 25 percent of current production. Furthermore, other methods of crop improvement that result in increased production require enhanced protection in order to be realized.

In Table 5, we also have calculated the increased supplies of food that could be made available if 20 percent of the current pest losses could be prevented on a worldwide basis. For example, if 20 percent of the current rice losses were saved, the additional 56 million tons of brown rice that would result could provide the foundation (2,500 calories per person per day) of an adequate diet for 177 million people--and we suggest that 20 percent is a conservative loss savings. In our discussion of Colombia in the Appendix, we assume that 50 percent of current losses can be saved.

A major methodological problem, however, complicates any assessment of successful innovations. It is difficult to translate the savings in crop yields that would result from improved pest control into economic terms that reflect the probable distribution of that savings. If the supply of a particular commodity is increased in an area due to the adoption of improved pest control practices, the price of that commodity will probably fall, and the effect of the lower price on small farmers, especially in economies that are not centrally planned, would probably be severe. For example, nonadopters and late-adopters of improved practices are particularly vulnerable because their production costs and yields will remain the same while the price they receive for their produce will decline. Unless additional concomitant measures are taken, the incomes and nutritional status of such farmers are likely to deteriorate. This prospect puts a special premium on selecting methods that are suited for adoption by small farmers.

Increases in yield are important, but improved pest control practices also result in more stable yields from year to year, which can be quite important. Without a sense of stability people are not likely to make investments in agriculture that require more than one growing season for amortization.

Global quantitative estimates of the likely effects of the different types of new pest control technologies are impossible, however; rough qualitative estimates are possible. Table 6 indicates some of the effects that are likely to occur should the research we are recommending actually lead to new practices. In the following sections, we discuss the effect that each type of control technology is likely to have on each factor listed in Table 6.

Government Capital Requirements

All techniques, except the development of pesticides in market economies, are likely to require substantial expenditures by governmental or other public agencies. The reasons for our projections of high public sector financing are varied. In some cases, the risk of the innovative strategies is so high compared to the potential payoff of success that private funds are unlikely to be attracted to the effort. In other cases, such as biological control and cultural control, successful innovation creates either knowledge or a self-perpetuating mechanism, both of which fail to lend themselves to monopoly control by private firms.

Table 5. Production increases from improved pest control[a]

Crop	Current loss, 1974 (million tons)	Potential increase (million tons)	Type of food[m]	Million people fed per year
Rice[b]	280	56	Calories	177
Wheat[c]	113	23	Calories	82
Maize[d]	156	31	Calories	121
Millet/sorghum[e]	57	11	Calories	44
Potatoes	150	30	Calories	25
Cassava[f]	53	11	Calories	16
Sweet potatoes[g]	46	9	Calories and vitamin A	11.5 and 252
Tomatoes[h]	12	2.4	Vitamin A	13
Soybeans[i]	23	4.6	Protein	86
Groundnuts[j]	12	2.4	Protein	21
Cottonseed[k]	8.5	1.7	Protein	20.5
Citrus[l]	7.9	1.6	Vitamin C	59

[a] Assume 20 percent of current losses are prevented. Losses calculated from Table 4.
[b] Loss and increase figures are for paddy. Calories for people are for raw, brown rice.

[c] Calories provided assume use of whole wheat flour.

[d] Calories provided assume use of unbaked cornmeal.

[e] Assume millet and sorghum have 350 calories per 100 g.

[f] Production figures assume 60 percent water by weight. Caloric figures assume dry tapioca with 352 calories per 100 g.

[g] Vitamin A content assumed to be 5,000 I.U. per 100 g. Water content of harvested and consumed product assumed to be equal.

[h] Vitamin A content assumed to be 1,000 I.U. per 100 g.

[i] Protein content assumed to be 34.1 g per 100 g. Daily requirement for protein assumed to be 37 g per day. Correction factor for protein quality was 1.35.

[j] Production figures include shells. Shells assumed to be 30 percent of harvested weight. Protein requirement set at 37 g per day; correction factor for quality = 1.54. Protein content of ground nuts (without shells, with skins) is 26 g per 100 g.

[k] Protein content of cottonseed assumed to be 20 g per 100 g. Protein requirement was 37 g per day; correction factor for protein quality = 1.23.

[l] Vitamin C content for raw, California navel oranges = 61 mg per 100 g. Daily requirement set at 45 mg.

[m] Caloric requirement = 2,500 calories/day. Protein requirement = 37 g/day. Vitamin A requirement = 5,000 I.U./day. Vitamin C requirement = 45 mg/day.

Sources: Davidson and Passmore (1967); FAO/WHO *Ad Hoc* Expert Committee (1973); Magness, et al. (1971); Manocha (1975); and Martinez, et al. (1970).

Table 6. Impacts of new pest control practices

Control technique	Relative capital requirements						Disparities between		
	Government		Private-farm		Private-nonfarm				
	R&D	Op	R&D	Op	R&D	Op	Regions	Crops	Classes
Biological	high	low	UTA	low	UTA	NA	high	high	low
Cultural	high	low	UTA	mod	UTA	NA	mod	high	mixed
Breeding	high	low	UTA	low	mod	NA	low	high	low
Pesticides									
CPEs	high	high	UTA	high	NA	NA	low	low	high
MEs	mod	low	UTA	high	high	NA			
Autolethal	high	mod	UTA	low	UTA	NA	low	high	low
Integrated	high	low	UTA	mod	UTA	NA	high	high	mod

Abbreviations:
R&D - research and development activities before adoption
Op - operational activities during and after adoption
UTA - unlikely to attract
NA - not applicable
H - herbicide
I - insecticide
F - fungicide
CPE - centrally planned economy
ME - market economy

(distinction applies
(for columns under
("Relative capital
(requirements" only

Effect on short-term labor requirements	Stability over time	Magnitude of loss reductions		Probability of success		Adverse environmental impact
		Short term	Long term	Short term	Long term	
none	high	mod	mod	mod	high	low
increase	high	mod	mod	mod	mod	mod
none	mod	low	high	low	high	low
decrease (H) increase (I+F)	high (H+F) low (I)	high	high	high	high	mixed
none	high	low	high	low	low	low
mixed	high	high	high	mod	high	mod

Private Farm Capital Requirements

Biological control, adoption of resistant varieties, and genetic control are likely to require little from the private farmer because these techniques use little or no machinery or manufactured materials above and beyond what the farmer already is purchasing or raising on the farm. In contrast, cultural control, pesticides, and integrated control may involve some expenditures of modest size for equipment or materials not currently purchased.

Private Nonfarm Capital Requirements

Pesticides in market economies form the only area of research that will require large capital investments from private, nonfarm companies. All other techniques are not likely to be attractive to such firms, and public agencies will have to be responsible for their development. We assume that pesticides, if they are developed in socialist countries, will be the responsibility of public agencies.

Regional Disparities

A major question facing those who assess innovation is whether people living in different areas are likely to be affected differently by the development and adoption of new pest control practices. For example, differential effects will arise from the unsuitability of the new practices for particular areas. Regardless of the cause of such effects, planners must be aware of their existence. In general, differential effects on different regions must be regarded as the negative effects of a new technology, although it is possible to ameliorate the undesirable features of such effects.

Biological control is likely to be successful only when it is designed for a specific region. Because most schemes for integrated control rely on biological control, integrated control schemes also are likely to be highly location-specific. Cultural controls generally involve creating microenvironments on the farm that are unfavorable to pest development. Thus it is likely that such manipulations, if identified, will be applicable over wide geographic regions, although some location-specific problem will occur. Genetic control and pesticides, as we know them, have been successful when adopted over wide geographic areas; hence large regional disparities are unlikely to arise from their adoption. New varieties that show some resistance to pest species can be crossed with traditional varieties and thus adopted to many regions; hence large differences among regions are not likely to develop from their use.

Crop Disparities

Biological control, cultural control, integrated control, genetic control, and breeding for resistant varieties will have highly different effects on pest control problems in different crops, especially when the pest to be controlled is a key pest on only one or a very few crops. A few pests that attack a large number of crops such as *Heliothis* spp. or *Pseudomonas* might be controlled if the above methods were practiced on all crops simultaneously. Pesticides to the extent that they are broad spectrum in their killing powers will be useful on many pests on many crops. If we are actually successful in developing more specific pesticides, then chemical control too would create highly disparate effects on different crops.

Class Disparities

The differential effects of successful innovation in pest control on different economic classes of agricultural people are the most difficult and yet perhaps the most important to analyze. New pesticides are likely to be adopted only by the wealthier farmers because they have better access to credit for purchasing the necessary materials and machinery. Hence this technology tends to be biased toward the richer farmers. Cultural control and integrated control will have mixed types of differential class effects. If the new practices require more labor to be successful, then wealthy, capitalized farmers may be at a disadvantage compared to poorer farmers using labor-intensive methods. On the other hand, if the new practices require the purchase of new machinery or the acquisition of new skills, then the wealthier farmers may be at a relative advantage. Biological control, the breeding of resistant varieties, and genetic methods of control will in many cases be operations performed with a high degree of public sector effort, and each will require the farmer to contribute little in purchases above and beyond that which is normal. Hence these latter technologies have less chance of favoring one class of agriculturalist over another.

Effect on Short-term Labor Requirements

When any proposed new technology is assessed a crucial question that must be asked is its effect on the labor requirements for agriculture. This question is particularly important in the nonindustrialized market economies in which unemployment and underemployment are frequently endemic and in which no alternative industrial employment possibilities exist. It also is important to distinguish the short-term effects on labor from the more long-term effects. Short-term effects are more likely to cause severe problems for a country while long-term effects can be ameliorated by proper planning. We comment here only on the short term (less than three years).

Biological control, the use of pest-resistant varieties, and genetic control are not likely to have immediate effects on labor requirements except for rare circumstances in which the controlled pest was formerly contained by labor-intensive means, such as hand picking or treatment. Cultural control is likely to require more labor as it involves manipulating micro-habitats on the farm, a labor-intensive enterprise. The adoption of herbicides would probably reduce labor requirements because the chemicals would replace cultivation, a labor-intensive process. The adoption of improved insecticides would increase the labor requirements if the use of chemicals was a new practice; labor requirements would remain the same if improved chemicals were substituting for older materials.

Stability over Time

The emergence of resistance to insecticides dramatizes the point that new technologies are not necessarily permanent additions to farmers' options in crop production. There are no theoretical reasons why resistance cannot and eventually will not emerge for any control practice directed against any pest on any crop. Thus a high premium should be given to improved technologies that offer the potential of longer use before resistance develops. Biological control, cultural control, and integrated control offer the best promise of long-term stability in their efficacies because each tends to rely on a number of different factors to reduce pests below economic thresholds. It is probably more difficult for a pest population to became resistant to a number of simultaneously controlling factors than to practices that rely on one factor. Genetic control techniques may have long-term stability, but recent setbacks in the control of screwworm (Bush et al. 1976) show that the sterile-male release method also may be subject to long-term failure and diminished effectiveness. Resistant cultivars will tend to have medium-term stabilities. The evolution of new biotypes of pests that attack formerly resistant plants will reduce the usefulness of resistant varieties over a long period of time. Insecticides, of course, have shown the most vulnerability to the development of resistance. New insecticides probably should not be relied on for long-term usefulness if they alone are effecting control. Resistance to fungicides and herbicides has been noted but has not generally become a severe problem. When pesticides are used in schemes of integrated control, their usefulness should be considerably more stable than when they are used alone.

Magnitude of Loss Reductions

It is seldom necessary for a pest control technique to kill 100 percent of the offending organisms in order to reduce the population below the economic threshold. Biological control techniques generally require that some of the pest organisms survive so that the controlling organisms have a residual food supply for their own survival. Hence useful innovations may provide kill rates of almost 100 percent down to considerably less than 50 percent. Each major type of control technique has the potential of reducing losses over a wide range of kill rates. Highly efficient control practices are likely to be based on a combination of several techniques (integrated control).

Probability of Success

Research on biological control, cultural control including breeding for resistance to diseases and insects, and integrated control is most likely to result in new innovations. The chances of success with autolethal methods are low.

The likelihood of finding improved pesticides is more problematic than innovation in other areas. Most pesticide screening is conducted in the high-income countries, including the United States, West Germany, the United Kingdom, France, and Japan. Such research efforts are currently dominated by private interests, and their major concern is the potential return on investment (ROI) in research expenditures. In general, a ROI of less than 15 percent will be judged as insufficient to warrant pursuit of the research goal.

Generally, adequate ROIs are more certain for broad spectrum compounds that are useful for several pests on several crops. From the point of view of designing integrated control schemes, narrow spectrum activity is likely to be more useful. Hence there could be a contradiction between the properties of a compound that make it economically attractive to a private company and the properties that might give it most utility when used in combination with other control techniques.

The extensive regulatory schemes that have developed around the pesticide industry, especially in the United States, add further difficulties. There is no question that increased regulation designed to protect the environment has increased the cost of registering new chemicals. The costs of discovering, developing, and registering a new chemical are now estimated to be as high as $20 million. The latest survey, however, failed to detect any noticeable major drop in the introduction of new material (NRC 1975b).

Despite institutional factors in the form of ROI considerations and environmental regulations, the probability of finding useful compounds by the screening schemes now available or that could be developed is high. However, the probability of a screened chemical being developed and marketed has dropped steadily since 1945.

Environmental Impact

Innovations in biological control, breeding for resistant varieties, and genetic control are not likely to create any direct adverse environmental impacts. If resistant cultivars contain toxic substances in their edible portions, then problems might arise. Also, elimination of a pest like the tsetse fly from Central Africa might create indirect environmental effects by opening up an area to agriculture that until now has not been used. Cultural control will, in general, have little adverse effect on the environment unless the particular practices involve cultivation. In such cases, soil erosion may result if the cultivation is improperly done. Pesticides are the most likely to have an adverse effect on the environment as their use involves introducing synthetic chemicals into the environment. Integrated control, because it relies on pesticides in addition to other means of control, is likely to have small or moderate adverse effects on the environment.

RESOURCES REQUIRED

Our major recommendation is that there be more emphasis on the concept of integrated pest management. This change in emphasis, together with an increase in the resources devoted to pest control, will result in the development of significant new pest control practices.

In 1972, $132 million was spent on pest control research in the United States, which supported 2,200 scientist-years of effort. We recommend that this number of scientist-years be increased by 50 percent, which will require about $110 million in additional funding. About $100,000 per year is required to adequately support a plant protection scientist, and this figure includes administration, support staff, and facilities. We also conclude that the current level of support for scientists is inadequate and should be increased from about $65,000 to $100,000 per person or a total of $88 million. The total increase needed, therefore, is approximately $200 million per year. This increased level of funding should be maintained for at least 10 years. During the first three years, consideration should be given to a start-up period in which the increased support would rise from $100 million in the first year, to $150 million in the second, and to $200 million for the third.

Three-fourths ($150 million) of the increased funds should be directed to the existing agricultural experiment stations (federal and state) and the land-grant universities. Such establishments already have the mechanisms necessary to initiate a higher level of effort on such research. They also have cooperative extension services for transferring new technologies to farmers.

One-fourth ($50 million) of the funds should be directed to (1) a grant mechanism ($5 million) as outlined in the report of Study Team 14, and (2) the support of an international plant protection center and overseas centers at a level of approximately $45 million per year. The grant fund would attract scientists to plant protection research and enhance the research effort through the infusion of new ideas and new people. The estimates below refer only to the 75 percent ($150 million) that should be allocated to existing agricultural research laboratories.

Integrated Pest Management Systems

Research on integrated pest management systems offers the highest potential of any research in crop protection for alleviating world hunger and for improving the human environment. Integrated pest management systems are adaptable to all pests on all crops in every region of the world, and have demonstrated their beneficial effects on crop productivity. The principles and practices of integrated pest management also can be transferred and adapted to different climatic conditions, from temperate to tropical; however, we emphasize that transferability is not automatic and cannot be made without careful adaptive research. In particular, the institutional arrangements upon which integrated pest management systems depend are less transferable than the biological principles involved. Research and extension personnel must be sensitive to the problems created in transferring technologies developed in the United States to the developing countries.

Successful integrated pest management systems require that more than one pest protection tactic be used. The tactics required may vary depending upon the geographic location in which they are to be used. No one traditional pest protection discipline can be expected to create successfully a truly integrated pest management system. Thus the disciplines of entomology, plant pathology, nematology, weed science, agronomy, horticultural plant breeding, economics, sociology, and others are required.

The kind of research effort needed has already been demonstrated in a project entitled, "The Principles, Strategies, and Tactics of Pest Population Regulation and Control in Major Crop Ecosystems," supported by the National Science Foundation, the Environmental Protection Agency, USDA, and several state agricultural experiment stations. In this project, some 260 state and federal scientists jointly seek practical alternatives to the extensive use of broad spectrum chemicals for control of certain pest complexes. Within this project a comprehensive national research program is concentrating on five major agricultural crops and on pests of pine trees. The major objective of the research program is to develop pest management systems that will optimize benefit-cost ratios on a long-term basis for both the farmer and society. The expertise and methods used in this program should be expanded and reinforced so that this approach can encompass more crops and attack the full spectrum of crop pests.

We recommend that 30 percent of the resources allocated to pest control research be used to develop integrated pest management systems. Increased funding of $45 million would allow an additional 450 scientist-years of effort annually.

Cultural Control

Cultural control such as cultivation, crop rotation, time of planting, and other practices have always been the core of pest control, and will continue to be so. In many cases, we do not know the scientific basis of cultural practices for pest control with any precision. The types of research we have recommended in this area are designed to enhance our understanding and exploitation of traditional practices. We anticipate good short-term and long-term returns to research, especially if proven practices can be applied on an areawide basis as part of a total pest population suppression program. Research on cultural methods of control also is essential because of the central role it plays in pest control. Newly trained people in agricultural fields must continue to be made aware of the importance of traditional practices, and we believe that such training is best accomplished by recognizing cultural practices as a separate type of research.

We recommend that 15 percent of the funds allocated to pest control be put into research on cultural practices and their utilization as a base for integrated pest management. Such an allocation will allow an additional $22.5 million per year which is sufficient to support 225 additional scientists annually.

Breeding for Resistance to Plant Pests

Pest control practices based on the genetics of the crop plant are most appropriate for the control of pathogens, nematodes, and anthropods. The control of birds, rodents, and other vertebrates also may be improved by genetic methods. However, there is less potential for breeding crop plants resistant to weeds. The best method continues to be searching for plants that are better adapted and more competitive than the usual weed flora. Breeding for resistance may be a long-term process. The origin of a new potato variety, for example, typically takes 15 years from initial cross to the distribution of a new variety to farmers. Sorghum varieties resistant to greenbugs, however, were distributed to farmers within six years. For this reason, efforts at plant breeding must be seen as largely long term. Pest-resistant varieties are now nearing final development and this research should be accelerated. Also, pest-resistant varieties are an essential part of integrated pest management, and they are one of the cheapest and most efficient pest control practices known.

We recommend that 25 percent of the funds allocated to pest control be put into research on breeding for resistance. Such an allocation will allow an additional $37.5 million per year, which is sufficient to support 375 additional scientist-years annually.

Biological Control

Experience with methods of biological control to date has demonstrated its broad applicability to pest management. We recommend that future research in this area continue to emphasize insects and that it be vigorously expanded to include the search for organisms to control pathogens, key weeds, nematodes, and vertebrates. We see little chance of success for biological control of the general weed flora in most field crops. Some research on biological control has a moderate chance of yielding modest returns in the short term. Importing an effective parasite to combat a key insect pest, for example, may result in pest control after only three years. For the long term, the chances are high of finding successful biological control agents that will yield high returns.

We recommend that 15 percent of the resources allocated to pest control be put into research on biological control. Such an allocation will allow an additional $22.5 million, which is sufficient to support 225 more workers.

Pesticide Research

The public sector in the market economies has three fundamental tasks in pesticide research: integrating chemicals into crop management systems; extending the use of chemicals to other target organisms, especially minor crops; and studying the effect of compounds released into the environment. For the short term, we believe this research with existing chemicals could yield high returns. Over the long term, similar research with improved pesticides from the private sector also could produce greater yields of the major crops worldwide. Similar results for more minor crops should be expected if the public sector performs the necessary research.

The task of identifying and marketing pesticides is likely to remain in the private sector of the market economies. The available evidence indicates that private firms will make the investments necessary to develop new chemicals for the world's major crops. As noted above, the task of developing chemicals for minor crops will fall to the public sector. Our recommendations for research apply to the public sector only.

We recommend that 15 percent of the money allocated to pest control be put into research on pesticides. Such an allocation will allow an additional $22.5 million, which is sufficient to support 225 additional workers.

Autolethal Control

Autolethal controls, where useful, will be a part of an integrated pest management scheme. Our recommendations for funding research on this control method are found in the section, "Integrated Pest Management Systems."

Personnel for the Research

Entomologists, weed scientists, plant pathologists, economists, chemists, biochemists, nematologists, vertebrate biologists, statisticians, systems analysts, toxicologists, technology assessors, anthropologists, and economic botanists are required for this research. All but the last three of the disciplines mentioned are already recognized in the agricultural sciences, and we want to indicate here the potential usefulness of the newcomers.

Technology assessment is a new endeavor that has grown out of concern over the unforeseeable effects of innovation on human culture. Individuals in this field are trained in such disciplines as rural sociology, economics, philosophy, history of science and technology, and agricultural history. The task of these individuals is to search for and identify the effects of innovation with the techniques and from the viewpoints of the social sciences and the humanities. The usefulness of such research comes not from its immediate contribution to the development of practical new techniques, but from its contribution to the planning for and amelioration of any effects that innovation may have in societies that adopt them. Personnel from the developing countries might well play a particularly vital role in such a task. Given the profound alteration of human life styles that have followed agricultural innovation in the past, we believe our recommendation for this type of researcher can play a vital role in humanizing not only pest control research but innovation in other areas of agriculture as well.

Anthropologists and economic botanists are not usually affiliated with agricultural research, but we believe that such people could play an important role, especially in research on traditional agriculture and cultural control techniques. Anthropologists also might play a vital role in technology assessment.

It is important to note that the increased funding of $150 million we are urging for the existing institutions should be directed toward scientists who have a sound ecological approach, for ecological principles underlie all of our research recommendations. Thus those who conduct research on pest control should have a grasp of: the principles of pest population dynamics; the interactions of pest populations with populations of predators, parasites, pathogens, and with the crop plant; the effects of pesticides on the target organisms and their surrounding communities; and the behavior of pesticides in the biosphere.

Finally, we wish to emphasize again that the results of research on pest management are largely of academic interest until implemented by farmers. Thus attention must be given to transferring laboratory results to the field. Present pilot programs for the extension of pest management systems show that new, innovative methods of pest management may be rapidly adopted by farmers if the methods are accompanied by appropriate technical and educational support from professional extension pest management specialists. This research must not be at the expense of adequate extension efforts either in this country or in other parts of the world. We recommend that appropriate funds and adequate planning efforts be devoted to building and implementing extension efforts. The report of Study Team 14 deals in more detail with the educational problems involved with such efforts.

Justification for Overseas Research by the United States

As we have noted, research on cropland pests is highly location-specific. Thus it is necessary that the research we recommend be conducted in areas where the pest is already present, preferably in the native habitat of the pest species. Ordinarily the pest fauna and flora associated with a crop are present in their most diverse and potentially virulent or destructive form at the center of distribution of the crop species. This center also is the best source of host plant resistance and of the natural enemies of the pest. Research in such locations would provide access to the greatest number of pests, natural control factors, and host plant resistance. Such locations also would require the least need for quarantine restrictions and other restraints on the full manipulation of the biological and ecological factors concerned.

One fortunate aspect of conducting research in these locations is that the preponderance of pest problems at the centers of distribution of crop plants usually makes large-scale production of the crop impractical. Thus field research on pests and disease would pose little threat to the surrounding agricultural economy. However, the location of the research would present political problems. Nations are unlikely to encourage or support within their territories research on crops that is not important locally and that will generate benefits largely applicable in other countries. Such factors could lead to possible compromises in locations and would properly require full support from sources outside the host country.

New Organizations for Pest Control Research

Some sorts of mechanisms are necessary for transferring pest control technology effectively to the developing world. This applies to the large body of technology already available and that which will be produced by the activities suggested in other parts of this report. In this regard, we suggest four mechanisms: (1) an international plant protection center based in the United States, (2) overseas centers to carry out special functions in plant protection, (3) a consortium of plant protection scientists in the United States, and (4) U.S. participation in the FAO/United Nations Development Programme (UNDP) Cooperative Global Programme for the Development and Application of Integrated Pest Control in Agriculture. Each of these mechanisms has its own rather independent role, but they should be implemented together in a coordinated fashion.

An International Plant Protection Center

This center would provide a core of permanent research and extension staff concerned with plant protection problems on a global basis. It would supplement the work of a variety of existing organizations in a valuable way by directly stimulating the enthusiasm of scientists for the needed pest control research. The United States presently does not have such a center.

The international research centers cannot give adequate attention to the entire complex of pest problems, nor can they alone develop the integrated control strategies needed. The pattern of activities of the Centre of Overseas Pest Research of the U.K. Overseas Development Ministry might be considered as a model. However, the proposed U.S. center should be concerned with all pests and have a strong integrated pest management philosophy.

Overseas Centers in Plant Protection

These centers would be essential to any broad world program of plant protection and also essential to the protection of U.S. agriculture. It is critical that U.S. scientists become familiar with the pests found worldwide in case they someday appear in the United States.

There are other special overseas needs, for example, an overseas insect virus laboratory that can produce biological agents or other control technologies not available in the United States.

Many crops important to the world food supply are not grown in the United States, or if they are grown here they do not occur with their most significant pests. These crops include cassava, rice, peanuts, coconuts, sorghum, millet, and cowpeas, among others. In the interest of an adequate food supply worldwide, the United States also should assist in the plant protection of these crops.

The programs of the established international agricultural research and training centers do not meet the needs described above.

U.S. Consortium of Plant Protection Institutes

The greatest concentration of talent and experience in plant protection exists in U.S. universities. On many occasions it will be critically important, in connection with an international problem, to tap this talent bank. A consortium of key U.S. institutions would provide the mechanism by which this talent can be put to work on international pest problems. The group of U.S. universities (Cornell, North Carolina, California, Florida, Miami, and Oregon State) working together on the US/AID Pest Management Project has shown in a small-scale operation the effectiveness of this arrangement.

The FAO/UNDP Program

The FAO/UNDP Cooperative Global Programme for the Development and Application of Integrated Pest Control in Agriculture is a mechanism for introducing the integrated pest control approach into the developing world. It also offers the means whereby sophisticated pest control technology of the high-income countries can be adapted to the ecological and social conditions of the developing world. The United States should participate in a major way in this program.

Appendix

COLOMBIA: A CASE STUDY OF PEST CONTROL INNOVATION AND NUTRITIONAL IMPROVEMENT

This appendix dramatizes the location-specific nature of pest control problems. Our general recommendations will be more useful if research administrators begin their work by developing analyses similar to that presented here for Colombia. The analysis given is brief and would need considerable refinement to serve as a planning aid in enhancing pest control research in Colombia.

GENERAL INFORMATION

Colombia, with a population of about 24 million (1976), is the fourth most populous country in Latin America and the fourth largest country (1,138,914 square kilometers) in South America. Its present rate of population growth is about 2.8 percent. Although the average population density is 55 persons per square mile, 96 percent of the people are concentrated in the western two-fifths of the country. Movement to urban areas is increasing as estimates placed 48 percent of the population in cities of 100,000 or more in 1975. Literacy was estimated at 73 percent in 1975. In 1974, Colombia's gross national product was estimated to be $10.59 billion, its annual growth rate was 6.2 percent, and its per capita income was $445. Agriculture employed 50 percent of all wage earners and contributed 30 percent of the gross domestic product in 1972.

Colombia, after Brazil, is the world's second largest producer and exporter of coffee (12 percent of the world's production). Principal agricultural exports are coffee, cotton, bananas, cattle, and sugar.

Colombia has many diverse climatic and agricultural zones, which range from coastal areas of hot-humid tropics with over 400 inches of rainfall per year, to highland agriculture close to the snow line.

From sea level to 1,000 meters (clima caliente or the hot region) cacao, sugarcane, coconuts, bananas, plantains, rice, tobacco, cassava, and most of the country's cattle are produced. Coffee, corn, vegetables, and a variety of fruits are produced from 1,000 to 2,000 meters (clima media or the intermediate region). From 2,000 to 3,000 meters (clima fria or the cold region) temperate crops such as wheat, barley, potatoes, cold climate vegetables, and dairy cattle are produced. Alpine meadows with native or cultivated vegetation and limited cropping where feasible are found above 3,000 meters.

The vast majority of farmers in Colombia either own no land or such a small amount that it is not sufficient to support minimum needs or to necessitate employing household labor throughout the year (Griffin 1974). In 1960, there were approximately 1.2 million farms in Colombia, and since that time it has been estimated that the number has increased about 2 percent per year due to new settlement and the continued division of existing holdings. Two-thirds of Colombian farms are less than 5 hectares in size. A land reform act was passed in 1961 and an Agrarian Reform Institute (INCORA) was established to execute land reform. Some progress has been made although the process is slow. Five percent of the landowners owned 71 percent of the land in 1966. In its first 10 years, INCORA deeded 8.3 million acres of publicly owned land to 105,000 farmers.

MAJOR PESTS

Because of the wide diversity of crop plants grown in Colombia and the broad range of conditions under which they are grown, to list even the major pests of any single crop is difficult, if not impossible. For instance, corn is grown from near sea level to over 3,000 meters, and the key pests at each elevation and in each isolated valley may be different. Thus pests found in Colombia are often more numerous than those found in a country as large and diverse as the United States.

Pests are often more serious in Colombia and cause greater losses because of the following factors:

-- The lack of a distinctly cold winter means that pests are usually present all year long. There is a dry and wet season in some areas and in other areas a wet-dry-wet-dry season. These seasons seldom stop plant growth and thus pests pass through more generations per year, which increases the chances for new races.

-- Many of Colombia's tropical ecosystems have higher temperatures and more rainfall than temperate zones. Thus conditions are generally more favorable for pests.
-- Cropping is continuous for crops such as sugarcane, bananas, plantains, and coffee. Two, three, or even four crops of many annual food crops can be grown each year. These practices often increase the seriousness and persistence of pests.
-- Pest-free seed, especially of asexually propagated crops such as potatoes, cassava, and plantains, often is not available.

Many of the major pests (insects, weeds, birds, rodents, and diseases caused by fungi, bacteria, viruses, and nematodes) are found in Colombia and often cause serious losses. The state of knowledge of pest identification and of the losses caused by pests varies according to how much governmental and private support has been given over time to research and extension activities on a given crop. Organizations such as the Coffee Federation, International Center for Tropical Agriculture (CIAT), and the Colombian Agricultural Institute (ICA) often have thorough and complete documentation of pest problems and their economic importance.

The following list of important food, fiber, and export crops is not complete, nor is the list of important pests that affect them. Weeds in particular have been omitted. This list is intended to emphasize the difficulty Colombian plant protectionists have in determining their priorities in research and extension.

<u>Barley</u>. "Enanismo" or dwarfing, a serious disease of barley, wheat, and oats found in the state of Narino, is of unknown etiology, although it is viruslike. The causal agent is transmitted by leafhoppers. The disease is unknown outside of Colombia and Ecuador. Barley yellow dwarf, several fungal leaf spots, and smuts also damage barley.

<u>Bananas</u>. Large quantities of fungicides are used to control Sigatoka disease while Panama disease and bacterial wilt also cause losses. Large commercial banana operations were once abandoned near Santa Marta because of Panama disease.

<u>Beans and other food legumes</u>. Severe disease and insect problems including viruses, rusts, nematodes, and various fungal diseases limit the production of beans and other grain legumes. One of CIAT's major goals is breeding beans for resistance to pests.

<u>Cassava</u>. Although once thought to be relatively free of pest problems, investigation has shown that cassava has many serious insect and disease problems. Cassava bacterial blight and superelongation are

perhaps the most serious diseases. CIAT is attempting to breed resistance to bacterial blight, superelongation, *Phoma*, *Cercospora*, thrips, spider mites, and shoot flies.

Cacao. Colombia was once a major exporter of cacao but now has to import millions of dollars worth primarily because of *Monilia* pod rot, *Ceratocystis* wilt, and witches broom. Other diseases and insects also attack cacao. Losses due to cacao pests have been estimated at 40 to 50 percent in Colombia.

Coconuts. Red-ring of coconuts is a nematode-caused disease of importance in Colombia. Porroca, another disease of unknown etiology, has killed hundreds of thousands of palms on the Atlantic Coast. Little knowledge is available about the pests that attack coconuts.

Coffee. The Colombian Coffee Federation works in both research and extension on coffee pests. Numerous diseases, insects, and nematodes attack coffee in Colombia, and there is great concern that coffee rust (introduced into Brazil in 1970 and Nicaragua in 1976) may eventually reach Colombia where the mountainous nature of the areas in which coffee is grown would make spraying difficult if not economically impossible.

Cotton. Cotton is the number one consumer of pesticides in Colombia. Overuse of chemicals is common although a pest management system is being introduced. The diseases, insects, and nematodes of cotton are well documented.

Fruit. Probably twice the number of fruits are grown in Colombia as in the United States, including both temperate and tropical varieties. Many fruits have serious pest problems; for example, papaya production is limited by insect-transmitted viruses, citrus viruses, and other pests. Attempts are being made to eradicate the fruit fly.

Grasses and forages. These crops cover 40 percent of Colombia's total land area. Serious insect and disease problems are present such as gummosis of Imperial grass (which occurs only in Colombia), spittle bugs and aphids on many grasses, a root rot complex on alfalfa and clovers, rust of rye grass, and many others. Considering the importance of grasses and forages in Colombia, the research efforts on pest control to date have been inadequate.

Maize. Maize is grown from sea level to 5,353 meters in Colombia. Pests are most serious in the hot, humid climates, but are present and cause losses at all elevations. Numerous insect pests including *Diatraea* and *Spodoptera* are important, and corn stunt together with other maize viruslike diseases and fungal diseases, such as those caused by *Helminthosporium*, *Diplodia*, *Fusarium*, and rusts, also are found. Maize varieties seem to have developed considerable resistance to pests in Colombia.

Oats. Except for limited use as a forage using imported seed, oats are not grown in Colombia although they are well adapted, especially in the high cold altitudes. Oat stem rust is the major reason oats cannot be grown. To date, attempts to find adequate resistance have not been successful.

Oil palm. The red-ring nematode causes losses in oil palms as in coconut. "Marchitez sorpresiva," a devastating disease of unknown etiology, recently has caused serious losses in Colombia on oil palms and coconuts.

Plantains. The moko disease (bacterial wilt) of bananas and plantains was introduced into Colombia about 30 to 40 years ago, and it devastated the Bluggoe or "chacoco" plantains. The bacterium is insect-transmitted. ICA has recommended simple and inexpensive sanitation measures that will control the disease adequately. Race 2 of *Fusarium* wilt (Panama disease) also can attack Bluggoe plantains. Many other insects, nematodes, and diseases attack plantains, but little is known of their economic importance.

Potatoes. Potatoes are grown by small farmers in the mountains of Colombia. These farmers must spray with both insecticides and fungicides to produce a crop. Some farmers spray 16 times per season, and potatoes are often grown two seasons a year. Growing potatoes in Colombia is particularly risky and expensive because of: leaf miners; aphids; leafhoppers; various soil insects; numerous viruses (including veinous yellows unknown outside of Colombia and Ecuador); fungal diseases such as *Rhizoctonia*, *Fusarium*, late blight, early blight, *Sclerotinia*, scab, and powdery scab; and nematodes (the golden nematode was recently found in Southern Colombia). Although European and North American potatoes developed from potatoes introduced into Europe from Colombia, yields in Colombia are among the world's lowest, probably due in part to the many pest problems found there.

Rice. Rice blast is the most important pest of rice. That and other diseases require the extensive use of herbicides, fungicides, and insecticides. Hoja blanca once destroyed thousands of hectares of rice in Colombia, but breeding of resistant varieties by ICA and CIAT has reduced its importance.

Sugarcane. Ratoon stunting disease is a major cause of reduced yields in sugarcane, but it can be controlled by hot air or hot water treatment of the seed cane. *Diatraea* and many other insects, diseases, and nematodes attack cane in Colombia. Sugarcane companies in Colombia use parasites and predators extensively to control insects.

Vegetables. Both cool climate and tropical vegetables are grown in Colombia, but not nearly as extensively as their value in nutrition would warrant. Most seed comes from the temperate countries and is poorly adapted to the tropics. As an example of a serious pest, the tomato pinworm recently caused tomato prices to soar in the Cauca Valley. The worm developed resistance to chlorinated hydrocarbons, carbamates, and phosphates, and control was virtually impossible.

Wheat. Enanismo, wheat stem rust, and yellow stripe rust are major diseases of wheat. ICA was the first to produce a multiline variety of wheat, "Miramar," with resistance to rusts.

PLANT PROTECTION ORGANIZATION AND INSTITUTIONS

Probably the most important single agency in plant protection in Colombia is the Colombian Agricultural Institute (Instituto Colombiano Agropecuario). It has research, extension, training, quarantine, and pesticide regulation activities in plant protection and an active program in pest management. ICA has major research stations and extension activities in all the major agricultural regions of Colombia, and has programs that deal with most of the major food crops in Colombia and some of the export crops with the exception of coffee. Also, ICA offers undergraduate training in plant protection in the state and national universities conferring the Inginiero Agronomo degree, and has a graduate school and confers the M.S. degree in cooperation with the national university. Training in entomology, weed science, plant pathology, and nematology is available through ICA. The Coffee Federation has its own research and extension organization that includes plant protection.

A major constraint in plant protection research in Colombia and in many other developing countries is the lack of continuity in research and research personnel. In one country, the minister of agriculture was changed almost twice a year for political reasons which resulted in personnel shifts in research, administration, priorities, and budgets. Rapid change and turnover in institutions and scientific personnel harms research, much of which must be long term to be meaningful.

There is considerable duplication of effort in plant protection, especially in extension, by numerous official and semiofficial agencies such as INCORA, ICA, the Coffee Federation, the Caja Agraria (agricultural bank), the Cocoa Federation, the Tobacco Institute, and many others. With 50 percent of Colombia's population engaged in agriculture, often in inaccessible mountainous areas, it is difficult to undertake extension activities and emphasis is often given to the larger, wealthier producers. The nutritional potential of pest control innovations will not be realized unless small farmers also are assisted.

Regulatory activities are under Sanidad Vegetal (Plant Sanitation Program). Colombia's extensive coastline (900 miles on the Pacific Ocean and 1,100 miles on the Caribbean) hinders these activities. Also, the fact that Colombia borders on Panama, Venezuela, Brazil, Peru, and Ecuador makes enforcement of quarantines nearly impossible.

CIAT, located in Cali, Colombia, is one of the international centers funded by the Consultative Group on International Agricultural Research (CGIAR). Its primary role is research on cassava, beans, beef and forage crops, and farming systems. It also has maize and rice programs linked to CIMMYT and IRRI. CIAT's research on plant protection in connection with beans and cassava is already having a positive effect on crop production in Colombia.

As an index of trained personnel in plant protection, 12 persons have doctorates in plant pathology in Colombia. Over 100 additional scientists with the M.S. and Ing. Agronomo degree also work as plant pathologists in Colombia.

ENVIRONMENTAL FACTORS

As are many developing countries, Colombia has been overly dependent on pesticides. Aggressive sales by European, North American, and Japanese chemical pesticide companies, often coupled with their extension services to farmers, has led to this overdependence. The development of pest-resistant varieties of wheat, barley, potatoes, maize, rice, cassava, etc. by ICA and CIAT has somewhat reduced this problem.

According to 1969 figures, rice, cotton, wheat, barley, and maize were the major consumers of herbicides, and potatoes, rice, and bananas were the major consumers of fungicides. Cotton, rice, potatoes, and maize (in that order) used the largest volume of insecticides.

Data on death and hospitalization due to pesticide poisoning are not readily available, but the situation appears to be serious and similar to that found in such Central American countries as El Salvador, Guatemala, and Nicaragua.

NUTRITIONAL POTENTIAL OF PEST CONTROL IMPROVEMENT

The Food and Agriculture Organization (FAO) estimates that the daily supply of energy in Colombia is 2,200 kilocalories per capita, 95 percent of the requirement. Protein supplies are estimated at 51 grams per person per day (FAO 1975b). The aggregate statistics thus indicate that Colombia has a shortage of food supplies, especially those used for their calories. "Most of the population is chronically malnourished and thus highly susceptible to diseases. Deficiencies exist not only in the level of caloric consumption but in minerals and vitamins needed for maintenance of proper health (FAO 1975b)."

Corn, rice, sugar, cassava, potatoes, plantains, bananas, wheat, barley, and beans are the most important ingredients of the Colombian diet. Table 7 gives the area cultivated, yield per hectare, and total production of Colombia's major crops in 1974.

It is reasonable to predict that the development and adaptation of improved pest control practices in Colombia could eliminate 50 percent of the current losses from pests. If such an achievement were realized, the increased production could theoretically provide the energy needed to support over 6 million people per year (Table 8) or 25 percent of Colombia's population in 1974. The increased number of beans that could be harvested by eliminating 50 percent of the losses from pests would be sufficient to supply the protein needs of 140,000 people per year.

Needless to say, one cannot assume that the commodities now lost to pests would be the basis for a nutritious diet if they were saved. For example, the sugarcane saved could provide energy enough for over 3 million people per year (Table 8), but sugar by itself would not be the foundation of a nutritious diet. No figures are given for potential increases in such crops as coffee or cacao because they are not directly nutritious. Such crops do, however, have economic potential as exportable commodities and could be traded for food crops on the world markets. Caution must be exercised accordingly in interpreting the figures in Table 8. Such difficulties should not, however, obscure the major point: pests now consume an appreciable amount of food, and the elimination of 50 percent of the losses from pests has the biological potential of feeding substantial numbers of people. The high probability of success in pest control research coupled with the potential for feeding many people is a strong argument for a considerably enhanced research effort in pest control.

PROPOSED RESEARCH AND DEVELOPMENT IN PLANT PROTECTION FOR COLOMBIA

Four major research and development efforts should be undertaken in Colombia:

- Strengthen research, training, and extension activities in pest management on the major food and fiber crops that are presently using large quantities of pesticides such as rice, maize, potatoes, and cotton.
- Determine the causal agents of diseases of unknown etiology in Colombia such as: enamismo of wheat, oats, and barley; veinous yellows of potatoes; porroca of coconuts; "marchitez sorpresiva" of African oil palm; and so forth.
- Determine the most effective methods of disseminating pest protection information to farmers.
- Establish a cooperative U.S.-Colombian program involving research, training, and workshops on controlling diseases of potatoes, plantains, and tomatoes caused by *Pseudomonas solanacearum*.

Table 7. Major crops of Colombian diets: area, yields, and total production, 1974

Crop	Area (1,000 ha)	Yield (kg/ha)	Production (1,000 tons)
Corn	650	1,192	775
Rice (paddy)	362	4,003	1,449
Sugarcane	367	49,905	18,315
Cassava	165	8,000	1,320
Potatoes	89	12,753	1,135
Plantains			1,527*
Bananas	68	14,029	954
Wheat	70	1,229	86
Barley	73	1,644	120
Beans (dry)	105	695	73

*1965-69.

Source: FAO (1975a) for all figures except plantains, and Bennett (1973) for plantains.

Table 8. Projected increases in Colombian food supplies if 50 percent of pest losses are eliminated

Crop	Production[a] (1,000 tons)	Pest losses (percent)[b]			Theoretical production[c] (1,000 tons)	Projected increase (1,000 tons)	People fed[d] E=energy P=protein (1,000 tons)
		Insects	Diseases	Weeds			
Corn	775	20	10	10	1,292	259	1,007 E
Rice (paddy)	1,449	4	6	11	1,834	193	609 E
Sugarcane	18,315	15	20	9	32,713	7,199	3,309 E
Cassava	1,320	5	17	2	1,737	209	322 E
Potatoes	1,135	15	20	3	1,831	348	290 E
Plantains	1,527	5	25	3	2,279	376	350 E
Bananas	954	5	25	3	1,424	235	219 E
Wheat	86	4	13	10	118	16	58 E
Barley	120	5	11	10	162	21	52 E
Beans (dry)	73	13	11	9	109	18	140 P
							TOTAL E 6,216

[a] From Table 7.

[b] Cramer (1967). Losses in plantains assumed to equal losses in bananas.

[c] Theoretical production is the production that would have been realized had no pest losses occurred. It is calculated with the equation: theoretical production = actual production / (1 - proportion of total losses).

[d] Corn: 3.55×10^5 kcal/100 g.
Rice: 3.60×10^5 kcal/100 g; loss of 20 percent on milling to brown rice.
Sugarcane: Assume cane is 75 percent juice, of which 15 percent is raw sugar; 3.73×10^5 kcal/100 g of raw sugar.
Cassava: 3.52×10^5 kcal/100 g, dry; assume harvest weight is 60 percent water.
Potatoes: 0.76×10^5 kcal/100 g.
Plantains: 0.85×10^5 kcal/100 g.
Bananas: 0.85×10^5 kcal/100 g.
Wheat: 3.33×10^5 kcal/100 g; assume use of whole wheat flour.
Barley: Assume barley milled to pot barley (35 percent weight loss) and assume 3.49×10^5 kcal/100 g.
Beans (dry): Assume 22.3 g protein/100 g; assume protein score = 47.
Assume energy requirements are 2,500 calories per day per person.
Assume protein requirements are 45 g per person per day (for protein score = 100).
Assumptions for both caloric and protein requirements are generous.

REFERENCES

Arthur D. Little Co. (1975) Evaluation of the Possible Impact of Pesticide Legislation on Research and Development Activities of Pesticide Manufacturers. Document No. EPA 540/9-75-018.

Bennett, G. A. (1973) Agricultural Production and Trade of Colombia. U.S. Department of Agriculture, Washington, D.C.

Brown, A. W. A., T. C. Byerly, M. Gibbs, and A. San Pietro (1975) Crop Productivity--Research Imperatives. East Lansing, Mich.: Michigan Agricultural Experiment Station and Charles F. Kettering Foundation.

Burton, G. W., E. H. DeVane, and R. L. Carter (1954) Root penetration, distribution, and activity in southern grasses measured by yields, drought symptoms, and P^{32} uptake. Agronomy Journal 46:229-233.

Burton, G. W., G. M. Prine, and J. E. Jackson (1957) Studies of drought tolerance and water use of several southern grasses. Agronomy Journal 49:498-503.

Bush, G. L., R. W. Neck, and G. B. Kitto (1976) Screwworm eradication: inadvertent selection for noncompetitive ecotypes during mass rearing. Science 193:491-493.

Carlson, P. S. and J. C. Polacco (1975) Plant cell cultures: genetic aspects of crop improvement. Science 188:622-625.

Cramer, H. H. (1967) Plant Protection and World Crop Production. Leverkussen, West Germany: Farbenfabriken Bayer. A.G.

Davidson, S. and R. Passmore (1967) Human Nutrition and Dietetics. Baltimore: Williams and Wilkins Co.

DeBach, P., ed. (1964) Biological Control of Insect Pests and Weeds. New York: Reinhold Publishing Corp.

DeBach, P. (1974) Biological Control by Natural Enemies. London: Cambridge University Press.

Djerassi, C., C. Shih-Coleman, and J. Diekman (1974) Insect control of the future: operational and policy aspects. Science 186:596-607.

Elkins, C. B., F. Lowry, and J. Langford (1973) Alleviation of mechanical impedance to cotton rooting in a dense subsoil by use of a sod. Agronomy Abstracts, 1973 annual meeting of the American Society of Agronomy, Las Vegas, Nevada.

FAO/WHO *Ad Hoc* Expert Committee (1973) Energy and Protein Requirements. Rome: Food and Agriculture Organization of the U.N.

Food and Agriculture Organization of the U.N. (1975a) Production Yearbook, 1974. Rome: FAO.

Food and Agriculture Organization of the U.N. (1975b) The State of Food and Agriculture 1974. Rome: FAO.

Griffin, K. (1974) Political Economy of Agrarian Change. Cambridge, Mass.: Harvard University Press.

Harlan, J. R. (1975) Our vanishing genetic resources. Science 188:618-621.

Hulse, J. H. and D. Spurgeon (1974) Triticale. Scientific American 231:72-80.

Kohn, G. K. (1975) Target-specific pesticides, an industrial case history. Pages 113-133 in Pesticide Selectivity, edited by J. G. Street. New York: Marcel Dekker.

Magness, J. R., G. M. Markle, and C. C. Compton (1971) Food and Feed Crops of the United States. Interregulational Research Project IR-4, Interregulational Bulletin No. 1, New Jersey Agricultural Experiment Station, New Brunswick.

Manocha, S. L. (1975) Nutrition and Our Overpopulated Planet. Springfield, Ill.: Charles C Thomas, Publisher.

Mao, Y. T. (1965) World List of Plant Breeders. Rome: Food and Agriculture Organization of the U.N.

National Research Council (1972) Genetic Vulnerability of Major Crops. Washington, D.C.: National Academy of Sciences.

National Research Council (1975a) Agricultural Production Efficiency. Washington, D.C.: National Academy of Sciences.

National Research Council (1975b) Pest Control: An Assessment of Present and Alternative Technologies. Volume I-V. Washington, D.C.: National Academy of Sciences.

National Research Council (1976) Insect Control in China. Washington, D.C.: National Academy of Sciences.

Ozbun, J. L., et al., eds. (1976) Researchable Areas Which Have Potential for Increasing Crop Production. New York State College of Agriculture and Life Sciences, Cornell University, Ithaca, N.Y.

Ridge, E. H. and A. D. Rovira (1968) Mycrobial Inoculations of Wheat. Transactions of the Ninth International Congress of Soil Science, Adelaide, Australia.

Wellhausen, E. J. (1970) The Urgency of Accelerating Production on Small Farms. In: Strategies for Increasing Agricultural Production on Small Holdings. International Maize and Wheat Improvement Center, International Conference, Puebla, Mexico.

Zelitch, I. (1971) Photosynthesis, Photorespiration, and Plant Productivity. New York: Academic Press.

BIBLIOGRAPHY

DeVries, C. A. (1975) Increasing crop yields--relative potential of specific crops by region and/or country. Pages 109-125, Man, Food and Nutrition, edited by M. Recheigl, Jr. Cleveland, Ohio: CRC Press.

Easten, J. D., et al., eds. (1969) Physiological Aspects of Crop Yield. American Society of Agronomy, Madison, Wisconsin.

Evans, L. T. (1969) The Induction of Flowering. Ithaca, N. Y.: Cornell University Press.

Evans, L. T., ed. (1975) Crop Physiology: Some Case Histories. London: Cambridge University Press.

Gifford, R. M. (1974) A comparison of potential photosynthesis, productivity and yield of plant species with differing photosynthetic metabolism. Australian Journal of Plant Physiology 1:107-117.

Hardy, R. W. F., U. D. Havelka, and B. Quebedeaux (1976) Opportunities for improved seed yield and protein production: (1) N_2 fixation, (2) CO_2 fixation, and (3) O_2 control of reproductive growth. In: National Research Council. Genetic Improvement of Seed Proteins. Washington, D.C.: National Academy of Sciences.

Leopold, A. C. (1975) Aging senescence and turnover in plants. Bioscience 25:659.

National Research Council (1975) Enhancement of Food Production in the United States. Washington, D.C.: National Academy of Sciences.

National Research Council (1975) World Food and Nutrition Study: Interim Report. Washington, D.C.: National Academy of Sciences.

Vince-Prue, D. (1975) Photoperiodism in Plants. New York: McGraw-Hill.

Wallace, D. H., J. L. Ozbun, and H. M. Munger (1972) Physiological genetics of crop yield. Advances in Agronomy 24:29.

Wardlow, I. F. (1968) The control and pattern of movement of carbohydrates in plants. Botanical Review 34:79.

Yoshida, S. (1972) Physiological aspects of grain yield. Annual Review of Plant Physiology 23:437.

Report of Study Team 2

ANIMAL PRODUCTIVITY

STUDY TEAM 2

Tony J. Cunha, CHAIRMAN, California Polytechnic State University, Pomona
Kenneth H. Shapiro, LEAD ANALYST, University of Michigan
James M. Fransen, International Bank for Reconstruction and Development
Harlow J. Hodgson, University of Wisconsin
James E. Johnston, The Rockefeller Foundation
Wilford H. Morris, Purdue University
Robert R. Oltjen, U.S. Department of Agriculture
W. R. Pritchard, University of California, Davis
Robert R. Spitzer, U.S. Agency for International Development
N. L. VanDemark, Cornell University

SUBGROUP A ANIMAL HEALTH

W. R. Pritchard, CHAIRMAN, University of California, Davis
Edward T. Braye, Tuskegee Institute
William M. Moulton, U.S. Department of Agriculture
Philip A. O'Berry, U.S. Department of Agriculture
Calvin W. Schwabe, University of California, Davis

ACKNOWLEDGMENTS

Study Team 2 is indebted to the following individuals who contributed to this report: W. M. Beeson, J. H. Conrad, V. W. Hays, J. P. Fontenot, and J. E. Oldfield, from the United States; and Claudio Chicco, Maracay, Venezuela; and Marco P. Cabezas, Guatemala City, Guatemala.

Subgroup A wishes to thank the following consultants who assisted with various aspects of their report: T. E. Carpenter, C. A. Hjerpe, Jr., J. A. Howarth, and J. E. Moulton.

TABLE OF CONTENTS

SUBGROUP A ANIMAL HEALTH

INTRODUCTION

Animals produce valuable food for humans from grasslands, cultivated forages, by-products, crop residues, wastes, and other materials that would otherwise be unused. About two-thirds of the world's agricultural land is in the form of permanent pastures and meadows. Furthermore, on most cropland almost half of the total digestible energy produced by a plant is left on the fields after harvest. As grains, soybeans, and other feeds become less available for animal feed, alternate feeding programs could be developed so that animals can contribute to the total food supply without competing with humans for basic food grains.

Coordinating crop and animal production is critical to many agricultural systems. Animal production efficiency needs to be improved per animal and per hectare. First priority should be given to ruminants because they can better use forages and other cellulosic feeds that are available in great quantities throughout the world. But swine, poultry, and game animals also contribute to our food supply and should not be neglected.

There is a tremendous potential for increasing ruminant production in the developing countries because of the large land areas there that could be used to produce forage. This is especially true for beef cattle and to a lesser extent for dairy cattle, goats, sheep, and buffalo. Most of this land area has little use other than for grazing ruminants since much of it is not suitable for intense tillage and some of it will not be needed for this purpose for decades.

Presently, the productivity levels of ruminants are low in the developing countries. Research and education programs are needed to: (1) raise the production efficiency of beef cattle, dairy cattle, buffalo, sheep, and goats; (2) raise the quality of the final product; and (3) improve the final product's marketing and distribution. In many areas, soil infertility and long dry periods greatly restrict year-round production of quality forage. But this could be corrected when the economics justify doing so. Ruminant production can be increased by: (1) expanding the total land area for ruminants, (2) intensifying the use of existing ranches, and (3) innovating and applying new technology.

Beef cattle have the greatest potential for expansion in the developing countries because of the large land areas available. Many of these areas are in sparsely populated, underdeveloped regions where beef cattle grazing is presently the preferred method of using the land and resources.

The developing countries also can expand their production of dairy cattle. Dairy animals can do well on rations consisting largely of forages and by-product feeds. Expanded dairy production could meet the increasing demand for milk in the developing countries.

Sheep and goats are important, especially in the developing countries of Europe, the Middle East, South Asia, and Africa. They are used in combination to graze rangelands that cannot be used effectively for any other productive purpose. Goats, unlike sheep, are well adapted to the humid tropics. There are approximately 400 million goats in the world, mainly in the developing countries. Goats and sheep are an important source of milk, meat, wool, and skins. Goats can be fed on grass, weeds, trimmed bushes, tree limbs, kitchen waste, and inedible fruits and vegetables.

Buffalo are very adaptable to many tropical areas. They can be used as draft animals and also can supply meat, milk, and hides. However, little research information is available on this animal. Their widespread use would seem to warrant an accelerated research program.

Poultry and swine are relatively efficient in converting feed to food for human consumption. By-product feeds, wastes, and other feeds can be used in their rations if necessary. Forages can be used to feed swine. Therefore, the developing countries should consider seriously raising more swine and poultry even though grain and soybean meal may be scarce. China is a good example of a nation using by-product feeds, wastes, and forages to produce large numbers of swine and fowl.

Game animals including wild birds and fish can supply a significant amount of food in many developing countries. In some areas, game animals are more resistant than livestock to tsetse flies, ticks, and other pests. Studies are needed to determine how game animal production can be increased without damaging forest and range resources or competing with domestic animals.

To increase animal productivity, it is important to: (1) supply adequate feed, (2) improve animal health, (3) increase reproductive efficiency, and (4) improve feed efficiency and genetic potential. The interactions among adequate nutritional levels, disease resistance, increased productivity, and proper management should be studied in various production systems. Integrated livestock-cropping systems should be evaluated. Programs using more than one class of livestock should be considered.

Table 1 outlines the resources needed in the form of scientist-years for the research areas described generally above and more specifically in our profiles.

Table 1. Scientist-years required for animal production research

	United States			Developing countries		
	First four years	Next nine years	Next 10 years	First four years	Next nine years	Next 10 years
Profile 1 Forages	64	144	200	84	189	230
Profile 2 By-products	60	90	50	40	90	100
Profile 3 Reproductive efficiency	80	180	50	40	90	100
Profile 4 Productive efficiency	60	90	100	60	135	150
Subgroup A Animal health research	280	360	150	60	180	250
Subgroup A Animal health control	20	45		80	450	300
TOTAL	564	909	550	364	1,134	1,130
Per year	141	101	55	91	126	113

THE ROLE OF LIVESTOCK

Livestock present an opportunity to produce valuable food from a wide range of resources that would otherwise make little, if any, contribution to feeding humanity. At the same time, livestock enterprises in integrated farming systems are often critical to increasing crop production, and they may play a key role in overall economic development. Animals also provide a host of nonfood by-products, and live animals represent a large emergency food reserve. Here we discuss each of these aspects of the role of livestock in feeding people.

NUTRITIONAL VALUE OF ANIMAL PRODUCTS

In 1972, animal products provided 34.8 percent of the energy in American diets and, reflecting the high nutritional value of those foods, they provided 66.8 percent of the protein, 81.9 percent of the calcium, 71 percent of the riboflavin, and 67.9 percent of the phosphorus (VanDemark 1976:9). (The question of possible health problems arising from a high consumption of animal products itself calls for continued research.) Most estimates for developing areas show animal products contributing between 12 and 35 percent of dietary protein (University of California Food Task Force 1974:203-205). These averages may be fairly accurate for the large rural populations but probably overstate the importance of animal products for the urban poor.

As population rates rise in the developing countries it will become increasingly important to improve animal productivity in order to prevent declines in per capita consumption. Declines in the availability of any protein source would be unfortunate in the developing countries, but a decline in animal protein would be particularly serious because of its high quality. As shown in Table 2, the value of the amino acid composition in animal protein varies from 60 to 100 percent of the ideal (egg protein), while in plant protein the figure is generally below 50 percent. Furthermore, animal protein is more digestible than most plant protein and thus has a higher rate of net utilization. Diets deficient in animal products must compensate with a greater variety and quantity of plant protein foods. This compensation may be difficult in some areas. Particularly important are the difficulties small children have in eating enough plant protein foods to obtain proper nutrition when animal foods are in short supply.

Although no plant protein foods offer the quality protein found in animal foods, legumes and pulses are a good protein source because of their high ratio of protein to dry weight and to calories. As Table 2 shows, these ratios approach, and in some cases surpass, those of some animal foods. However, there may be problems in relying too heavily on legumes and pulses as protein sources. Foods composed of legumes and pulses tend to be indigestible, are often unacceptable to weaning children, and their protein quality is no greater than that of most cereals (and less than that of rice).

Another problem is consumer preferences. Whereas animal products generally enjoy strong consumer demand, legumes and pulses do not. This difference in consumer preferences is reflected in the respective income elasticities of demand for legumes and pulses and animal products. For animal products in the developing nations, the figure is usually equal to or above 1.0, while for legumes and pulses it is much lower, often below 0.3. Thus although farmers may eventually be able to grow more legumes, they may not wish to eat more, and they may find a relatively low market price for their surplus.

ANIMALS AS RESIDUAL USERS OF AGRICULTURAL RESOURCES

Economic conditions in the United States have encouraged farmers to feed significant amounts of grain to livestock. This phenomenon may have obscured the fact that animals are residual users of agricultural resources, eating grain only when other demands for that grain are relatively low and, more importantly, deriving most (and in many developing areas, all) of their nutrition from resources that would otherwise not be used to produce human food. These resources may be considered in two broad categories: rangelands, meadows, pastures, and cultivated forages; and residues, by-products, and wastes from crop and animal production and processing.

Table 2. Quality of some common food proteins[a]

Food	Food protein				Rat biological value[b] (percent)	Net protein utilization[b] (percent)	ND_pCal[c] (percent)	PER[d]	Egg-based chemical score[e]
	Percent as purchased	Percent of dry solids	Percent of total kcal	Digestibility[b] (percent)					
Hen's egg, whole	13	48	33	99	94	94	31	3.92	100
Cow's milk, whole	3.5	27	23	97	84	82	19	3.09	60
Fish	19	72	61	98	83	81	49	3.55	70
Beef	18	45	29	99	74	73	21	2.30	69
Soybeans	38	41	39	90	73	66	26	2.32	47
Dry beans, common	22	25	22	73	58	42	9	1.48	34
Peanuts	26	27	16	87	54	48	8	1.65	43
Green leaves	1.5-4.5	23-31	18-45	85[f]	64[f]	54[f]	6-24	-	33
Yeast, brewer's	39	41	54	84	66	55	30	2.24	45
Wheat, whole grain	12	14	13	91	65	59	8	1.53	44
Wheat, white flour	11	12	12	99	52	51	6	0.60	32
Corn, whole grain	10	11	7	90	59	53	4	1.12	41

Rice, brown	8	9	7	96	73	70	5	-	57
Rice, polished, white	7	8	7	98	64	63	4	2.18	56
Potato, white	2	9	7	89	67	60	4	-	34
Cassava (manioc)	2	2	1	No information				-	41

---

[a] From FAO Nutrition Studies.

[b] Determined by rat feeding studies. Digestibility is the amount of fed protein absorbed, and biological value is the portion of absorbed protein that is retained as body tissue. Net utilization is simply digestibility x biological value.

[c] Net dietary protein calories as percentage of total calories. The percentage of calories from protein in the food is adjusted according to the net utilization, or quality, of the protein, i.e., (g protein/100 g food x NPU x 4 kcal) kcal/100 g food.

[d] Protein Efficiency Ratio is the grams of weight gained per gram of protein eaten by the rat.

[e] Chemical score is based on amino acid composition. The amount of the most limiting amino acid present is expressed as a percentage of the amount present in egg protein.

[f] Values listed are for kale; net utilization of other leaves may be higher (mustard greens, 60) or lower (cabbage, 35).

Source: Bogert, L., G.M. Briggs, and D.H. Calloway (1973) Nutrition and Physical Fitness. Philadelphia: W.B. Saunders.

Rangelands, Meadows, Pastures, and Cultivated Forages

Permanent grasslands constitute approximately 67 percent of the world's agricultural land (O. Scoville 1976, "Assorted Tables on the Role of Ruminants in Support of Man," unpublished data). In Africa and Latin America, the proportions range from about 60 to 85 percent, in North America and Europe from 30 to 60 percent, and in Asia (excluding China and Russia, in each of which permanent meadows and grasslands constitute about 62 percent of all agricultural land) from 10 to 35 percent. Much of this pasture and meadow land has a very low potential for crop agriculture because of agronomic, climatic, or topographic constraints. Other lands are in sparsely populated regions where labor inputs and demand may be insufficient to support crop production. In some areas where crop agriculture is possible, it may yield lower net returns than grazing operations that have very low costs, relying on nature for seeding, manure for fertilization, and animals for harvesting. It has been estimated that over 60 percent of the world's grazing land is not suitable for cultivation (University of California Food Task Force 1974:132). Thus much agricultural land would provide little if any human food if not grazed by ruminants, which have the ability to convert herbage and browse into meat and milk.

Residues, By-products, and Wastes

Residues refer primarily to those parts of the crop, such as rice straw, that are left on the field after harvesting. By-products are those parts of harvested food and industrial crops that are discarded during processing for human use, such as rice bran and cottonseed cake. Included under wastes are animal manure and human sewage.

On most cropland about half of the digestible energy is left on the field after harvest (R. R. Oltjen 1976, personal communication, Agricultural Research Service, U.S. Department of Agriculture [USDA]). These crop residues are now fed to ruminants, but that portion could be increased by developing more fully integrated farming systems. As crop production expands, the availability of these residues also expands and their full use as animal feed should increase the profitability of the whole farm enterprise. Byerly (1966) estimated that full use of crop offals and roughages could produce 22 grams of milk protein per capita per day in non-Communist Asia, 78 grams in Africa, 54 grams in Latin America, and 75 grams in the United States. The actual use of these products is, of course, largely determined by the strength of competing economic demands.

As new technologies are developed to improve the feed value of those residues, by-products, and wastes already in use and to utilize those not yet in use as animal feed, the potential for livestock production should greatly improve.

LIVESTOCK'S CONTRIBUTION TO CROP PRODUCTION

Organic Wastes

In the United States, animal manure has the potential for contributing the "equivalent of approximately 70 percent of the 8.5 million metric tons of nitrogen applied as fertilizer to croplands... (VanDemark 1976:32)." In 1971, organic wastes in the developing countries contained 48 million tons of nitrogen, 16 million tons of phosphorus, and 39 million tons of potassium that were potentially available as soil additives. Cattle manure constituted the largest single source of these nutrients, contributing about one-third of each (see Table 3). At 1973 world prices, the nutrients from organic wastes in the developing countries would have been worth about $16 billion. Their combined weight of 103 million tons may be compared to developing country use of only 13 million tons of those nutrients in mineral fertilizers in 1970-71 (Duncan 1975:355-357).

The actual use of organic wastes as soil additives is considerably below the potential. In India, for example, it is estimated that only one-third of the 1.33 billion tons of farmyard manure produced annually actually is applied to cropland (Duncan 1975:361). Of the remainder, one-third is burned as fuel, and we could not find information on the last third. The current competition between the use of manure for fuel and its use for fertilizer could be avoided by the utilization of small, relatively simple and cheap anaerobic methane gas producers. A gas plant costing about $270 and using manure from three cows could produce about 100 cubic feet of methane gas per day, which is adequate for a family of five (Singh 1975:22). Gas plant processing leaves manure with more nitrogen and organic matter than is left in the same volume of manure processed by traditional methods (Singh 1975:23). Thus the same manure could be used for both fuel and fertilizer; those uses need not be competitive.

The development of more fully integrated farming systems will not only encourage the use of manure as

Table 3. Total annual production of soil nutrients (nitrogen, phosphorus, and potassium) through organic wastes in the developing countries, 1971 (actual) and 1980 (estimated)*

Source		Nitrogen (million tons)	Phosphorus (million tons)	Potassium (million tons)
Human	1971	12.25	2.87	2.61
	1980	15.26	3.57	3.25
Cattle	1971	17.80	4.91	14.12
	1980	22.25	6.14	17.65
Farm compost	1971	9.54	3.34	9.54
	1980	11.93	4.18	11.93
Urban compost	1971	.48	.38	.57
	1980	.60	.48	.71
Urban sewage	1971	1.43	.29	.86
	1980	1.79	.36	1.08
Other**	1971	6.63	4.44	11.35
	1980	8.29	5.55	14.19
TOTAL	1971	48.13	16.23	39.05
	1980	60.12	20.28	48.81

*Excludes Central America and Oceania; includes socialist Asia.

**Bonemeal, poultry litter, bagasse, sheep/goat litter, oil cake, and press-mud. (Several other sources were not included due to their small potential for all of the developing world.)

Source: Van Voorhoeve (1974).

fertilizer, but also will encourage the growth of livestock enterprises since these would become more profitable when animal manure has a valuable use. Indeed, Perkins (1969:72) has argued that pig production in China would be uneconomical if not for the manure produced.

Pigs are not the only monogastric small animals that would fit well into an integrated farming system. Under fairly good scavenging and range conditions, upgraded Indian chickens should be capable of laying 90 to 100 eggs per year. Furthermore, "33 to 40 laying birds can produce in one year a no-cost by-product of one ton of deep litter manure which can make possible the production of an extra ton of grain from one acre of irrigated land (Whyte 1975:14)."

Draft Power

Integrated farming systems often call for the use of animal draft power as well as the use of animal manure, and in some systems the latter may depend on the former. An example is an incompletely integrated farming system near Lake Victoria in Tanzania (Shapiro 1976). Approximately one-third of the farmers sampled raised cattle that depended on crop stubbles, fallows, and nearby pastures for their entire nutrition. The animals were kept in a kraal at night and the cows were milked daily. However, neither animal manure nor animal draft power were used.

The lack of draft power prevented the use of manure for two reasons. First, large quantities of manure are required to obtain a significant amount of nutrients, and thousands of kilograms may have to be transported from the kraal to the cropland. Without animal draft power (or mechanical power) this is an imposing task. In many parts of Africa and Latin America where labor is not so abundant as in much of Asia, hand movement of manure to croplands may not be the best use of the available labor. However, if animals pulled the carts, the use of manure might become more widespread.

A second inhibition to the use of manure is the greater weed growth that could result from the additional nutrients. In many areas of the developing world, weeding time requires the greatest amount of labor, and many farm families may not have enough workers to handle the task. Where weeding is done by hand the problem is intensified, and additional weed growth because of manure may seriously set back the entire farming operation. However, if animal-drawn weeders were used, this labor bottleneck could be prevented, thereby encouraging the use of manure.

In general, animal power is important to crop production because it enables farmers to perform many operations more easily, more quickly, and with better quality control. Table 4 shows the labor requirements for systems in which (1) various tasks done by hand (columns 1-5), (2) land preparation and weeding are done with oxen (column 6), and (3) only land preparation is done with oxen (column 7). (The last column may be symptomatic of problems arising when there is an incomplete shift to oxen power.)

Faster land preparation obviously means more land may be brought under cultivation in a given time period, if it is available. In some areas, extending production will cause bottlenecks in subsequent operations, although ox-drawn weeders help avoid some of that problem. In other areas, the use of oxen power for land preparation (and perhaps weeding) may allow fuller employment of the labor force for the rest of the season by virtue of the larger area in production. These would be areas where large labor requirements for land preparation and planting sharply curtail the area under hand hoe cultivation, but where the requirements for subsequent operations on the diminished area are not large enough to employ fully the labor force. Thus while animal power is usually considered labor-saving, there may be areas in which it serves to diminish seasonal underemployment.

Increasing the speed of land preparation and weeding could mean performing these operations closer to ideal time periods. In drier areas, land should be prepared and planted immediately after the onset of enough rain. Where new varieties permit multiple cropping, rapid land preparation may be a necessity. (Indeed, this is often cited as one reason for the spread of tractors in India and Pakistan.) In many areas, early weeding is recommended to minimize competition for soil nutrients. Animal traction improves the timeliness of these operations.

Operations performed with animal-drawn implements are often better done. As Johnston and Kilby note (1975:413), the new high yielding varieties of grain call for better seed bed preparation, planting techniques, and weed control. With proper implements animal power can improve these operations. The seed-fertilizer drill is often cited as an important aid in the Green Revolution.

Aiding Crop-Fallow Rotations

In addition to aiding crop production directly by providing power and manure, animals can contribute to improved systems of crop-fallow rotations by converting

Table 4. Labor inputs in typical savanna crops with hoe cultivation and ox-plough cultivation

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Hoe cultivation					Ox-plough cultivation	
Crop	Groundnut	Millet	Maize	Maize-sorghum	Cotton	Groundnut	Cotton
Location	Kaolack	n.a.	n.a.	Sukumaland	Sukumaland	Kaolack	Sukumaland
Country	Senegal	Upper Volta	Upper Volta	Tanzania	Tanzania	Senegal	Tanzania
Year	1966	n.a.	n.a.	1963	1963	1965	1963
Land preparation and planting (hours ha^{-1})	169	88	152	390	370	136	120
Weeding (hours ha^{-1})	376	180	252	250	430	110	700
Harvesting and preparation for sale (hours ha^{-1})	210	208	64	300	690	210	700
TOTAL (hours ha^{-1})	755	476	468	940	1,490	456	1,520

Source: Ruthenberg, H. (1971) Farming Systems in the Tropics. London: Oxford University Press.

fallow herbage into valuable food. For example, in North Africa and the Middle East a native legume, *Medicago* or medic, is being reintroduced into wheat-fallow rotations. In Algeria alone, medics could be grown on 2.5 million hectares of annual fallow and thereby place $45 million worth of nitrogen in the soil annually, double wheat yields, and allow twice as many livestock to be fed (Berth 1975:2). In the Mediterranean area, wheat farmers rent out their fallows to sheepherders. Thus the introduction of medics should raise farmers' incomes from that source as well as from higher cereal yields. In many areas, the added return from animals grazing the fallow may be necessary for an improved rotation system to be profitable. Thus measures to increase livestock production may be prerequisites for increasing crop production.

HIGHER INCOMES AND OVERALL ECONOMIC DEVELOPMENT DUE TO LIVESTOCK ENTERPRISES

The sale of animal products obviously contributes to farm cash incomes, particularly because of their high consumer demand. Thus while the sale of surplus food crops may be constrained by low demand, animal products usually do not have this problem. Furthermore, as incomes rise the demand for nonanimal foods does not rise nearly as fast as the demand for animal foods (see Table 5). Thus the latter may represent a greater long-run potential for farm earnings in a developing economy. Finally, it should be noted that livestock enterprises usually have relatively smooth year-round labor requirements and product flows, thereby providing employment and income during otherwise slack seasons.

Another way livestock enterprises further overall economic development is by encouraging specialization and structural transformation. Specialization is one of the keys to increasing productivity, and hence to economic development. As the nonagricultural sectors take over the tasks of producing farm implements and inputs, processing and marketing food and fiber, and providing more services to farm households, farmers can specialize in their most productive endeavor, raising crops and animals. Structural transformation is the term used to label these transfers of tasks, increases in specialization, and the change in size of sectors that result. Many developing nations may have difficulty stimulating structural transformation for two reasons: low market demand for agricultural products may limit farm incomes and hence limit farmers' demand for goods and services produced in the

Table 5. Representative income elasticities for selected foods

Food	India	Brazil	Japan	Australia	European Community	United States	World
Wheat	.50	.40	.10	-.10	-.32	-.30	-.24
Rice	.40	.20	-.10	.00	.11	.20	.23
Maize	-.10	-.30	-.50*	.00	-.12	-.10	.10
Sugar	1.03	.09	.39	-.10	.31	.10	.29
Fruits	.80	.49	.57	.71	.58	.25	.55
Meat	1.17	.48	.79	.07	.48	.24	.32
Fats and oils	.92	.68	.40	.05	.13	.01	.22
Total food	.43	.19	.13	.02	.08	-.01	.10
Farm value	.57	.34	.28	.11	.25	.04	.19

*Coarse grains.

Source: FAO (1971).

nonagricultural sectors, and inadequate farming technologies may prevent domestic manufacture of some inputs. Livestock enterprises could help overcome both of these difficulties.

The demand generated for animal-drawn implements is another way that livestock enterprises may further structural transformation. While the advantages of animal traction over the hand hoe or digging stick are obvious, the advantages over tractors and power tillers should be elaborated. First, animal-drawn implements are cheaper. Thus more farmers can afford them and thereby generate sizable effective demand. Similarly, because animal traction is better adapted to small fields and holdings, it can be adopted by larger numbers of farmers. Finally, compared to mechanical power technologies, far more of the implements (and inputs for producing the implements) for animal traction can be produced within the developing countries. The mechanical power technologies call for a high level of imports. Johnston and Kilby (1975:380) found that in Pakistan, on a per hectare basis, the bullock equipment package generated 49.0 rupees of demand in the domestic manufacturing sector while the power tiller package generated 27.4 and the tractor package only 10.0. Combined with the wider adoption of animal traction, this higher per hectare generation of demand is likely to be a significant stimulus to structural transformation and overall economic development.

ANIMALS AS A SOURCE OF FOOD RESERVES AND NONFOOD BY-PRODUCTS

Worldwide grain reserves in 1974 were said to represent 27 days of consumption. Some observers (Brown 1974) claimed that this was a dangerously low level, but a U.S. Department of Agriculture (1974) analysis showed that reserves of that quantity were more than sufficient to cover any shortfalls with more than 5 percent probability of occurrence. These and similar analyses of the world food situation in the early 1970s concentrated almost exclusively on grains, which is certainly appropriate in general but is too limited with regard to food reserves.

Most analysts seem to have overlooked a fact of great importance to many farmers in the developing nations: the security represented by food stored in live animals. Compared to 27 days worth of grain reserves, there were almost 40 days worth of animal reserves in the world in 1974. This figure is based on the caloric value of meat on animals _not_ slaughtered in that year (see Table 6). These are animals maintained for future consumption, breeding, draft power, and milk. Some of these services and products would be sacrificed if some of these animals were consumed, but the critical point is that the meat is immediately available to avert tragedy in an emergency. As shown in Table 6, over 75 percent of the reserves are represented by cattle.

Animal food reserves differ in at least one important way from grain stockpiles. While grain is stored in a few surplus-producing nations, animals are spread throughout the world. Thus in an emergency countries with shortages do not have to rely solely on long-distance international transport, and farmers far from ports and airports do not have to depend totally on domestic rail and road transport. Countries and farmers, therefore, have some "cushion" time represented by their own livestock.

Calculating days of consumption of grain and animal reserves is a useful measure but perhaps is misleading. It is unlikely that all nations will run out of all food at once and will have to rely solely on their reserves for extended periods. Rather it is more likely that individual areas will suffer production shortfalls temporarily calling for reserves to bridge the gap until the next harvest. In such circumstances, farmers may slaughter more animals for subsistence consumption to supplement and thus stretch out the available grain supplies. Often this measure would be sufficient and the stock of animals would not be decreased too much. In other cases, farmers may need supplemental supplies of grain reserves from abroad, with livestock providing a cushion until supplies arrive.

In addition to providing valuable foods, animals also supply a host of important nonfood products. Leather and wool play major roles in our way of life and also represent relatively large foreign exchange earnings for several countries. Insulin, extracted from the pancreas of sheep, oxen, and so forth, is of critical importance to the world's diabetics. Other important animal by-products include hair, lanolin, and enzymes such as rennin.

Table 6. Food reserves represented by live animals, 1974

	World	High-income nations	Developing nations
Population (000)[b]	3,904,898	750,021	1,926,712
Cattle			
Kg meat per slaughtered animal[b]	193	234	163
Animals not slaughtered (000)[b]	936,252	203,103	612,702
Meat reserve in unslaughtered animals[c] (000,000 kg)	92,954	23,763	49,935
Per capita meat reserve (kg)	23.8	31.68	25.92
Days of consumption from meat reserves[d]	29.76	47.52	25.92
Buffalo			
Kg meat per slaughtered animal[b]	157	160	143
Animals not slaughtered (000)[b]	123,418	145	92,450
Meat reserve in unslaughtered animals[c] (000,000 kg)	9,688	11.6	6,610
Per capita meat reserve (kg)	2.48	.02	3.43
Days of consumption from meat reserves[d]	3.10	.03	3.43
Pigs			
Kg meat per slaughtered animal[b]	68	72	54
Animals not slaughtered (000)[b]	379,217	0	52,970
Meat reserve in unslaughtered animals[c] (000,000 kg)	12,893		1,430
Per capita meat reserve (kg)	3.30		.74
Days of consumption from meat reserves[d,e]	4.12	0	.93

Sheep			
Kg meat per slaughtered animal[b]	15	16	14
Animals not slaughtered (000)[b]	677,946	202,857	312,474
Meat reserve in unslaughtered animals (000,000 kg)	5,085	1,623	2,187
Per capita meat reserve (kg)	1.30	2.16	1.14
Days of consumption from meat reserves[d]	1.62	3.25	1.14
Goats			
Kg meat per slaughtered animal[b]	11	10	10
Animals not slaughtered (000)[b]	268,912	7,223	212,486
Meat reserve in unslaughtered animals (000,000 kg)	1,479	36.1	1,062
Per capita meat reserve (kg)	.38	.05	.55
Days of consumption from meat reserves[d]	.47	.07	.55
Total days of consumption represented by meat reserves in live animals	39.07	50.87	31.97

---

[a] U.N. classification. Does not include U.S.S.R., China, and some other centrally planned economies.

[b] FAO (1975).

[c] Assumes that unslaughtered stock would provide meat production at one-half the rate of slaughtered stock.

[d] Based on information on calories in different grades of meat in Watt and Merrill (1950). We assume 3,000 calories per kilogram of meat in high-income nations, 2,000 in developing nations, and 2,500 for the world. Consumption per day is taken as 2,000 calories per day in emergencies.

[e] Pork in developing nations is assumed to yield 2,500 calories per kilogram.

Profile 1

IMPROVING FORAGE AND RANGE PRODUCTION

INTRODUCTION

Natural grasslands and cultivated forages provide the principal feed resource for the world's large population of ruminant livestock (cattle, buffalo, sheep, goats, camels, wild ruminants, and others). In the high-income countries, sizable quantities of feed grains and by-products are fed to ruminants, but even in those countries forages and grasslands provide 75 percent or more of the feed units consumed. In the developing countries, virtually all of the feed for ruminants is derived from natural grasslands, cultivated forages, and crop residues. On a worldwide basis then, probably 95 percent of the feed units consumed by ruminants are supplied from these sources.

About 60 percent of the world population of domesticated ruminants is in the developing countries where the production of food per animal unit is at very low levels. It is significant that Africa and South America have large ruminant populations with low productivity, vast areas of natural grasslands, and rapidly growing human populations who are faced with food deficits (Hodgson 1976).

Three principal means of increasing productivity of ruminant livestock populations are: (1) improving reproductive or weaning rates, (2) improving growth rates, and (3) increasing milk production. However, disease, genetic, and other factors can impinge on these means.

In the developing world particularly, the chief vehicle for increasing livestock productivity is improved nutrition, which is necessary before other improvements can be made. Because grasslands and forages provide such a large portion of the ruminant feed supply, improvement in forage and grassland technology is essential for improved animal production. In the high-income countries, it is anticipated that less grain will be used as feed over the long term, leading to an increased dependence on forages and grasslands.

The large grassland and ruminant resources, together with the desire by 85 percent of the world population for more animal protein (Tracey 1975), indicate that future planning for a world food supply should pay strong attention to increasing the productivity of these resources.

RESEARCH NEEDS

Accelerated Program of Tropical Legume Development and Utilization

Nearly 1.2 billion hectares of tropical grasslands are situated in subhumid and humid climate types to which an array of tropical legumes are adapted. These legumes could be adapted to an additional 0.4 billion hectares of grasslands in drier climate types. Hundreds of species of forage legumes evolved in these tropical zones, particularly in Latin America, and are well adapted to the low fertility, acid, high aluminum soils that cover much of the area. Research done in Australia, Colombia, and Hawaii indicate that if selected cultivars of tropical legumes are incorporated into grasslands and properly grazed by cattle, reproductive rates are increased by 50 percent or more and growth rates are doubled, tripled, or quadrupled. This would increase the offtake of animal products.

Tropical legumes also are capable of filling a vital role in crop rotations on difficult-to-manage soils by improving their nitrogen content and physical characteristics. Such use might shorten the fallow period in production systems of small holders thus increasing total food production, providing a feed base for draft animals and other ruminant livestock, and providing the means for additional sales of crop and livestock products.

The potential of improved tropical legumes appears so great that they should no longer be neglected. A program on their development and use should be integrated into a worldwide network of organized and coordinated activity that includes:

-- Germ plasm and associated <u>Rhizobia</u> of a wide array of genera and species of herbaceous and woody tropical legumes should be collected and given a preliminary evaluation at a number of centers, followed by wider distribution and evaluation of promising germ plasm.

-- Breeding efforts will be required to combine desired characteristics into improved cultivars that are environmentally adaptative, pest-resistant, and so forth. Several centers concentrating on this activity are already established in the tropical zones.

- Experience shows that appropriate associations of legume species with races of *Rhizobia* are essential to establish a strong symbiotic relationship and for good forage production. Nodules containing *Rhizobia* should be collected along with crop germ plasm. Microbiological research could be concentrated at relatively few centers to isolate and develop more effective races of *Rhizobia* and to provide for their production.
- Seed multiplication and distribution of improved cultivars are necessary if they are to be used. Specialized centers for seed multiplication should be established and national or international procedures for seed certification developed. New seed industries could even be developed given the potentially large volume of seeds that might result.
- Improved cultivars will have the greatest use when established in native grasslands or grown with improved grasses in intensively managed production systems. The latter include fattening ranches or dairy enterprises.

Tropical forage legumes are thought to have great potential. These legumes have an enormous capacity for capitalizing on the vital biological nitrogen fixation process and for incorporating millions of tons of nitrogen annually into agricultural production systems.

Improved Forage Production and Management

Forage production and management involve both plant and animal systems and their interactions. It is complicated and so has not received enough attention. Many forage species are involved, compared to a limited number of field crop species. These are used by a variety of ruminant livestock in a wide assortment of production systems involving grazed and harvested forages. Furthermore, forages are managed for herbage production rather than for seed. Therefore they require more complicated and carefully executed packages of production technologies than are needed for most annual food and feed crops.

Research on the energy digestibility and protein availability of legumes for animals should take place in all environments and involve all production and management inputs. Emphasis on dry matter production alone is inadequate. The technologies of irrigation, fertilization, time of harvest, grazing intensity and frequency and timing, together with animal management strategies, should be integrated into production systems that provide maximum economic return to investment. Research on maximizing digestible energy output without increasing energy subsidy per unit of digestible energy output appears especially promising of payoff.

Knowledge of cultural practices for temperate zone forages is fairly adequate. Much less is known about optimum cultural practices in the tropics. We must learn more about these practices if tropical cultivated forages are to approach their potential production levels.

Improved Range Management

Rangelands occupy much of the world's land surface and support much of the world's ruminant livestock populations. They are found in environments ranging from very arid to humid with corresponding productivities. In general, rangelands occupy areas not suited to cultivation. Although the goal in the management of rangelands should be using this resource without contributing to its deterioration, many of the world's rangelands have been severely overstocked and overgrazed. This is particularly true in Africa and the Middle East. In much of this area, the problem is applying known range management principles (such as deferred grazing systems) rather than lack of knowledge. The solution may be found in political decisions regarding range resource use and in development of marketing systems that encourage movement of animals from rangelands to fattening ranches and to market.

Research on rangeland ecosystems is needed in the form of systems analyses followed by model synthesis that covers the whole field of soil and moisture conservation, primary production, grazing, animal production, herd management, and marketing (Van Keulen and de Wit 1975).

The potential of browse species, particularly legumes, in increasing primary production should be determined as these can provide grazing during dry seasons and may be especially important to associated wildlife.

Research also is needed on range seeding with adapted grass, legume, and browse species. Legumes are perhaps the only practical means of improving the nitrogen status of natural pastures and thus they are particularly important in attempts to improve primary production. And since animal production on arid lands is often limited by protein intake, legumes also may have a great effect on secondary production.

Improved Forage Conservation

Principally, conserved forages provide feed for livestock during periods of low pasture or rangeland productivity, such as winter periods in temperate zones and dry seasons in tropical zones.

One primary research area is the development of harvesting systems in humid areas that minimize digestible energy losses, time and labor, and energy requirements. Digestible energy losses during harvest in temperate humid zones may often reach 40 percent of production, and reduce animal productivity by as much as 50 percent. Most of the high-income countries are in this zone and, while animal productivity is relatively high, prevention of harvest-related losses could increase total productivity substantially and also increase the efficiency of producing animal products. This will become exceedingly important as lower levels of grain feeding become a reality. Indeed, adequate meat and milk supplies may depend on solving this problem.

The potential role of conserved forages in tropical areas (where reasonably long dry seasons prevail) in improving total offtake from animal production systems also needs study. Conservation of forages is not often practiced. Animals thus lose large amounts of weight, decreasing average growth rates and increasing market age. Therefore, research is needed on the economics of conserved forage as it affects reproductive and growth rates.

Genetic Improvement in Grasses and Legumes

Hundreds of species of forage grasses and legumes are important worldwide. Yet the total research effort on genetic improvement is probably less than on rice, wheat, or maize. For some important species, there is no breeding effort. And there is a paucity of genetic information even on those forage species that receive the most effort. Research on rice, wheat, maize, and other field crops has resulted in improved yield and other traits. Similar gains can be expected of forage species if genetic research is undertaken. Given their increasingly important role in animal production, such research should be initiated forthwith.

An important objective of breeding should be increased yield. Recently released alfalfa cultivars yield about 15 percent more than standard varieties released 10 to 20 years ago. Breeders estimate a potential average yield increase of 1.5 percent per year from breeding research, a rate approaching that for breeding maize.

Research is needed to identify the physiological components of biological efficiency, and the limiting factors in the production of herbage by perennial forages. These may be different than those for seed production in cereals. Basic research is needed on the genetics and heritability of these components in forage species and on the development of appropriate breeding technologies to produce superior forage cultivars with higher yield capability.

Dry matter digestibility, protein content, and palatability of herbage are factors in genetic improvement. In Bermuda grass, an increase in digestibility of 10 to 12 percent increased animal productivity by 30 percent (Burton et al. 1967). Thus efforts at increasing digestibility of dry matter should be especially rewarding. Research is required to identify plant characteristics that influence digestibility, intake by animals, and animal performance from forages.

Most tropical grasses are C_4 species with little or no photorespiration and high photosynthetic potential. This, together with associated characteristics, results in high yield potential. Yet most tropical grasses have relatively low dry matter digestibility which decreases more rapidly with maturity than in temperate grasses. Therefore, animal productivity is lower than desired. There is a good possibility that dry matter digestibility and other quality components in tropical grasses can be improved, thereby increasing animal productivity. Such grasses are grown in the summer in the southern United States and the payoff to this country from an increased effort of this type could be great.

Forages grow throughout the growing season, or over several growing seasons, and by management systems much lower in degree of environmental control than for annual cereal crops. This demands a much wider range of environmental adaptability for forage cultivars. Furthermore, photosynthetic tissue is removed by grazing, sometimes frequently, and hence successful cultivars must be able to withstand defoliation and renew growth quite quickly. Research on the relationship of the physiology and genetics of forages to these traits could prove useful.

Research to improve the efficiency of nitrogen fixation in legumes and to develop effective symbiotic relationships between forage grasses and certain microorganisms also should be increased markedly (see Profile 3).

Integration of Livestock Production with Tree Systems

Large areas of the world are cropped in long-term monocultures such as tree crops. For example, about 7 million hectares produce coconuts. There is evidence that ruminant livestock production could be profitably combined with the production of coconut and other tree systems. In Tanzania, for instance, clearing of brush and grazing livestock under coconut palms resulted in a 60 percent increase in coconut production, doubling of milk production, and reduced calf mortality (Childs and Grom 1964).

Expanded research on effectively combining tree crop and forage-livestock production into simultaneous double cropping systems could have a high payoff. Grazing as well as harvested forage systems are possible. Much of the world's tree crop production is in areas where additional animal products would contribute importantly to human nutrition.

IMPACT

The effect of tropical legume development on world food production would perhaps equal or exceed that made by the international centers for rice, wheat, and maize research. Its effect would be felt primarily in the tropics with possible spin-off into some subtropical areas (such as the southeastern United States) in the form of much needed summer-growing legumes.

When improved forage production and management technology are sufficiently developed, the energy and protein produced by forages can equal or exceed that of cereal or oilseed crops and with lower fossil energy subsidies (Reid et al. 1975).

IMPLEMENTATION

An accelerated, comprehensive worldwide research effort that includes and builds on ongoing research should be initiated as soon as possible. Because the United States and other high-income countries will need to use increasingly higher levels of forages in animal diets, they should participate in research in all problem areas. It is important that they develop efficient forage production systems. U.S. scientists should collaborate and maintain liaison with the international centers and the national centers in the developing countries.

The international centers should play a major role in all of these problem areas and especially as they apply to their area of the world. Their personnel would cooperate and maintain liaison with national centers in the developing countries where some of the technology developed can be interchanged to the benefit of all concerned.

Profile 2

OPTIMIZING THE USE OF BY-PRODUCTS, CROP RESIDUES, AND WASTES FOR ANIMAL FEEDING

INTRODUCTION

By-products, crop residues, and wastes constitute a tremendous possible source of animal feed in the United States and in the developing countries. In 1971, the percentage of by-product feeds used in animal rations in the United States were: poultry, 35.6; swine, 14.9; dairy cattle, 10.4; beef cattle on feed, 8.0; and all beef cattle, 4.1 (Bundie 1974). And in 1971, roughly 27.2 million tons of by-product feeds were used in the United States (USDA 1973a). During the 1972-73 feed year, animal industries in the United States consumed the following percentages of feed in all of their rations: grain, 35.6; supplements and by-product feeds, 10.0; and roughages, 54.4 percent (USDA 1973b). Forages, crop residues, by-product feeds, and high protein sources, which are actually by-products of oil extraction, amounted to 64.4 percent of the total feed units consumed by all livestock and poultry in the United States. Of the grain used, 76 percent was corn; the remainder was grain sorghum and other grains. Most of the grain, especially the corn, sorghum, and barley fed to livestock, is not used for human food in the United States. A similar situation exists overseas since 85 percent of the feed grains exported by the United States are being used for animal feeding (Butz 1975).

Table 7 presents the estimated feed units available from offals and roughage in the world (Byerly 1966) and their potential value in animal protein production. This table indicates that if full use were made of the offal (by-products) and roughages available, they would support the production of a tremendous amount of animal protein for human consumption. These feeds are not ordinarily consumed by humans, so animals and humans would not be competing for their feed supply.

Table 7. Offals and roughages for animal feeding

Area	Feed units from offals and roughages* (million tons)	Animal units feedable at 2.45 tons per animal unit (millions)	Daily food protein per capita thus produced from Milk (grams)	Daily food protein per capita thus produced from Meat or eggs (grams)
United States	198	81	75	40
Canada	30	12	33	18
Europe	201	82	103	60
U.S.S.R.	273	111	105	57
Latin America	189	76	54	30
Communist Asia	163	67	15	8
Other Asia	314	128	22	12
Africa	320	130	78	43
Oceania	157	64	600	330

*These are feeds not generally eaten by humans.

Source: Byerly, T.C. (1966) The role of livestock in food production. Journal of Animal Science 25:552.

In the United States and other high-income countries, the trend over the past 30 to 40 years has been toward using higher levels of grain in animal feeding because grains were in abundant supply and were an economical source of energy. The recent domestic scarcity, however, has caused less grain to be used for animal feeding. In the future, as the demand increases for grain, soybeans, and other feeds for direct human consumption, the animal industries will adjust by changing their feeding, management, and production programs (Cunha 1974, 1975a; Council for Agricultural Science and Technology 1975). This can be done by using more feed sources not consumed by humans such as forages, by-product feeds, crop residues, and wastes.

A good example of the role of animals as utilizers of by-products and wastes is found in China. In a review article, G. F. Sprague (1975) states about China:

> It is estimated that 250 to 260 million swine were produced there in 1972. This represents about a fourfold greater swine production than in the United States. Swine are valued almost as much for their manure as for their meat. They are fed on waste materials not suitable for human food such as vegetable refuse, ground and fermented rice hulls, corn husks, sweet potatoe vines, soybean vines, water hyacinths, and so forth.

This is a good example of what a nation can do in raising livestock without competing with humans for the feeds they need. Undoubtedly more of this will be done throughout the world in the future.

Scientists have already fed hens successfully on rations consisting entirely of by-product feeds (Van Horn et al. 1972, Scott 1975). A few dairy rations that contain as little as 5 percent grain are already being used in the United States. They consist largely of by-product feeds because the cattle fed these rations are in areas where higher levels of by-product feeds are available. Beef grading "USDA Good" can and is now being produced on forages without any grain feeding. More pasture and other forages also can be used by the swine industry if it becomes necessary to do so. Therefore, rations that minimize the use of grain for all species can be formulated in animal production (Cunha 1975b).

Basic chemical, biological, mechanical, and enzymatic treatments of roughages and crop residues are needed to improve their digestibility and utilization by animals. Vegetable and fruit crop wastes, cereal grain straws, corn stalks, sugarcane bagasse, aquatic weeds, wood sawdust, and other cellulose wastes are a few examples of materials that can be improved and used as feed sources. Ruminants can even convert sources of cellulose and hemicellulose, such as cardboard boxes, paper sacks, and newspapers, to energy. In 1964, it was estimated that 173 million tons of agricultural cellulosic feedstuffs were available in the United States (Ott 1964). Recently it was estimated that 150 pounds of cellulose waste may be produced daily for each of the world's 4 billion people (Wittwer 1975). But most of this residue cannot be collected economically from millions of hectares of crop and forage lands (Council for Agricultural Science and Technology 1975). It also was estimated that if only 5 percent of the total waste cellulose materials could be collected and processed economically, this would provide enough dietary energy to produce the world's current protein needs through ruminant animals (I.A. Dyer et al. 1974, "Animal Protein for the World's Population," unpublished data, Washington State University). This research on cellulose wastes has tremendous implications for the United States and the rest of the world, especially the developing countries (see Profile 4).

Recycling animal wastes has considerable possibilities for the future (Fontenot and Webb 1974, 1975). The total solid waste from farm animals in the United States is estimated to be approximately 1.6 billion tons (Couch 1972, Fontenot and Webb 1975). The wastes available in all other countries would be quite a sizable figure since the United States has only 8 percent of the world's animals. In the United States, cattle contribute 1.09 billion tons of waste; swine, 380 million; sheep, 64.5 million; and poultry, 30.5 million (broilers, 11.6 million; turkeys, 2.9 million; and layers, 16 million). The remainder comes from other animals. The use of just part of certain animal wastes could substitute for a great deal of concentrate feeds since in 1971 there were only 404.9 million tons of feed units used by all dairy, beef, swine, and poultry in the United States.

There is still a great deal to learn about feeding animal waste to make sure it is always safe to do so. But many foreign countries have been using it as feed for years. Proper safeguards have already been developed for feeding dried poultry manure in the United Kingdom where the practice has been used for several years (Blair and Knight 1973). Research indicates that many animal wastes can be recycled by feeding them to food-producing animals without adversely affecting human and animal health (Fontenot and Webb 1975). Thus enough information is available to warrant more research to determine the specific conditions under which different animal wastes can be used with various classes of animals.

Manure has been characterized by species to make possible a fully integrated cycle using the crude protein of poultry manure to provide supplemental protein for cattle and the high quality microbial protein of cattle manure to support poultry (Ward and Seckler 1975). In their calculations, Ward and Seckler assumed a ratio of 30 laying hens per head of feedlot cattle in the United States. The cattle being fed could provide the supplemental protein for 120 million hens, about 40 percent of the layers in the United States. These hens, in turn, could provide the supplemental crude protein requirements of 4 million feedlot cattle. Therefore, the recycling of manure in animal feeding has tremendous potential if it can be done safely and economically.

RESEARCH NEEDS

A greatly expanded research program is needed to determine the optimum feeding value (and feeding systems) of the by-product feeds shown in Table 8 for various classes of animals. This table provides only a partial list of many products that have possible value as animal feeds. Some of these feeds are being used because some information is already available on them. But even more information is needed to determine if they can be used to better advantage, especially at higher levels in the diet. Very little is known about many of these feeds.

The following information is needed on these by-product feeds (the research needed will vary depending on the feedstuffs involved):

-- the extent to which the by-product can substitute in a ration for grain or protein supplements that might better be used for direct human consumption;
-- which animals can consume the by-products and their optimum feed level at various stages in the life cycle (growth, gestation, and lactation);
-- whether the by-products are safe for use and whether they are free from potentially dangerous residues, contaminants, or harmful substances that would affect animal products;
-- the effect of the by-products on animal productivity and animal product quality (including eating quality).

With animal and human wastes and certain by-products, it will be necessary to measure residues in animal products to make sure there is no problem with

Table 8. Examples of by-product feeds for animal feeding

High protein	High energy	Low energy
Shrimp meal	Broken rice	Tree pods
Feather meal	Rice bran	Tree parts
Poultry by-product meal	Rice polishings	Whole trees
Leather meal	Dried bakery products	Peanut hulls
Blood meal	Distiller's dried grains with solubles	Soybean hulls and bran flakes
Crab meal	Wheat bran	Cottonseed hulls
Fish solubles	Wheat middlings	Sugarcane bagasse
Hydrolyzed hog hair	Citrus molasses	Sugarcane tips
Distillers solubles	Cane molasses	Cassava leaves
Corn gluten feed	Beet molasses	Spent coffee grounds
Citrus seed meal	Wood molasses	Banana stems
Yeasts	Wet brewer's grains	Pineapple wastes
Single-cell protein feeds	Dried brewer's grains	Fruit wastes
Animal and human wastes	Beet pulp	Vegetable wastes
Cheese whey	Citrus pulp	Corn stalk silage
	Homing feed	Wood sawdust
	Cull peas	Newspapers
	Animal fats	Malt sprouts
	Kapok and shea nuts	
	Waste bananas	
	Cassava	

heavy metals, pesticides, pathogens, mycotoxins, and medicinal drug residues.

IMPACT

Presently about 7 to 10 percent of the feeds used in the United States are by-product feeds. This amount might be doubled or tripled if all or some of the by-products listed in Table 9 could be utilized at their optimum rate. Another impetus for the use of such by-products as feeds is that in many cases their disposal otherwise may pose environmental pollution problems.

Proper utilization of all potential by-product feeds could save at least 7 to 20 percent of the feed fed to animals (i.e., if feed unit consumption in the United States is 500 million tons, the full use of by-product feeds could save 35 to 100 million tons of feed). The savings could be added to the available feed supply, or it could release grain and protein feeds for export or human use.

Assuming that by-product feeds would have about a 40 percent replacement value of grain feed (R.R. Oltjen and L.W. Smith 1976, personal communication, USDA), they could free the use of 14 to 40 million tons of grain in the United States. This is in the range of the developing countries' net grain imports which were 37 million tons in 1974-75 (Oyer 1976). The Food and Agriculture Organization (FAO) of the United Nations (1974) estimates that the net grain deficit in the developing countries will be 85 million tons by 1985. Thus the full use of by-product feeds throughout the world could go a long way toward substituting for grain needs in the world.

In the developing countries, the full use of by-product feeds would not save much grain since these countries used only 50.9 million tons of the 422.4 million tons of cereal grains consumed as feed in the world in 1970 (CGIAR, TAC 1976). It would save some feed grains, but the main effect would be increasing the feed supply available for animals, which is very low.

A good research program on by-product feeds could lead to increased animal productivity in the developing countries. This is indicated by the fact that while the developing countries have about 60 percent of the world's animals, they produce only 22 percent of the world's supply of meat, milk, and eggs (Caton 1970). A lack of feed is one of the major factors in this low animal productivity. The optimum utilization of by-product feeds in the developing countries could increase animal production by at least 25 percent and could achieve such production with maximum economy. In

1970, the developing countries produced 250.3 billion pounds of animal products (Caton 1970). A 25 percent increase would amount to an additional 62.6 billion pounds of animal products produced for human consumption.

In the United States, the solid waste produced by farm animals amounts to about 1.6 billion tons (Fontenot and Webb 1975). The amount available in other countries would be many times this tonnage. Blair and Knight (1973) state that the dry matter digestibility of manure is about 60 percent in ruminants but only 10 to 20 percent in the nonruminant, indicating that manure would have its highest feeding value for ruminants. Its low digestibility would limit the use of manure to low levels of 5 to 10 percent in the rations of nonruminants. It is too early to estimate the possible feed savings that might occur from feeding manure to farm animals. More studies are needed to answer the many problems that limit its use, but these problems are not insurmountable.

IMPLEMENTATION

The United States should conduct research with its available by-products and wastes as it has the facilities, scientists, and interdisciplinary groups to study some of the more sophisticated problems involved. This would especially be the case in determining residues in animal products and their possible implications in human and animal health.

Most of the more critically needed work on by-product feeds in the United States could be conducted in a 10- to 15-year period. The research on animal and human wastes, however, might require another five years to complete because of the long-term human health problems that must be investigated. In the developing countries, research will probably require 20 to 25 years due to the lack of facilities, funds, and trained scientists to conduct the studies (except at a slow pace).

The necessary research cannot take place unless the additional funding is supplied for this purpose. Most of the U.S. research can be undertaken by the universities and USDA. The private sector should be encouraged to do more in this line of work. The United States will need to support additional research in this country and also in the developing countries through the U.S. Agency for International Development (AID), USDA, and international centers and national programs.

The developing countries, and other countries too, should conduct studies on the by-products and wastes peculiar to their areas. Moreover, the developing countries would need to conduct studies to adapt some of the U.S. research findings to their conditions.

Profile 3

INCREASING REPRODUCTIVE EFFICIENCY

Reproduction is essential to perpetuate a species and to produce animals that can be used for food and milk production. Large losses in potential animal products are sustained in the high-income countries, and to a greater extent in the developing countries, because, due to many reasons, animals fail to reproduce either for shorter or for longer periods of time. Failure to correct such conditions and to eliminate animals that are not reproducing contributes greatly to the amount of feed needed to maintain these animals as well as to their failure to contribute to food supplies.

In the United States and other high-income countries, an estimated 50 percent of the potential animals in several livestock species are lost because of low reproductive performance, death prior to or soon after birth, and poor management of animals resulting in low reproductive periods over an extended time. Losses in the developing countries are unknown but must surely greatly exceed those in the high-income countries.

RESEARCH NEEDS

1. Develop improved feeding, housing, and management systems for use under hot and other adverse conditions to shorten the period to puberty and production of first viable offspring, as well as to reduce duration of the anestrous (nonreproductive) periods. Level of feeding, which in turn affects growth rate, chiefly regulates when an animal will reach puberty. In some cases, animals may reach puberty but grow so slowly during the period of gestation following breeding that they are incapable of delivering the offspring. Thus the slow growth caused by underfeeding may delay first calving in cattle to an age of three or four years, whereas well-fed cattle in

the high-income countries begin reproducing at two years of age, or younger. Similar delays are frequent in other species of animals as well.

Nutritional problems are intensified, particularly in the lowland tropics, by the effects of high temperatures and humidity which reduce appetite and inhibit grazing. These effects are most severe when breeds from temperate areas are introduced to the tropics, whether directly or through crossbreeding, without suitable modifications in housing, feeding, and management practices. These same factors, which delay puberty and initiation of reproduction, cause further losses through induction of prolonged anestrus.

Despite the demonstration in the high-income countries that the natural intervals between offspring can be greatly reduced, the minimization of this interval is seldom achieved. For example, regular calving at yearly intervals is possible with beef and dairy cattle in the United States and many high-income countries; however, even with the knowledge at hand to accomplish this, the calving interval is often 13 to 15 months. In many developing countries and under restricted feeding conditions (largely because of lower levels of nutrition), cattle frequently calve only every other year. Similar delays are found in the interval between offspring in many other species. Thus research is needed on a wide variety of animals worldwide to reduce the time lost between offspring.

The nutritional aspects of these problems are covered in other sections of this report but development of practical and effective breeding, housing, and management systems is essential to take full advantage of greater nutrient availability in increasing reproductive efficiency.

2. Develop methods of preserving semen under ambient conditions to avoid the need for refrigeration. The development and perfection of artificial insemination techniques have contributed greatly to improving species of cattle, sheep, and poultry in most of the high-income countries. Highly productive breeding stock have been perpetuated by this means, reflecting a greater improvement in animals than could be obtained in the same length of time from natural breeding.

Efforts to transfer artificial insemination technology to the developing countries have been relatively unsuccessful because of failure to adapt technology to the general lack of refrigeration, transportation, communications, and level of education of both farmers and technicians. Inadequate records of production levels to support progeny testing and other methods of selection of outstanding individuals also have reduced the effectiveness of artificial insemination programs.

Methods of preserving bull semen by freezing and storage at extremely low temperatures (using dry ice and liquid nitrogen) now permit storing semen of outstanding bulls for periods of years. Perfecting this kind of technique for other species has lagged, however.

In areas of the developing countries where refrigeration requirements cannot be met, techniques of maintaining fertility at ambient temperatures would improve the chance of using artificial insemination to upgrade livestock. Some progress in the ambient temperature storage of semen was made in the United States and other countries in the late 1950s and early 1960s. These research efforts were largely abandoned with the development of frozen semen storage. It appears possible to chemically control sperm metabolism and survival at ambient temperatures, but more research is needed to reach the point where these techniques would be both satisfactory for the developing countries and include the range of species required. Such technology could be quickly implemented in existing artificial insemination programs in the developing countries. It could result in new programs in areas where suitable improved stock are available but not effectively used. Its greatest effect would be to improve milk production in the humid tropics.

3. Improve techniques to synchronize the estrus of large numbers of females so that they can be bred during a short time period with pregnancy rates equal to or better than those of natural mating. Difficulties of estrus detection and poor communication and transportation facilities have been major deterrents to the use of artificial insemination in the developing countries. It has long been recognized that these problems could be overcome if a method to economically synchronize estrus in large numbers of animals could be developed. Use of this technique would permit the breeding of large numbers of females at one time and thus would use the capabilities of experienced insemination technicians to a much greater advantage. It also would allow regulation of the birth of offspring when feed supplies are ideal and enable concentration of management resources to minimize postnatal losses.

We now can control the onset of estrus by using hormones, but fertility levels have not equaled those obtained in naturally occurring estrus. Recent developments suggest that many of the difficulties involved in fertility levels are being overcome. However, more research is needed to perfect techniques and to develop procedures that are easily adaptable to conditions in the developing countries. Success in this effort would significantly benefit genetic improvement through artificial insemination in the United States as well as in the developing countries.

4. Investigate the causes of prenatal and postnatal death rates in domestic animals and means of reduction. There is no single part of the large domestic food animal life cycle more subject to loss than the reproductive process, from the mating of the parents through the successive stages of fertilization, embryogenesis, development, and parturition to the successful accommodation of the newborn to the hazards of early life. There is attrition to some degree at each step of the process, induced by conditions including disease, season of the year, age of the parents, feeding, and management. The magnitude of losses varies, and as a general estimate not much over 60 percent of the matings result in viable young, and 10 percent of those born die before they reproduce. A high percentage of the viable eggs shed appear to be fertilized, but 25 percent or more of them die as embryos. With the loss of some 50 percent of possible offspring, the magnitude in terms of losses of potential food is enormous (VanDemark 1976).

The above estimates pertain largely to livestock in the high-income countries. Few estimates of the magnitude of the problem in the developing countries are available. Research will be required to determine the fundamental causes of embryo and fetal death before we can increase food production efficiency through reduced prenatal and postnatal mortality.

5. Develop practical methods of detecting pregnancy early in gestation. Delays in achieving efficient reproduction are partly caused by the lack of methods to detect pregnancy in the early stages of gestation. Often much time is lost before it is determined that breeding animals are not reproducing. When the reproductive process is a seasonal one and successful rearing of offspring depends upon seasonal, climatic, and other conditions, the fact that pregnancy has not occurred and is not detected can cause delays of as much as a year in the reproductive process. Thus there is a need for research in early detection of pregnancy so that the time lost can be minimized.

6. Develop technology to permit increased numbers of viable offspring per gestation without sacrificing the future reproductive potential of the female, and develop effective methods of superovulation, embryo transfer, long-term storage of ova, in vitro fertilization, and sex determination to make the widest use of genetically superior females both possible and practical. A number of recent, basic biological findings have suggested that the number of offspring

per breeding unit can be increased by "causing" multiple births. Superovulation and embryo transfer, already proven successful under laboratory conditions, are procedures that may be better developed for field use.

The number of eggs that a single female can be induced to shed can be increased by certain hormone treatments. This procedure, if appropriately regulated, can be used to increase the number of offspring by embryo transfer. In this procedure, fertilized eggs from a superovulated female are recovered and placed in the reproductive tract of a recipient female usually of lesser breeding value. Successes with these techniques have reached the 60 to 80 percent level. The procedure is still too costly to be used widely because of the need to synchronize the estrous cycle in the recipient and the donor, and because surgical techniques are still required to recover the superovulated eggs and transfer them to the recipients. Prospects are promising for the development of nonsurgical techniques. These procedures, combined with determining the sex of the offspring and the possibility of bringing about in vitro fertilization, offer considerable potential for controlling the reproductive processes in domestic animals.

Although some twinning occurs in cattle, twins and triplets are common in sheep, and litter size in swine and rabbits varies with the breed, consistent increases in offspring per gestation have been gained very slowly through genetic improvement. Much research is still needed to get the desired increase in number of young without the production of more embryos than can be carried successfully to term.

Improvements along the lines described above would have immediate application in the United States and other high-income countries. Applicability to the developing countries would be limited to those areas where intensive animal production is well underway.

IMPACT

Much of the improvement of animal production in many parts of the world and especially in the tropical zones will depend upon the effects of improved nutrition and disease control. Improvement in these areas will bring rapid increases in reproductive efficiency. The agronomist, nutritionist, and veterinarian will be responsible for the initial and continuing research, but the reproductive physiologist will be an essential member of the research team.

Research items 1-5 would have an immediate effect on animal production in the high-income countries, including the United States, and should permit an increase of at least 20 to 50 percent in production levels by 2000. The greatest effect will likely be on production in the developing countries. Item 1 is an essential prerequisite to the others and could easily result in doubling present production of animal products in most of the developing countries. Solving the problems outlined in items 2 to 5 will not only make this initial doubling more easily attainable but should pave the way for further significant increases. Item 6 is likely to take much longer to solve and implement but would again open the way for further increases in productivity. When one considers that we should be thinking in terms of increasing the worldwide production of animal products by two- to threefold within the next 25 to 30 years, the need for this research emphasis becomes obvious.

IMPLEMENTATION

The necessary research to solve the problems outlined in items 2 to 6 can best be funded and largely conducted in the United States and other high-income countries. Problems 1, 2, 4, and aspects of 6 also could be studied in the international research centers. Some aspects of these same four problem areas also could be researched in some of the developing countries where the resources are available to do so. To apply technology that evolves in the high-income countries to the developing countries, however, it will be necessary for scientists in the high-income countries to establish linkages with their counterparts in the developing countries.

Profile 4

IMPROVING THE FEED EFFICIENCY AND GENETIC POTENTIAL OF FOOD-PRODUCING ANIMALS

IMPROVING FEED EFFICIENCY

The future diet of the world's ruminants will consist largely of feedstuffs (including forages) and by-products that are not directly usable by humans. This will mean a marked change in diet for many animal species in the high-income countries but essentially no change for most species in the developing countries, including monogastric animals, since little grain is used for animal feeding in those countries. In much of the world the answer to improved nutrition may simply be a reduction of the animal population so that the remaining animals can be supplied with enough nutrients to be more productive. In other areas, it will be a matter of upgrading the present diet.

Most of the feed eaten by domestic animals is used to maintain their bodies; only after this requirement is exceeded can they produce meat, milk, eggs, and wool. The problem becomes more acute as diets become less digestible as would be the case with feeding noncompetitive diets (diets not consumed by humans such as cellulose wastes, nonprotein nitrogen [NPN], by-products, and the like). For example, it has been demonstrated that cattle gain 1.3 kilograms (kg) daily when fed a cereal diet (80 percent total digestible nutrients [TDN]) and 1.1 kgs daily when fed a forage diet (60 percent TDN) of pelleted alfalfa hay (Oltjen et al. 1971). Feed intakes were 2.2 percent and 3.2 percent of body weight, respectively. Cattle fed only cottonseed hulls (42 percent TDN) plus NPN, minerals, and vitamins can gain .5 kgs daily but require cottonseed hull consumption equal to 3.3 percent of body weight to obtain this rate of gain. Therefore, as digestibility declines ruminants must consume more feed to be productive. Rate of fermentation and removal from the rumen are important in the response.

Currently there are feed additives that hold promise for appetite stimulation.

Cellulose is the most abundant organic material on earth. The ruminant is uniquely equipped to derive energy from cellulose but lignin encrustation, resins, silica, and so forth, limit its usefulness. The problem becomes more severe as the lignin content increases. Also, it has been demonstrated (Weston and Hogan 1973) that cobalt deficiency as well as nonnutrient materials such as tannins, isoflavones, and alkaloids may impair metabolic processes and feed intake (Bradin and McDonald 1970). Therefore, endogenous forages and other feedstuffs should be analyzed for components that could impair animal performance. This would include feed toxicology, especially the mycotoxins generated by fungus infections of stored feeds.

Cellulose wastes, including crop residues, are poor sources of most nutrients and must be carefully supplemented to obtain good performance. They are the most deficient in protein, minerals, and vitamins (usually in this order) which should be added to diets containing these wastes. Protein deficiency causes a depression in feed intake; therefore, it is important to supply a deficient diet with protein or nonprotein nitrogen.

Ruminants are uniquely equipped to use NPN as a protein substitute. A recent report (NRC 1976a) summarizes the "state of the art" on the use of urea and other NPN compounds in ruminant diets. Urea is the most economical and widely used NPN source in the world. It is most efficiently used in diets rich in soluble carbohydrates but is poorly utilized in forage diets. Presently there is enough knowledge available to make recommendations on the safe use of NPN compounds in ruminant diets that contain moderate quantities of readily available carbohydrates. Proper management is the key to successful use with these diets. Some NPN sources contain phosphorus and sulfur as well as nitrogen which may be of added value with certain diets.

Due to the anaerobic nature of the rumen (the first of four stomachs of a ruminant), there is a limit to the quantity of microbial protein that can be synthesized from the ammonia released from NPN sources in the rumen. To achieve optimum ruminant performance, protein is needed in the diet, preferably protein that escapes ruminal fermentation and is digested in the lower digestive tract. Some proteins are by nature partially resistant to ruminal degradation (fishmeal) while others are not but can be made so by chemical treatment (Peter et al. 1971). The advantage of this technique is that the ruminant can be fed diets that are largely noncompetitive with feeds consumed by monogastric animals or humans. These diets will be digested and transformed into useful nutrients in the rumen, while other vital nutrients are protected to escape rumen fermentation. These other nutrients are then digested and absorbed in the lower digestive tract resulting in improved host animal performance.

The nutrient requirements of food-producing animals in the high-income countries under controlled environments are fairly well known, while those under different environments, nutritional stresses, and disease vectors are not. The requirements of goats, buffalo, and other animals are not well defined. In some African and Middle Eastern countries, goats contribute a large portion of the meat and milk supplies (Scrimshaw et al. 1975). There are approximately 150 million domestic water buffalo in the world, which constitute a major source of farm power, milk, and meat. Little has been done to increase their productivity through feeding, management, and use of superior germ plasm (FAO 1976).

Wild animals offer a potential source of protein that has not been actively explored (Novakowski and Solman 1975). Wild animals are efficient users of native vegetation and they also can adapt to human-modified habitats.

Research Needs

In many developing countries, swine and poultry are fed by-products or scavenge on their own. High quality forage and by-products should replace competitive feedstuffs in these countries when the nutrient requirements of these animals are low, as during gestation.

A nutritive evaluation (chemical and animal) of major feedstuffs in the developing countries is needed before animal diets can be properly supplemented. This effort is underway but should be intensified until all feedstuffs are evaluated. Research also is needed to determine the nutritional requirements of food animals under different environments, nutritional stresses, and disease vectors. This would be very helpful in the developing countries.

NPN use in ruminant diets was estimated at 800,000 tons in the United States in 1973 (G. Allen 1974, personal communication, Economic Research Service, USDA). This spared 4.5 million tons of 50 percent protein supplements for monogastric or human use. Although NPN use in the developing countries has increased, its use can be further extended because 60 percent of the world's food-producing animals are in these countries. The challenge is to conduct research to make NPN more effective and safe for use in low quality diets.

An intensive global effort to find an economical method of separating cellulose from lignin would enable enormous quantities of cellulose to become available for animal feeding. This is a very difficult problem but such a method, if successful, will yield enormous benefits since trees, crop residues, and cellulose wastes can be fed to ruminants. Presently, chemical treatment increases cellulose digestibility by only 10 to 15 percent, and the treatment methods are expensive and time-consuming. Breeding plants for increased availability of cellulose also offers promise.

Protein "bypass" of rumen fermentation is a new technique that has been shown to improve sheep growth by .05 kgs daily. This technique has not always been successful but the concept holds great promise in improving the performance of ruminants fed noncompetitive diets. When properly applied, it will increase the utilization of supplemental dietary protein in the ruminant by 20 percent. Lipids, selected amino acids, vitamins, and other vital nutrients also may be bypassed to improve animal performance.

The inclusion of an "appetite stimulator" into the diets of cattle fed a low quality hay diet increased feed intake by 7 percent and gains by .1 kg daily (Dinius and Baille 1976). Similar additives are available and a .05 to .1 kg increase in daily gain seems reasonable. Feed additives, such as monensin, stimulate rumen fermentation, resulting in a 10 percent improvement in feed efficiency of cattle fed concentrate diets. Research is needed to assess the value of monensin in forage diets. Other additives decrease dietary protein degradation in the rumen.

Current growth promotants such as DES antibiotics increase ruminant performance by 10 to 15 percent. New ones are needed in the future for all types of livestock.

Impact

Increasing the availability of cellulose will have a global payoff, especially for the developing countries where it could improve ruminant product output 25 percent. A major source of nutrients for ruminants with diets lacking in energy should result. Furthermore, competitive feedstuffs could be spared. Research will require 20 years to develop techniques and 5 to 10 years to apply them at the farm level.

Determining the nutritive value of endogenous feedstuffs and the nutrient requirements of endogenous livestock, and supplementing the present diets of all farm animals will have an immediate payoff, probably a 20 percent improvement in animal performance. Protein "bypass" will require 5 to 10 years more research in the United States, and then it will have immediate application. This technique will work well with NPN in low quality diets. NPN's usefulness will increase in the developing countries, especially when it is fed with molasses. We already know quite a bit about NPN use in moderate quality diets, but new research findings making NPN compatible and safe for use in low quality diets will further increase production.

Discovering new additives to stimulate appetite and to promote growth and a metabolite related to superior animals and adaptation ability will require 10 to 20 years. It will take at least 5 to 10 more years to apply these discoveries. Successful application should increase meat production 15 percent.

IMPROVING GENETIC CAPACITY

Lower levels of animal production are due largely to nutrition, diseases, and management. Genetically inferior animals also cause lower levels of animal production. The performance of farm animals could be greatly improved by detecting and developing genetically superior animals for given purposes and environments. These animals should be used as seed stock for herds and inferior animals slaughtered.

Research Needs

The results from a recent symposium (NRC 1975) indicate that although the potential for isolating and exploiting genetically important nutritional traits is not great, there are differences due to breed variation. Wilham (1976) reported that "the heritability of fat deposition in red-meat domestic animals is high and related to rate of maturity in the young animal destined for slaughter." The British breeds of beef cattle are bred for meat and fat production, and their performance is judged on predominantly concentrate diets. Trends in the United States and in other countries indicate that in the future ruminants will be fed predominantly forage and by-product diets. Therefore, research emphasis should be placed on breeding "meat-type" ruminants using endogenous animals as much as possible. Furthermore, the performance of ruminants should be tested when they are fed predominantly forage diets and diets containing NPN since there seems to be more variation in growth between animals fed diets high in NPN than between animals fed diets supplemented with protein (Oltjen 1969).

Tremendous progress toward increasing the productivity of beef cattle in the high-income countries has been made by the systematic use of crossbreeding. Crossbreeding Zebu with Criollo cattle increased pregnancy rates and carcass weights 16 percent each (Bauer 1968). Also, Zebu-type cattle have higher feed intakes on low quality diets and at higher environmental temperatures than do the British breeds of cattle. This and other observations led Warwick and Cobb (1975) to conclude that "genetic differences in voluntary feed intake are of a magnitude that makes selection rather effective." The success of this program, however, has not been fully exploited in the developing countries where planned systematic crossbreeding and selection programs are needed to upgrade herds. The dairy industry in the United States doubled milk output/cow/year during the past 25 years (NRC 1976b). Roughly one-third of this increase can be attributed to genetic improvement and the remainder to nutrition and management, an example of what could be done in the developing countries.

Many breeds of livestock are now in danger of being supplanted by the comparatively few, highly bred animals of modern agriculture (Collins 1975). A priceless and irreplaceable reservoir of genetic raw material is therefore threatened. With the need for new approaches to agriculture, everything should be done to ensure genetic heritage.

Presently several sets of progeny as well as subjective criteria are used for the early detection of superior performance of food-producing animals. Usually it takes several years to determine the "meat potential" of large animals. A rapid biochemical assay that is highly correlated with superior performance is needed. Also, it would be desirable to develop a laboratory assay for the components of adaptation to new environments.

The discovery of one metabolite in an animal's body that correlates with protein production and another that correlates with the ability of an animal to adapt to new environments could drastically reduce the cost and time involved in progeny testing. Also, livestock could be moved from the temperate to tropic environments and vice versa with the assurance that they will adapt and be productive. Research toward these ends should receive intensive effort.

Impact

Selection to develop highly productive animals under developing country environments should result in a 500 to 1,000 kg/cow/year increase in milk production in 25 years. Meat production in the developing countries should increase by 25 percent for each animal slaughtered after 25 years of careful selection. Current knowledge is sufficient to initiate this plan, but nutrition, management, and disease control also will have to improve. Payoff would be greatest in the developing countries. Selection for production on noncompetitive diets--from which the United States will have an equal benefit--will require more time. Saving the genetic potential of "endangered species" of food-producing animals will insure the genetic base. It is impossible to quantify the value of saving this genetic base.

Implementation

The research effort described in this two-part profile should be dispersed depending on the complexity of the research and its best location.

The United States should conduct most of the basic research on: (1) detecting a biochemical metabolite that is highly correlated to meat production potential and adaptation to environment, (2) increasing the availability of cellulose in cellulose wastes, (3) achieving rumen bypass of protein, and (4) determining the nutrient requirements of most food-producing animals. Animal species not endogenous to the United States could be imported and studied here. Research in this area could be conducted equally well at universities, by USDA, or by the private sector.

International livestock centers in the developing countries should conduct research on selection for developing highly productive animals fed noncompetitive diets because of the need to use endogenous animals, and native feedstuffs and environmental conditions. This effort would include research on genetic capacity, crossbreeding, and breeding for animal product production. The United States also should have an active program in this area. A network of centers in the developing countries could be responsible for maintaining genetic diversity of selected farm livestock.

Selected research centers in the developing countries should be responsible for chemical and nutritional evaluation of their endogenous feedstuffs. Possibly certain feedstuffs could be sent to the United States for additional analysis. Nutrient requirements of water buffalo, goats, monogastric animals, and game animals also should be determined at these centers and rumen microbiology studies should be conducted in these centers as well as others.

Much of the study on management and proper balancing of diets for farm animals could be undertaken at research centers in each developing country, and the results disseminated to farmers. The training of extension workers also should be handled at these locations. These centers will make the most progress in animal husbandry and in getting the information out to the people who will actually use it.

The germ plasm of many diminishing breeds of livestock should be conserved in international centers. The best system should be quickly determined and placed into practice.

Report of Subgroup A, Study Team 2

ANIMAL HEALTH

INTRODUCTION

The diseases that afflict agriculturally important animals are the major impediments to increased food production in both the high-income and developing countries. Not only do diseases cause the loss of animal protein and other important nutrients needed in human diets, but they reduce crop production by their effects on draft animals. Certain epidemic diseases inhibit or prevent the development of modern livestock industries while others seriously restrain world trade. Many animal diseases also adversely affect human health and productivity.

This report provides an overview of the world livestock disease situation and indicates as fully as current data permit the effect of animal diseases on world food production and human health. We will identify areas in which research is most needed, indicate major institutional and resource requirements for research to achieve effective control of livestock diseases, and define a U.S. role in these activities.

Epidemic Infectious Animal Diseases

In various parts of the world there are highly contagious and economically disruptive infectious animal diseases such as rinderpest, contagious bovine pleuropneumonia, and African trypanosomiasis. These diseases not only cause deaths and losses of productivity, but also stifle the development of modern livestock industries (see Table 9). Livestock producers do not make the investments needed to increase productivity if they are continually confronted with the possibility of a disastrous outbreak of animal disease. Unless economic control procedures are implemented where these diseases exist, it makes little or no sense to attempt to institute modern principles of livestock production. Whatever progress is made is cancelled by the next disease

Table 9. Major disruptive epidemic infectious animal diseases

Disease	Cause	Status of control technology
Rinderpest	Virus	Effective vaccine available
Food-and-mouth disease	Virus	Vaccine needs improvement
African swine fever	Virus	Need a vaccine
African horse sickness	Virus	Effective vaccine available
Newcastle disease	Virus	Effective vaccine available
Fowl plague	Virus	Effective vaccine available
Hog cholera (swine fever)	Virus	Effective vaccine available
Contagious bovine pleuropneumonia	Mycoplasma	Vaccine and diagnostic tests need improvement
African trypanosomiasis	Protozoa	Vector control—need new control procedures
Theilerioses	Protozoa	Vector control—need new control procedures
Babesioses	Protozoa	Vector control—need new control procedures
Coccidiosis	Protozoa	Effective control techniques exist
Pullorum disease	Bacterium	Effective control techniques exist

epidemic. Because draft animals provide so much of the agricultural power in the developing countries, control of these diseases also has important implications for crop production.

Epidemic animal diseases have caused tremendous economic losses throughout history because of their ability to decimate large populations of animals (see Appendix). For example, between 1710 and 1769 rinderpest alone killed an estimated 200 million head of cattle in Europe and seriously threatened the economic stability of several countries. In the 1890s and early 1900s, it destroyed most of the cattle and buffalo and many of the wild ruminants in Africa. During World War II, another great rinderpest epidemic in Burma killed over a million cattle and buffalo, many of them draft animals, resulting in an indirect animal loss of 3 million tons of badly needed rice before control was effected. Although effective means for its eradication exist, rinderpest still occurs over extensive areas and thus poses a continuing threat to cattle and buffalo throughout the world.

Hemoprotozoan diseases severely limit cattle production in tropical areas. Approximately 700 million hectares of land in central Africa, estimated to be capable of supporting 125 million cattle, have at present a cattle population of only 7.5 million because of African trypanosomiasis. In eastern Africa, East Coast fever limits efficient cattle production. The livestock industries in much of tropical South America are severely constrained by piroplasmosis and anaplasmosis. Streptothricosis, a disease for which there is not yet an effective means of control, is an equally important epidemic disease of cattle in West Africa.

African horse sickness has periodically destroyed large equine populations in Africa, killing 70,000 horses in Rhodesia in one year alone. In 1959-1960, this viral infection spread into southwest Asia killing 300,000 horses and donkeys, thus indirectly causing large crop losses over a broad geographic area. African swine fever, another infection previously confined to Africa, reached Portugal in 1957 and Spain in 1959 and by 1974 had cost Spain $600 million in direct losses. This highly fatal disease, for which effective control is unavailable, occurred recently in Cuba, France, and Italy and was eradicated only after approximately 10 percent of the swine populations of these countries died or were destroyed. Foot-and-mouth disease, which affects all the major livestock-producing countries of the world except New Zealand, Australia, and North America, is the major barrier to international commerce in animals and meat.

A still larger group of infectious animal diseases (Table 10) are those that reduce productivity and result in a significant wastage of animal protein and economic losses, but do not usually prevent the development of viable livestock industries. Their effects may be (but usually are not) as obvious or dramatic as with the major epidemic diseases (see Table 9). Brucellosis, tuberculosis, leptospirosis, and several other important diseases of this class are estimated to affect 10 to 20 percent of the world's cattle. Bat-transmitted rabies alone is estimated to kill 100,000 to 250,000 head of cattle annually in Central and South America. Pasteurellosis kills more than 1 million cattle and buffalo per year in Asia, many of them draft animals. Sheep and goat populations are often afflicted with pox viruses which greatly reduce their overall productivity. Mycoplasma infections of goats also reduce meat and milk production in a species upon which rural people in much of the world depend so heavily. Reliable estimates of how frequently some of these diseases occur is lacking for many developing countries, but existing epidemiological data show that they have depressing effects on productivity of livestock in many of these countries.

Endemic Animal Diseases

Another large group of more insidious diseases, known as endemic animal diseases, markedly increase the cost of production. Often of complex infectious, toxic, genetic, metabolic, and nutritional etiologies, sometimes in combination, they afflict agriculturally important animals throughout the world. This group includes important multicausal infectious complexes such as mastitis, neonatal diseases, multiple gastrointestinal, and other parasitisms and conditions that reduce reproductive efficiency. Similar problems include bovine respiratory disease complex, transport tetany, and other stress-related syndromes; metabolic imbalances such as ketosis and grass tetany; bloat and other widespread problems related to the dysfunction of particular organ systems; frank nutritional disorders and much more common marginal malnutrition-infectious complexes provoked by deficiencies in minerals and other essential nutrients; and often obscure toxicoses due to industrial and other mineral poisons, poisonous plants, and mycotoxins. Infestations with ticks, lice, and biting insects are themselves other important contributors to livestock inefficiency and the medical importance of many of them is enhanced by their serving as vectors of other diseases.

Table 10. Examples of epidemic infectious animal diseases

Disease	Cause	Status of control technology
	Cattle and buffalo	
Anaplasmosis	Protozoan	Vaccine needed
Brucellosis	Bacterium	Effective vaccine available
Leptospirosis	Bacterium	Improved vaccine and chemotherapy needed
Pasteurellosis	Bacterium	Effective vaccine available; need improved diagnostic tests
Bovine viral diarrhea	Virus	Need improved diagnostic tests and vaccination procedures
Rabies (bat-transmitted)	Virus	Effective vaccine and bat control available
Streptothricosis	Fungus	Present control inadequate
Tuberculosis	Bacterium	Effective vaccine available for buffalo
Vibriosis	Bacterium	Effective vaccine available; need improved diagnostic test
	Equines	
Equine infectious anemia	Virus	Vaccine needed
Equine encephalomyelitis	Virus	Effective vaccine available
	Sheep and goats	
Bluetongue	Virus	Vaccine available
Contagious caprine pleuropneumonia	Mycoplasma	Improved vaccine needed
Pox	Virus	Improved vaccine needed
	Swine	
Transmissible gastroenteritis	Virus	Vaccine needed
Swine vesicular disease	Virus	Need studies on epidemiology and economics
	Poultry	
Infectious bronchitis	Virus	Effective vaccine available
Marek's disease	Virus	Effective vaccine available

Some endemic diseases are capable of killing large numbers of animals. However, they produce their greatest effects by reducing the productivity of livestock. As a group they tend to be more complex epidemiologically than most of the epidemic infectious animal diseases, that is, they generally result from multiple and sometimes obscure etiologies, with direct causal factors highly interrelated with livestock production and other farm management practices, as well as with environmental and other less direct determinants of their frequencies. In the high-income countries, endemic diseases are responsible for the majority of the animal disease losses, which have been estimated by international and national agencies as approximately 15 to 20 percent of the productive potential of livestock industries in those countries. They constitute similar but even less obvious problems in the developing countries, but will become relatively more important there as livestock development proceeds. Effective control methods for many diseases of this type are lacking.

Zoonoses

Many animal infections also afflict people, resulting in illness, debility, or death. Collectively these infections are called zoonoses and constitute 80 percent of all infections to which humans are susceptible. Throughout history zoonoses such as plague and rabies have been some of the most feared scourges affecting people. Today, human infections with brucellosis, salmonellosis, tuberculosis, rabies, trichinosis, hydatid disease, and at least 200 other zoonotic infections (see Table 11) are public health concerns everywhere, but especially among rural people in the developing countries. There the prevalence rates of many of the zoonoses are high in animals, and people and animals frequently live in close association. New instances of such important zoonotic relationships are revealed yearly. For example, recent knowledge that completely new human influenza strains may arise from hybridization of existing human and animal strains has altered many once-held beliefs about that disease. Controlling many of the zoonoses in animals is the only effective way to protect people from them. Two points about these zoonotic infections are particularly relevant to this study. The first concerns the magnitude of expected direct and indirect human health benefits from their study and control in livestock. To consider only the single example of tuberculosis, the direct effect of controlling bovine disease in many countries has been the complete

Table 11. Some livestock diseases transmissible to humans

Infection
Actinomycosis
Anthrax
Aspergillosis
Brucellosis
Coenurosis
Colibacillosis
Contagious ecthyma
Cowpox
Crimean hemorrhagic fever
Eastern equine encephalomyelitis
Erysipeloid
European tick fever
Fascioliasis
Fasciolopsiasis
Gastrodiscoidiasis
Glanders
Hydatid disease
Influenza, parainfluenza
Japanese B encephalitis
Leptospirosis
Listeriosis
Louping ill
Middleburg fever
Newcastle disease
Pasteurellosis
Piroplasmosis
Psittacosis-ornithosis
Q Fever
Rabies
Rhinosporidiosis
Rift Valley fever
Ringworm
St. Louis encephalitis
Salmonellosis
Schistosomiasis
Sporotrichosis
Streptococcosis
Streptothricosis
Taeniasis, cysticercosis
Tetanus
Trichinosis
Trichostrongylosis
Trypanosomiasis
Tuberculosis
Venezuelan equine encephalomyelitis
Vesicular stomatitis
Vibriosis
Viral encephalitis
Wesselbron fever
Western equine encephalomyelitis

Source: Schwabe, C.W. (1969) Veterinary Medicine and Human Health. Baltimore: Williams and Wilkins.

elimination of the crippling extrapulmonary forms of tuberculosis in humans and a reduction of about 10 percent in formerly existing levels of human pulmonary infections. In 1900, tuberculosis was the principal cause of human deaths in the United States at a rate of 190 per 100,000 persons.

The second point is that instances of livestock transmitting new zoonoses to humans or of other roles for livestock in the zoonoses are constantly forthcoming. The possibilities of this happening are heightened whenever we exploit new ecosystems or introduce animals into new environments. For example, the babesioses were not known to affect people until 1957 when the first malaria-like human babesial infection was diagnosed in a cattle farmer in Yugoslavia. There have been many similar diagnoses since. Seven human cases were found on Nantucket Island, Massachusetts, between 1969 and 1975.

RESEARCH NEEDS

Epidemic Infectious Animal Diseases

The highest priority for animal disease control worldwide is the elimination of the major disruptive epidemic infectious animal diseases that constrain food production. The main research needs are biological (i.e., the development of new and improved vaccines, improvement of diagnostic tests, better means of controlling vectors) rather than methodological. With relatively minor additions and modifications, the basic methodological approaches to epidemic disease control used in the high-income countries during the past century are adequate for today's needs in the developing countries. In many poorer developing countries, however, local economic and social conditions must be taken into account where these approaches are to be applied.

Serious problems exist with several of the epidemic infectious animal diseases. For example, developing technology to control African trypanosomiasis appears to be a formidable task. However, considering the states of veterinary knowledge now and then, these diseases appear no more difficult than the problems faced in the United States in the last century with the control of Texas fever, a disease then nearly as important to cattle production in the southern and southwestern United States as African trypanosomiasis is to African cattle production. It is significant that success in the control of Texas fever resulted from a major technological breakthrough, that is, the discovery that by eliminating the arthropod vector, which is capable of transmitting a pathogenic microorganism, the disease could be eradicated. This principle has been used since in controlling some of the most important epidemic diseases of both humans and animals.

Important biological research needs for the control of the major epidemic diseases include:

- -- African trypanosomiasis: (1) effective immunizing agents; (2) improved means of vector control; (3) cheap, long-lasting prophylactic chemicals; (4) a better understanding of the epidemiology of this disease under differing local conditions; and (5) a better understanding of host resistance and tolerance.
- -- Other hemoprotozoan diseases (the theilerioses, the babesioses, and anaplasmosis): effective immunizing agents, as well as cheap, long-lasting chemotherapeutic and prophylactic agents.
- -- Foot-and-mouth disease: improved, longer-lasting vaccines.
- -- African swine fever: an effective immunizing procedure (swine all over the world are threatened by this devastating disease for which no effective means of control now exists).
- -- Contagious bovine pleuropneumonia: improved diagnostic tests and immunizing agents.

Other research needs for the control of these diseases are indicated in Table 9 and in the Appendix.

Research on livestock production systems for areas where they cannot now exist because of trypanosomiasis should receive very high priority. This research will require a multidisciplinary effort by agriculturalists, economists, and anthropologists, as well as animal production and health scientists.

Research also is necessary to control many of the lesser animal infections, particularly under differing local circumstances. Needs vary from disease to disease depending upon what we now know. But research needs most often include the development of (1) sensitive and specific diagnostic tests for epidemiological surveillance; (2) effective, economical immunizing agents; (3) effective, economical means of controlling vectors; and (4) cheap, effective chemicals for mass treatment, thereby reducing the level of infections. (See Table 10 and the Appendix.)

Endemic Animal Diseases

Methodological and biological research is needed for the control of endemic diseases. The veterinary and biological research establishment is well equipped generally to conduct the biological research. The methodological research, on the other hand, will be more difficult as it will require new ways of looking at diseases and their causes and control, as well as new analytical techniques and competencies. This latter will involve training a new generation of investigators and practitioners.

Much is known about some of the important endemic animal diseases and surprisingly little about others. Reliable means of control are available for a few, while prevention and control procedures are disturbingly inadequate for most of the others. For example, despite all that has been learned about calf diarrhea since the classical studies of over a half century ago, it continues to be one of the most important causes of neonatal losses in cattle in both the high-income and developing countries. Neonatal losses of up to 40 percent may occur even on intensively managed dairy farms in California. Similarly, we have learned a great deal about mastitis through research during the past 50 years, yet it is still estimated to cost the world over $1 billion annually. Essentially the same situation applies to shipping fever, mixed parasite infections, and many other insidious disease complexes.

Controlling these insidious diseases is more difficult than controlling epidemic diseases because of their etiological complexities. Determinants of these diseases may include such diverse things as husbandry practices on the farm, specific viruses, climatic factors, genetic predispositions, nutritional factors, the immunological state of the animal, and/or various environmental conditions in any combination.

We must develop a better understanding of the causative factors of disease and of disease and management interactions. Powerful methods are available from other disciplines, such as sociology, economics, and genetics, to sort out the causal relationships of the various biological and epidemiological factors contributing to the occurrence of endemic disease. A few investigators are beginning to use multivariant analytical techniques, such as step-wise regression, step-wise discriminant, and factor analysis, in an attempt to understand how the factors that cause neonatal diseases might function. This approach has great potential even though it does not fully interpret possible causal relationships.

More recently a modification of regression methods called path analysis (an approach developed by a population geneticist 50 years ago and more recently employed by sociologists) has been adapted to epidemiological use. It allows an intuitively appealing approach to interpretation of relationships in linear causal models of complex disease situations. This technique permits the investigator to use biological knowledge of the system being studied in the construction of models that help interpret causal relationships. The usefulness of this technique for the study of insidious disease complexes needs to be more fully explored.

These methodological breakthroughs can probably best be realized in the context of concentrated attacks on two or three very important disease complexes of this endemic type. The training of personnel for such research also will be furthered by such an approach. The direct implications of such efforts would be greater initially for the high-income rather than for the developing countries. To optimally use scarce personnel and other support elements and the available data, these initial attacks should be mounted in the United States. The neonatal loss problem in cattle and gastrointestinal helminthic parasitism in sheep would be excellent subjects for such combined research and training efforts. Both are serious problems globally. They represent different basic types of endemic disease problems and are probably two of the problem areas in which the most relevant work has already been done. An optimal approach to either problem would initially require teams of "conventional" specialists who would be able to "synthesize" new epidemiologists with the spectrum of specialized competencies in the several areas indicated.

Another problem in dealing with these disease complexes is that we have tended to focus many veterinary efforts on the individual animal and its medical problems, when we should focus on the health of the entire enterprise from the standpoint of economics and productivity. The health of the individual animal is not significant other than as it relates to the productivity of the entire enterprise. The occurrence of these insidious diseases and the resulting losses in a livestock enterprise are the combined effect of certain direct determinants such as specific disease agents (e.g., toxins, parasites, etc.), environmental factors, and the specific production and management practices employed in the enterprise. It is no longer tenable to contend that E. coli or a Reo virus is the cause of neonatal calf diarrhea when, in the presence of "good management," neither may cause a high frequency of fatal neonatal diarrhea in calves. The problem is one of identifying the specific management determinants of calf diarrhea in particular livestock units. It no longer makes sense, therefore, if it ever did, to separate disease prevention and husbandry practices at the enterprise level.

Veterinarians and other animal scientists should combine their talents and develop integrated management systems that take disease prevention into account as a central feature of production. This principle is of equal if not greater importance in small farming systems found in many developing countries as it is with the more advanced farming systems of the high-income countries.

Resistance of Animals to Infections

The most practical way of controlling many animal infections has been to increase the animals' resistance through immunization instead of relying upon therapeutic procedures following infection. Although progress has been made in applying immunological principles to the control of epidemic animal infections, it appears from the present state of knowledge in molecular biology and immunology that the potential for developing host resistance is still greater than generally appreciated. We strongly recommend that immunology research to develop systems for increasing the resistance of food-producing animals to infections receive high priority for research support.

Genetic Resistance to Infections

A closely related area that requires major research emphasis is the genetic resistance of various livestock species to disease in general, as well as to specific diseases. The potential for using genetic resistance to certain parasitic infections is one of the most promising possibilities for reducing losses from parasitism. Genetic factors play important roles in susceptibility and resistance to many important animal diseases, yet too little effort has been devoted to this potentially valuable approach to animal health. Recent progress in immunology and immunogenetics and related technologies suggests that genetic markers associated with disease resistance exist in animals. There are histocompatability-disease resistance relationships that could make the study of the genetic resistance of agriculturally important animals to diseases practicable.

The Use of Biological and Chemical Agents for Animal Disease

Research is needed on the development of effective, economical chemotherapeutic agents for the control of animal infections. Currently the same antibiotics and many other chemotherapeutic agents are used for food-producing animals and for people. As a result, there is a growing international concern about the drug residues found in the animal products we consume and the possibility that we could develop drug resistance from the use of these products. There is need to develop specific chemotherapeutic agents for exclusive use in animals. There is also a need for improved chemicals to control animal parasites, particularly chemicals that are longer lasting, easier, and more economical to use. Improvements are needed in the means of administering these drugs to animals maintained under various husbandry practices.

Research Programs on the Economic Effect of Animal Diseases

Research programs on the economic effect of animal diseases are vitally needed for policy decisions on alternative disease control strategies and to assist in the development of priorities for allocating resources. Currently we have insufficient data on the economic effect of diseases and disease control procedures.

Social and Cultural Aspects of Animal Production

In many livestock-dependent societies, especially in the developing countries, the sociological and economic factors relating to livestock production and marketing need study. There are many examples of protein-deficient populations living concurrently with an overpopulation of livestock. Animals fulfill a variety of customary and religious functions, and they are often the measure of wealth. Frequently they are retained after they are no longer productive and disposed of only when at the point of death from old age or disease. Consequently, there is overgrazing and overbrowsing, resulting in a deterioration of land that could be used productively. Use of disease control under these conditions may not be desirable.

There is also need for anthropological and sociological studies to determine how customs may be appropriately modified. Until emphasis is placed on the sociological deterrent to efficient livestock production, it will not be possible to obtain the maximum effect from disease control.

IMPACT

Development of the Livestock Sector

A number of infectious diseases are capable of taking a catastrophic toll on animal populations. The direct losses through death and reduced productivity can inhibit or prevent the development of productive livestock industries wherever these diseases exist and cannot be economically controlled. Modern livestock industries have never developed anywhere in the world until such major epidemic diseases have been eliminated or significantly reduced. These diseases preclude all efforts to develop or expand livestock production through improvements in breeding, nutrition, and other available management practices.

The major epidemic animal diseases also pose a potential and constant threat to livestock in both the high-income and developing countries where they do not now occur. As long as highly infectious epidemic diseases exist anywhere in the world, livestock in countries where they do not presently occur are at perennial risk. The recent invasion of California by Asian Newcastle disease and of the Iberian peninsula by African swine fever are cases in point.

The situation in regard to foot-and-mouth disease (FMD) is somewhat different. Its direct and indirect effects are highly disruptive and costly where control measures are not implemented. Productivity is lost and high producing stock are permanently damaged. Death losses are not high in adult cattle; consequently, livestock industries can develop where FMD occurs provided vaccination is practiced. Repeated vaccination during the entire life of all susceptible domestic animal species and the restriction of trade in meat and animal products in countries in which FMD occurs are costly features of this disease.

Effect of Zoonoses on Human Health and Productivity

Rural and farming populations worldwide particularly risk acquiring zoonotic infections--animal infections that under some conditions can affect humans. While some of these zoonoses are transmitted to humans only through contact with animals and their excretions, many also may be transmitted to a broader, more remote consuming public through meat, milk, and other animal products. New problems in the spread of zoonoses may arise from recent proposals for the use of animal wastes and other by-products of animal production. Protecting humans from the majority of zoonotic infections are more veterinary than human medical problems.

Effects of Animal Diseases on World Trade

Many livestock diseases also inhibit world trade in animals and animal products. Foot-and-mouth disease, which occurs widely in the developing countries, has been excluded from several countries at great effort and expense. In addition to the ongoing costs of inspection and quarantine and other means of excluding the disease, costs also are incurred when an outbreak occurs. A 1967-68 outbreak of FMD was successfully extinguished in the United Kingdom at a cost of $425 million. The 1952 outbreak of FMD cost Canada $750 million in the six-month period required to eradicate it. The United States has experienced nine outbreaks between 1870 and 1929 (on one occasion spreading to 22 states and on another establishing itself in California deer), but each has been successfully eradicated. USDA has estimated that should FMD be introduced into the United States and no control measures implemented, the first year losses would amount to approximately $10 billion. Because FMD virus may persist for many months in animal products, including certain meat products that have been processed for human consumption, most countries free of FMD restrict the importation of animal products from countries in which this disease exists.

Embargoes on importation of animals and animal products are imposed by many countries, including the United States, against countries in which any of the major epidemic livestock diseases are present. The economic losses to both the high-income and developing countries resulting from reductions in trade are great. Importing animal products from certain developing countries is not possible under this policy, and this trade could serve as vitally needed sources of foreign exchange for these countries. The international exchange of animal genetic materials is also limited including importation into the United States of genetic lines and breeds of livestock that would benefit our livestock industries.

Wastage of Animal Protein

There is a dearth of published quantitative data on the wastage of animal protein that results from animal diseases although the importance of and need for such data are widely recognized. The first comprehensive estimate of the worldwide loss caused by animal diseases was published in the 1962 FAO Animal Health Yearbook as a preliminary survey. It concluded that in countries in which veterinary services had existed for many years, losses ranged from 15 to 20 percent of total annual production, and in countries in which veterinary services were less intensive and more recently established, losses ranging from 30 to 40 percent were encountered. Although these estimates were stated as preliminary, no further quantification of disease losses from this source has been forthcoming. This is largely because reliable data on incidence and prevalence rates on various animal diseases are not available.

Using FAO data on world production of livestock products for 1970, we have calculated the losses of meat, milk, and eggs from animal diseases using a 17.5 percent annual loss for Europe, U.S.S.R., North America, and Oceania and 35 percent for Asia, Latin America, and Africa (see Table 12).

If these data are at all accurate, and we believe they probably are good estimates, the world loss of meat, milk, and eggs directly attributable to animal diseases is tremendous. Disease control activities should pay handsome dividends and would justify a high priority for the allocation of funds for this purpose. This has clearly been the case for most high-income countries.

Cost of Disease Control

Data on which to base reliable estimates of future disease control costs are scarce. The costs of prior control and eradication programs give some idea of past efforts but have relatively little predictive value (see Table 13).

Epidemiologists and veterinary economists are only now beginning to carry out benefit-cost analyses of animal disease control programs. Using this technique various programs may be evaluated and alternative policies compared. Although still limited in numbers, they have revealed the favorable ratios indicated in Table 14.

Table 12. Estimated wastage of meat, milk, and eggs from animal diseases (million tons)*

	High-income countries	Developing countries	Total
Beef cattle	44.55	4.59	49.36
Sheep and goats	.64	1.20	1.84
Swine	4.21	4.59	8.80
Poultry	2.15	1.89	4.04
Milk	53.88	30.45	84.33
Eggs	2.25	2.81	5.06

*Based upon 1970 FAO _Animal Production Yearbook_ data.

Table 13. Costs of eradicating certain diseases

Disease	Date	Country	Cost ($)
Contagious pleuropneumonia[a]	1892	USA	1,502,100
Fowl plague[a]	1925, 1929	USA	101,495
Dourine[a]	1934	USA	314,926
Glanders[a]	1942	USA	35,078
Piroplasmosis[a]	1943	USA	11,999,511
Foot-and-mouth[a]	1870, 1880, 1884, 1902, 1908, 1914-1916, 1924-1925, 1929	USA	9,170,411
Foot-and-mouth[b]	1952	Canada	850,000,000
Foot-and-mouth in Mexico (joint Mexico-U.S. program)	1954	USA	134,571,653
Vesicular exanthema[a]	1959	USA	11,158,737
Screwworms (Southeastern)[a]	1959	USA	10,000,000
Foot-and-mouth[c] (indemnity only)	1968	UK	425,000,000
Newcastle[d] (Viscerotropic velogenic)	1973	USA	56,000,000

[a] Pritchard (1966).
[b] Wells (1970).
[c] Power and Harris (1973).
[d] Sharman (1974).

Table 14. Benefit-cost relationships of animal disease control programs

Disease	Ratio	Year calculated
Heelfly control[a]	31.8	1968
Foot-and-mouth[b]	12.7	1967
Mastitis[c]	4.55	1968
Bovine tuberculosis[d] (different approaches)	1.99-10.45	1970
Swine fever (eradication)[e]	3.43	1972
Brucellosis (control)[f]	5.07	1975
Brucellosis (eradication)[f]	3.82	1975

[a] Adam and Meith (1968).

[b] Gimeno and Salces (1967).

[c] USDA (1968).

[d] USDA (1970).

[e] Ellis (1972). Calculating benefits <u>only</u> for direct savings realized by the meat industry in heat and cold processing of pork.

[f] Carpenter and Heron (1975).

The Economic Effects of Animal Diseases

It is difficult to assess the economic effects of animal diseases for many reasons. One of the most important limiting factors is the lack of an adequate data base on: the distribution of diseases, the prevalence of diseases, morbidity, mortality, and losses attributable to disease as contrasted to other long-run processes. Consequently, effects are hard to assess on a short-run basis. This is especially true in the transitional phase between a positive and zero disease status. Not only is it difficult to assess the effect of disease on a national or international scale, but it is equally difficult on a regional or local basis for many of the reasons already stated and because of market substitution. There is a pressing need for the development of sound data on the economic effect of animal diseases and animal disease control programs.

Taking these limitations into consideration, USDA has estimated that the annual U.S. losses from various animal diseases exceed $20 billion. Table 15 shows other estimates of losses from various diseases.

Dramatic recent advances in the field of veterinary economics have developed from computer simulation modeling and linear programming. Given specific data, a model may be constructed so as to obey epidemiological and economic constraints. The model may then be used as a rapid and simple method of evaluating a myriad of prospective disease control programs. Further research is needed to develop and perfect these techniques in evaluating animal health economics. Included in the Bibliography to this report are a number of references on the economic aspects of animal disease to assist those interested in the development of this area.

Effect on Crop Production

Diseases of draft animals including oxen, buffalo, horses, asses, mules, and camels may result in catastrophic losses to grain and other crop production where animals provide power for cultivating crops and pumping irrigation water, transport for agricultural commodities, and transportation. In 1966, FAO estimated that animals provided 85 percent of the draft power in the world and 90 percent in the developing countries. With recent increases in the cost of fossil fuels for energy and the devastating effect of such increases on the economies and balance of payments for many developing countries, strong pressures to maximize

Table 15. Estimated annual losses from various animal diseases

Disease	Year esti- mated	Annual monetary loss	Country or state
All poultry diseases	1966	U.S. $33 million[a]	Canada
All poultry diseases	1967	£ 50 million[b]	Great Britain
Coccidiosis in poultry	1970	U.S. $63 million[c]	USA
Marek's	1967	£ 10 million[c]	Great Britain
Leukosis	1970	U.S. $200 million[d]	USA
Chronic respiratory	1970	U.S. $123.5 million[d]	USA
Foot-and-mouth	1973	£ 144 million[e]	Great Britain
Mastitis	1974	U.S. $600 million[f]	USA
Mastitis	1971	£ 9 million[g]	Great Britain
Mastitis	1971	£ 7.2 million[g]	Australia
Mastitis	1971	Rs. 4.3 million[g]	Ceylon
Anaplasmosis	1973	U.S. $100 million[h]	USA
Anaplasmosis	1976	U.S. $20 million[i]	California
Brucellosis	1976	U.S. $25 million[j]	USA
Brucellosis	1976	U.S. $630,000[k]	California
Contagious bovine pleuropneumonia	1976	N 5 million[l]	Nigeria
Cattle tick infestation	1973	£ 42 million[m]	Australia
Enzootic pneumonia	1971	£ 3.5-7.0 million[n]	Great Britain
Liverfluke	1970	Dfl. 204 million[o]	Netherlands
Bovine fascioliasis	1970	fr500 million[p]	France

[a] Nadeau (1966).
[b] Stevens (1971).
[c] Reid and Kowalski (1970).
[d] Cockrill (1971).
[e] Power and Harris (1973).
[f] NRC (1974).
[g] Wanasinghe (1971).
[h] McCallon (1973).
[i] Carpenter (1976).
[j] McCallon (1976).
[k] Carpenter and Heron (1975).
[l] Oloukun (1976).
[m] Cattle Tick Control Commission (1973).
[n] Goodwin (1971).
[o] Horner (1970).
[p] Euzeby (1974).

the use of animal power will and probably should persist in the future.

Animals convert crop residues and agricultural wastes to highly nutritious food and provide vitally needed manure to maintain soil fertility for crop production. Consequently, animal disease may have a direct effect on crop as well as animal production.

Effect on Animal Diseases

Control of animal diseases on a worldwide basis will have a spectacular effect on food production, and we are optimistic about the prospects for significant reductions in the occurrence of diseases. We believe that a reduction of disease losses in the developing countries to 50 percent of the current level is a realistic goal for the short run (15 to 20 years) and near elimination of losses from all of the epidemic diseases a realistic goal for the long run (50 years). The high-income countries have already nearly eliminated most epidemic animal disease losses.

Reducing losses from the insidious endemic diseases is more difficult because improvement in control will depend upon methodological as well as technological progress. We are optimistic, however, that new control procedures and delivery systems will be developed and that the losses from endemic diseases in the high-income countries as well as in the developing countries can be strikingly reduced. Assuming research support becomes available, it probably will require 15 years to develop the necessary research methodologies and control procedures. We would expect that most of the endemic diseases could be effectively controlled within 50 years.

IMPLEMENTATION

Epidemic Infectious Animal Diseases

To control the spread of major epidemic infectious animal diseases, countries free of these infections usually attempt to keep them out by strictly limiting the movement of animals, animal products, and potentially contaminated material into the country. Such inspection control and quarantine activities are expensive and do nothing toward eventual elimination of the threat. USDA budgeted more than $31 million in 1976-77 to keep exotic epidemic diseases out of the United States. However, current procedures are not always successful, necessitating expensive emergency eradication campaigns when they fail. As an example, the recent occurrence of highly pathogenic Newcastle disease in California cost $56 million in eradication expenses. Reportedly, Cuba had to destroy 10 percent of its national herd recently to eliminate African swine fever.

For a more productive approach to these disruptive plagues the high-income countries should institute cooperative programs of research and control designed to eliminate these diseases as rapidly as possible. Cooperative strategies for the control of rinderpest and contagious bovine pleuropneumonia were used successfully in efforts to control these diseases in Africa. In most instances, the cost of this alternative approach from both the shorter and longer runs would be much less than to continue to concentrate efforts on excluding the threat. This approach is a further extension of the concept of identifying threats at their sources as enunciated by the McGregor Task Force (1973) which studied alternative means of providing protection from exotic pests.

Regional Approach to Epidemic Animal Disease Control

Diseases do not respect political boundaries, and it is often difficult to control the movement of domestic animals, wildlife reservoirs and vectors, and infective materials between countries. Animal disease control is relatively costly because it requires highly trained personnel, biological and chemical products derived from expensive technologies (and often with specific potency requirements for their storage and efficacy requirements for their administration), as well as complicated diagnostic laboratory facilities. For these and other reasons, regional strategies for the control of all epidemic animal infections would be more economical and effective than purely national approaches, particularly in small developing countries with limited resources to allocate to animal disease control.

Such regional activities would best be directed toward: (1) epidemiological and economic surveys for the development of appropriate strategies to control epidemic infections and priorities for their implementation; (2) development and support of effective diagnostic laboratory capabilities; (3) procurement or production of needed biological and chemical agents and standardized diagnostic reagents and materials; (4) development of the epidemiological capability to solve problems uncovered by routine control procedures, to evaluate control progress through appropriate surveillance systems, to assist with the modification of control strategies when necessary, and to provide data from which benefit-cost relationships of alternative control strategies may be determined; and (5) planning for and support of training scarce veterinary personnel, including technicians and animal health assistants.

U.S. Role in Worldwide Disease Control

The United States could help the developing countries control major epidemic diseases by participating in three areas: (1) research essential to control; (2) training of veterinarians and other personnel from the developing countries in epidemiology and disease control as well as for research in epidemic disease control problems--the fundamental objective of training must be to develop a viable, stable animal health service for the country; and (3) direct assistance at regional and national levels with planning and implementation of control procedures. The estimated personnel requirements are indicated in Table 1.

Research

The United States should make a commitment to participate in animal disease research of importance to world food production, whether or not the diseases currently relate to animal health in the United States. Much of this research can be conducted by U.S. research organizations. The developing countries can participate in research at the national and regional veterinary research laboratories scattered worldwide. Some of the research could be accomplished in collaboration with several of the international centers. The U.S. effort should be coordinated with these programs whenever feasible.

Mobilization of the necessary personnel to carry out this research would not be particularly difficult. The U.S. veterinary research establishment is conditioned to respond to changing national priorities in research which are normally expressed through changes in federal and private funding. If funds to support research on control problems of the major epidemic diseases become available, adequate numbers of skilled and experienced scientists most likely would be attracted to the effort.

Research could be safely conducted in laboratories almost anywhere in the United States (at the Plum Island Animal Disease Center, for example), while some would have to be conducted in laboratories and in the field in the developing countries where the diseases are present and laboratory facilities are available.

The United States should develop a laboratory or laboratories in which U.S. scientists would work in one or more developing countries in Africa. This would maximize the effectiveness of the U.S. research effort on the major epidemic diseases and eliminate the many problems that inevitably result when a long-term U.S. research effort is mounted entirely in laboratories owned and operated by other nations. Another such laboratory dealing with research on foot-and-mouth disease should be established in South America. Establishing a laboratory to solve a problem through research should be clearly distinquished from a technical assistance initiative.

The United States should expand its research effort on African swine fever through a joint program with Spain. The disease in Spain is the prototype of what the problem will be in the United States should African swine fever gain entry. The Spanish government, with the assistance of a World Bank loan, is in the process of expanding its research on African swine fever and has expressed interest in cooperating with the United States on this important problem. We strongly recommend that steps be taken to expand the U.S. research effort on African swine fever as an item of the highest priority. An effective immunizing agent is badly needed but will require a new immunological approach as the African swine fever virus does not produce neutralizing antibodies in either infected or recovered pigs. It is difficult to understand why so little research is being conducted on this disease today given its importance.

The United States should continue to support the International Laboratory for Research on Animal Diseases (ILRAD) and its research on African trypanosomiasis and the theilerioses. Further research support should be made available so that limited numbers of U.S. scientists who wish to acquire experience and competency in research on trypanosomiasis and the other hemoprotozoan diseases may do so. Presently U.S. scientists have limited experience with these diseases.

Training Personnel

In order to control the major epidemic diseases, research and control personnel must be trained. Even though many skilled, experienced people are already working in both research and control organizations in the developing countries, many more are needed. Training in epidemiology and modern mass disease control technology is especially required. Some of the training can be provided in the United States and some in the developing countries.

Research Training. With few exceptions, the capability to train veterinarians and other scientists for research on the control of epidemic diseases does not exist in the developing countries. Individuals needing such training should be sent to U.S. institutions to obtain it. Their research training must be directed toward the kind of control problems that they will be required to solve in their own country. Trainees generally would be expected to complete the research for their dissertation in the United States. There ordinarily would not be an advantage to returning to the developing countries for dissertation research where, in many cases, adequate guidance would not be available.

Training in Epidemiology and Mass Disease Control Technology. Specific training programs are needed in epidemiology, statistics, and mass disease control technology. Such programs are currently available in the United States for veterinarians experienced in the practical aspects of animal disease control. They usually entail a 12-month intensive course of study involving work in problem solving. Other such programs are vitally needed. The possibility of the United States establishing and funding one or more such programs in the developing countries, with long-term skilled guidance provided by experienced U.S. institutions, should be explored.

Veterinary Education. Most developing countries have numerous quality veterinary schools. Most of these institutions were modeled after veterinary schools in the United States and Europe and still ascribe to the standards and objectives of those schools. Veterinarians, however, function differently in the developing countries than they do in the high-income countries. In the developing countries, they function almost exclusively in public preventive programs that deal with animal disease in the context of the herd, region, or country. Individual animal problems occupy most veterinary effort in the high-income countries.

Veterinary schools in the developing countries need guidance in orienting their programs toward training in epidemiology and preventive medical principles to better prepare their graduates in the control of epidemic diseases. Unfortunately, most veterinary schools in the high-income countries are ill-equipped to provide this guidance.

Training Diagnostic Laboratory Personnel. It is important to train personnel to operate the diagnostic laboratories that will support control programs on epidemic disease. Diagnostic laboratory specialists should be trained in the theoretical aspects in U.S. veterinary institutions that also can provide practical experiences in a diagnostic laboratory environment. Practical training programs conducted at the National Animal Disease Center in Ames, Iowa, the Plum Island Animal Disease Center, and other institutions where advanced techniques essential to the support of control programs can be demonstrated would be especially valuable.

Training Veterinary Assistants. Assistants needed to implement disease control programs should be trained in the developing countries, preferably by nationals of the country in which they will function. U.S. veterinarians might assist with some parts of the program.

Assistance with Control Programs

The United States should provide direct assistance to the developing countries by making available trained personnel, equipment, and perhaps funding for the implementation of control programs designed to eliminate the major epidemic diseases that could threaten the U.S. livestock industry. U.S. efforts would best be expended within the context of a cooperative effort by the high-income countries and within the framework of the regional strategies already described.

U.S. input would be especially useful in planning, operation of diagnostic laboratories, epidemiological support, and possibly the production of biologicals. The latter activity is one that the U.S. private sector might find attractive. However, it would probably not prove to be very profitable since in nearly every developing country the production of vaccines is a government function.

Appendix

CURRENT STATUS OF ANIMAL DISEASE CONTROL PROGRAMS AND MAJOR RESEARCH NEEDS

AFRICAN HORSE SICKNESS

African horse sickness is an insect-borne viral infection of equine animals, which is usually acute and fatal. Other livestock are resistant to the virus. It is caused by a diplornavirus with nine immunologically distinct serotypes. It is transmitted by culicoides and mosquitoes. This disease is found in southern, equatorial, and northern Africa. During the late 1950s and early 1960s, major epidemics occurred in the Near East.

African horse sickness is a serious threat to horses, mules, and donkeys wherever appropriate insect vectors exist. Experience in areas that this disease has periodically invaded, such as the Middle East, shows that this infection is fully capable of decimating the horse, mule, and ass populations of an extensive area in a very short period of time. Its effect upon food production where equine animals provide draft power can be devastating.

Control programs currently used in infected areas depend upon the use of polyvalent mouse brain attenuated tissue-culture propagated vaccines that are reasonably effective, plus vector control. Research is needed on the identification of reservoir hosts in Africa, the carrier state, potential vectors, more rapid diagnostic procedures, and improved techniques for the production and standardization of vaccines.

AFRICAN SWINE FEVER

African swine fever (ASF) is an unusual and important threat to world food production that warrants more attention. When European breeds of pigs were introduced to East Africa and began to mingle with the native wart hogs, they developed an acute, fulminating, febrile disease with a nearly 100 percent fatality rate. Only where contact with wart hogs was controlled, could European breeds of swine be raised safely. In the Portuguese colonies of Africa, where pigs were raised in a semiwild state, domestic pigs often came into contact with wart hogs, bush pigs, and forest hogs, all of which are now known to serve as nonsymptomatic reservoirs of ASF virus. Occasionally European pigs exposed by this means developed a chronic infection and survived. In this way the virus slowly adapted itself in these colonies to a domestic pig host. ASF virus was subsequently introduced into Portugal in 1957, and in 1959 spread to Spain. The disease as it is seen today in the Iberian peninsula is no longer an acute, fulminating disease but rather a chronic, debilitating affliction. Many affected pigs are stunted and nonsymptomatic carriers result. The swine population throughout Spain and Portugal is now infected and approximately 1.5 million pigs in Spain alone have died or have been killed. Direct losses between 1959 and 1974 are estimated at $600 million.

Although Spain and Portugal wish to eradicate this disease, little progress has been made. A principal reason is that the ASF virus is unique among animal pathogens. It is an icosahedral, cytoplasmic DNA virus that does not stimulate the production of classical protective antibodies in the host. Consequently there appears little immediate possibility of developing a vaccine for ASF. It is the only icosahedral DNA virus that affects warm-blooded animals. Some others, interestingly enough, infect plants, insects, amphibia, and fish.

ASF thus constitutes a serious worldwide threat to food production. In recent years, it has appeared in Cuba, France, and Italy, and in each instance approximately 10 percent of each country's swine were destroyed to eliminate it. In its present chronic form it could conceivably spread widely before being detected, making eradication either impossible or extremely expensive. On the basis of the Spanish experience, it could reduce the productivity of a swine industry by 30 to 40 percent should it become established. There is no means of control except slaughtering infected and exposed animals.

Despite its potential importance, very little research has been conducted on ASF. The total world research effort in 1976 consisted of three scientists at the USDA Plum Island Disease Center, one at the Pirbright Veterinary Laboratory in the United Kingdom, and approximately six senior and 10 to 12 junior scientists in Spain. This is a grossly inadequate effort in view of the threat posed by the disease to the swine industry of the world. It is also unfortunate because research on the unique ASF virus would unquestionably have important implications for other infections of humans and animals. The United States should expand its research program on ASF and develop a cooperative effort with Spain as a high priority livestock research effort.

AFRICAN TRYPANOSOMIASIS

In the humid mid-tropics of Africa, there are about 700 million hectares of land that cannot be fully used for livestock production because they are infested with tsetse flies, the vectors of African trypanosomiasis. It has been estimated that 125 million head of cattle and perhaps as many sheep and goats could be raised in this region were trypanosomiasis controlled. At present, there are only about 7.5 million cattle in the area. This disease and other hemoprotozoan diseases, the theilerioses and babesioses, are among the relatively few highly disruptive infections of livestock for which economic control methods are still seriously wanting.

The International Laboratory for Research on Animal Diseases has been established in East Africa to conduct research on trypanosomiasis and theileriosis and to assist in the coordination of worldwide research on these diseases. It is supported by the major international technical assistance agencies under the auspices of the Consultative Group on International Agricultural Research (CGIAR). ILRAD is concentrating initially on immunological approaches to control. More research also needs to be conducted on means of economically controlling the tsetse fly vector, as well as on genetic resistance or tolerance of cattle to infection with trypanosomes. Several breeds of short-horned native cattle, relatively intolerant to this infection, exist in some parts of Africa. Little is known, however, about the nature of this resistance and whether or not it can be exploited in the development of practical systems of cattle production. Comprehensive epidemiological/economic/anthropological studies in local areas are necessary to define trypanosomiasis transmission in terms of the different systems used to maintain indigenous cattle and the practical potentials for meat and milk production in different parts of the continent.

The latter is of particular importance because trypanosomiasis control, when and if economical control methods become available for general application, must be coordinated with the development of improved agricultural production systems in Africa. Only this will ensure the proper use of certain ecologically marginal tropical areas. The soil types, rainfall, and temperature are such for much of the area of Africa now "protected" by the tsetse fly that the agricultural potential of such areas could be seriously compromised by overstocking should trypanosomiasis be eliminated and no concurrent control imposed on livestock numbers or land use.

ANAPLASMOSIS

Anaplasmosis is characterized by anemia and fever and the presence of this protozoan parasite in red blood cells. It is responsible for extensive losses both from mortality and reduced productivity. *Anaplasma marginale*, the causative agent, is found throughout the cattle-producing regions of the world, especially in the warmer regions of both the high-income and developing countries. It is transmitted by arthropods, mainly ticks. An effective, preferably noninfectious vaccine is needed to prevent this disease.

AVIAN INFECTIOUS BRONCHITIS

Avian infectious bronchitis is an acute, contagious respiratory disease of chickens and turkeys that causes mortality and loss of weight gain in growing chicks, and reduced egg production and loss of egg quality in laying birds. It is found worldwide and can result in significant losses. An effective live virus vaccine is available, but must be used annually.

THE BABESIOSES (PIROPLASMOSIS)

This is a group of tick-borne diseases that affect a wide spectrum of wild and domestic animals, especially in tropical areas. The parasite develops in erythrocytes and in the tick vector. In areas where these diseases widely occur, young animals become infected shortly after birth while they still retain some passively acquired resistance. If that occurs, repeated reinfections throughout life seldom develop into clinical disease. The disease problem exists mainly at the interface of free and infected areas and when susceptible animals are moved into infected areas. In the latter instance, the fatality rate is very high. No evidence is available to indicate how much the productivity of chronically infected animals may be reduced. Babesioses seriously constrain livestock improvement in many countries. Much research is required on almost all aspects of these diseases before effective control measures can be designed. Particular emphasis is required on the immunological aspects of the host-parasite interactions and improved methods of vector control. The United States succeeded in eradicating this once prevalent and costly infection. This was possible because of the rather unusual single host tick vector in this country, an advantage not found elsewhere.

BLUETONGUE

Bluetongue, an insect-borne viral infection of sheep, goats, cattle, and wild ruminants, occurs in Africa, Asia, North America, and Europe. The principal vector is a culicoides fly. There are at least 16 serotypes of the virus. The morbidity rate of the disease in sheep is higher in Africa than in the United States. Polyvalent vaccines are effective against the appropriate antigenic strains.

BRUCELLOSIS

Much is known about the causative agent, transmission, and diagnosis of this important bacterial disease of humans, cattle, and other animals. And considerable progress has been made recently in reducing the prevalence of this disease in the high-income countries. Several effective vaccines and practicable diagnostic tests are available and have been successfully used in control efforts. There is need, however, for the development, through research, of systems and methods for applying existing technology to control this disease in the areas of the world where it still exists.

CONTAGIOUS BOVINE PLEUROPNEUMONIA

Usually a subacute disease of bovine animals, this is also one of the world's most destructive livestock diseases. It was the first epidemic disease to be eradicated from the United States. Once nearly eradicated from the world, it is now of increasing importance in Africa because of relaxed control of movement of cattle in some newly independent countries. It also occurs today in India and central Asia. This disease could be eradicated globally with present methods but elimination would be much easier and more economical if better diagnostic tests and an improved vaccine were available.

CONTAGIOUS CAPRINE PLEUROPNEUMONIA

This infectious respiratory disease of goats occurs widely in Africa, the Mideast, and Asia, as well as sporadically in Europe and Mexico. Morbidity and mortality rates are high. Improved diagnostic tests, chemical treatments, and vaccines are needed.

EQUINE ENCEPHALOMYELITIS

Encephalomyelitis killed tens of thousands of horses and mules in the United States in the 1930s and early 1940s, and an epizootic of the Venezuelan strain rapidly moved up through Central America and Mexico into the United States in 1971 causing extensive losses in its wake. This viral disease is infectious for humans and is transmitted by mosquitoes. Effective vaccines are available. Additional research is needed on the identification of the reservoirs of this virus in wild and domestic animals and birds.

EQUINE INFECTIOUS ANEMIA

Equine infectious anemia is a viral disease that is most prevalent in poorly drained, low-lying areas of the world where biting insects are the most numerous. Animals that survive the initial attack usually remain carriers and periodic shedders of the virus for life. A highly reliable diagnostic test is available. Research is needed on an immunizing agent to give lasting protection to the world's equine population. No effective therapeutic agent is available.

FOOT-AND-MOUTH DISEASE

Foot-and-mouth disease (FMD), a viral infection of cloven-footed animals, occurs widely throughout the world and causes morbidity and often permanent loss of productivity in adult animals, with high mortality occurring only in the young. It is responsible for large but difficult-to-quantify losses wherever it occurs because of its low fatality rate among adult animals. A recent USDA economic analysis indicates that should FMD become established in the United States, the first-year losses would approximate $10 billion.

Controlling FMD is difficult because there are seven distinct types of virus, with 62 known subtypes, and either vaccination or natural infection afford protection only against that type of virus for four to six months. Full control on a worldwide basis would be facilitated by improved vaccines or by alternative control methods. Research also is needed on the rapid and economical identification of types and subtypes of FMD virus, on the economical assay of vaccines intended for field use, and on practicable means of rendering meat and other products from animals with the FMD virus noninfective. The latter would require techniques to inactivate FMD virus that can be easily and economically applied under practical processing systems. Concern about the spread of FMD is the main reason for most present constraints on international commerce in meat and animal products. Therefore, the availability of this technology would have other beneficial, indirect effects on world food supplies as well as on the economic and social development of many developing countries.

FOWL PLAGUE

Classical fowl plague is an acute, highly fatal disease of chickens, turkeys, and other species of fowl caused by a highly pathogenic member of the type A influenza group of viruses. It has occurred widely throughout the world including the United States where it was last reported in 1929. Other less pathogenic members of the type A group of influenza viruses are found in the United States and elsewhere. The epidemiology of the diseases caused by this group of viruses is poorly understood. Although effective vaccines are available for use against the highly pathogenic form of this disease, the diversity of subtypes and lack of antigenic relationships between members of this large group of viruses complicates the use of these vaccines in control programs. More research is needed on the epidemiology of influenza viruses.

HOG CHOLERA (SWINE FEVER)

Hog cholera is an acute, highly contagious viral infection of swine characterized by sudden onset, high morbidity, and high mortality. Chronic forms can mean low mortality in adult animals, but abortions and deaths of young animals also can result. The causative RNA virus, which apparently does not exist under natural conditions in animals other than swine, is spread by pig-to-pig contact, contaminated clothing, and equipment and supplies, and can result from feeding animals uncooked garbage. It is inactivated relatively easily. The most troublesome problem, therefore, in the control of hog cholera is identifying chronic and subclinical infections. Effective attenuated and inactivated virus vaccines are available and useful for reducing the incidence of this disease.

Hog cholera, one of the few epizootic animal diseases to have originated in the United States, is now a serious problem in Latin America, Africa, Asia, and Europe, but is not found in Australia, Canada, and the United Kingdom. This disease is nearing eradication in the United States as a result of a 15-year effort (which ended in 1975) at a cost of nearly $125 million.

Hog cholera is an important threat to world food production. Although the technology for its control is relatively adequate, additional research is indicated on possible reservoirs of this virus in nature, adaptation of hog cholera virus in pigs, as well as on the development of improved vaccines possibly from immunologically related viruses such as bovine viral diarrhea. The latter would eliminate the need to use attenuated vaccines, an approach not compatible with total eradication.

INFECTIOUS COMPLEXES

Examples of infectious complexes are neonatal diseases in most animal species, diseases that reduce reproductive efficiency, mixed ecto- and endoparasitisms, and bovine mastitis. These are probably the single most important group of livestock diseases. Some of these complexes produce acute or chronic clinical disease while others reduce productivity without inducing clinical signs. Some are stress-related conditions such as bovine shipping fever (bovine respiratory disease complex) and transport tetany. In many, a range of poorly known and often opportunistic pathogens are involved as one or more of a number of etiologic factors.

LEPTOSPIROSIS

Leptospirosis is a complex bacterial disease caused by Leptospira interrogans, an organism with more than 100 different serotypes. First described as a human disease, it affects all species of warm-blooded animals. Leptospirosis in cattle can vary from a mild to a severe infection. Research is needed on improved vaccines or new chemotherapeutic methods that prevent or eliminate the renal carrier state of this disease.

MAREK'S DISEASE

Marek's disease, which probably has caused greater losses to the poultry industry than any other disease, is caused by a herpesvirus. In 1967, USDA estimated the U.S. loss to be in excess of $150 million per year. Annual world losses were thought to exceed $1 billion. An effective vaccine that spectacularly reduces losses has recently been developed.

NEWCASTLE DISEASE

Newcastle disease is a highly contagious viral infection of domestic poultry and other birds which is found worldwide. It is caused by a myxovirus of the parainfluenza group with pathotypes varying from highly pathogenic to nonpathogenic. The introduction of highly pathogenic, exotic strains of the Newcastle disease virus to the United States and other countries where they are not present is a serious threat to world poultry production. The recent introduction of a highly pathogenic, viscerotropic strain of this virus in California cost $56 million to eradicate. More information is needed on the host range of this virus and on the pathogenicity and other characteristics of the wide range of Newcastle disease virus strains.

PASTEURELLOSIS

Hemorrhagic septicemia, the specific form of pasteurellosis of major worldwide importance, is caused by highly virulent strains of *Pasteurella multocida*. It is an acute, highly fatal bacterial infection of cattle and buffalo and is especially troublesome in the developing countries. Environmental stress factors are usually associated with outbreaks of this disease. Although it has occurred in Europe, Africa, and Asia, it is a significant problem only in areas of the world in which cattle and buffalo are intimately associated. Improved diagnostic tests are needed to effectively control this disease.

RABIES (BAT-TRANSMITTED)

Rabies, a viral disease of most warm-blooded animals, generally is spread from animal to animal by means of a bite. A special problem is the common vampire bat which is found from Mexico south to northern Argentina and which roosts in natural caves, hollow trees, and mine shafts. The number of vampire bats in this area has increased with the development of the livestock industry. Most of the bats in vampire bat colonies are infected with the rabies virus which is often transmitted to cattle. The annual loss of cattle from bat rabies in Latin America has been estimated from 500,000 to 2 million and the annual economic loss from $100 to $250 million. Effective vaccines against rabies in cattle and effective means of controlling the vampire bat are available.

RINDERPEST

Rinderpest, an acute, highly fatal viral infection, particularly of cattle and buffalo, has been one of the great plagues of history. It occurred once in the Western Hemisphere in Brazil and was immediately eradicated. In the great African rinderpest epidemic that began in the 1890s, 90 to 95 percent of the cattle and domestic buffalo were killed in many areas within a few weeks after the disease appeared.

Rinderpest currently occurs in the Sahelian and Sudanian ecological zones of north Africa and adjacent areas on the Indian Ocean. Methods that are now available to eradicate rinderpest have been highly successful in Africa. If judiciously applied, they could lead to worldwide eradication of this disease at a relatively moderate cost.

SHEEP POX AND GOAT POX

Sheep pox and goat pox are highly contagious, viral diseases caused by closely related viruses. These frequently fatal diseases occur in Africa, Asia, and Europe, and cause extensive losses in many developing countries. Recovery from the natural disease results in immunity. Vaccination procedures using live as well as killed virus vaccines are only partially effective; consequently, improved vaccines are needed.

STREPTOTHRICOSIS

Streptothricosis, caused by a fungus, affects many domestic and wild animal species and occasionally humans. It causes significant economic losses in cattle worldwide, particularly in the tropics where it produces a chronic dermatitis. The prevalence rates are reportedly high: 41 percent, Madagascar; 80 percent, Rwanda; 5 and 13 percent in Ghana for the dry and rainy seasons respectively; and 10 to 12 percent, Nigeria. In sheep, the chronic skin lesions called lump wool disease (Argentina, Uruguay, South Africa, Australia, and the United Kingdom) and strawberry foot rot (Scotland) result in major losses. Presently available treatments are not very effective. Some African breeds of cattle, such as Muturu, the N'dama, and the Baole, are resistant to natural infection.

SWINE VESICULAR DISEASE

In 1966, Italian workers identified a vesicular disease in swine that clinically resembled foot-and-mouth disease but was produced by a picornavirus of the enterovirus group. In 1971, pigs used in an FMD vaccine evaluation trial in Hong Kong developed vesicular lesions that were the result of an enterovirus. The disease subsequently appeared in several countries of Europe. Between December 11, 1972 and March 1976, Great Britain had to pay over $16 million in indemnities alone in their attempts to eliminate the disease. The swine vesicular disease (SVD) virus closely resembles the human Coxsackie B5 virus. While antibodies to Coxsackie B5 are prevalent in North Americans, the SVD virus has not yet been identified.

Research on this newly appearing disease should determine (1) its economic significance, (2) its relation to enterovirus infections in humans, (3) epidemiology and means of transmission, (4) efficacy of various control-eradication procedures, and (5) effect of chemical and physical influences on the virus.

THEILERIOSES

This group of tick-borne diseases is caused by protozoan parasites of the genus *Theileria* which infect lymphatic cells and erythrocytes in their hosts. The most important theileriosis is East Coast fever (ECF), an infection of cattle. This form of theileriosis is responsible for disease in cattle in the Middle East and in the Mediterranean area, and yet another form causes a mild or nonpathogenic infection of cattle throughout much of the world including the United States and is only occasionally associated with mortality. Still other forms affect sheep and goats.

East Coast fever significantly inhibits cattle production in the vast areas of tropical Africa. The most effective control requires treating animals up to two times a week to eliminate ticks. If an area is kept free of cattle for 15 months, the tick population becomes free of infection. There is need for more effective, longer-lasting means of controlling ticks, and for immunizing agents against ECF. Research to develop immunization procedures has been conducted with FAO support in Muguga, Kenya, and is now being pursued at ILRAD. These research programs should be continued.

TRANSMISSIBLE GASTROENTERITIS

Transmissible gastroenteritis is a highly contagious disease of swine caused by a coronavirus that produces degenerative changes in the intestinal mucosa. This disease occurs widely in the United States and other countries. The morbidity rate of newborn pigs is 75 to 100 percent; however, deaths seldom occur in animals over five weeks old. No effective control measures are available. Improved diagnostic tests are needed as well as effective vaccination procedures.

TUBERCULOSIS

Tuberculosis is a chronic, debilitating disease that has affected cattle and humans at least since Biblical times. Research is needed on reliable and practical noncultural diagnostic methods that will detect infected cattle.

VIBRIOSIS

Vibriosis, a major reproductive disease of cattle, is spread by venereal contact or artificial insemination when improperly treated bull semen is used. It is a major impediment to expanded use of artificial insemination of cattle in the developing countries. Vaccines are available, but they do not prevent infection. Research is needed on a rapid, reliable, noncultural diagnostic test that can be applied under field conditions.

VIRAL DIARRHEA

Viral diarrhea affects cattle throughout the world. This ailment is characterized by a febrile reaction and erosions and ulcerations of mucosol surfaces and destruction of lymphatic tissue. Morbidity is high but many infected animals do not develop clinical signs. Modified live virus vaccines are available but not widely used. Improved diagnostic tests and more effective and economic vaccination procedures are needed.

NOTES

1. The question of possible health problems arising from very high consumption of animal products calls for continued research.
2. This excludes China and Russia, in each of which permanent meadows and pastures constitute about 62 percent of all agricultural land.

REFERENCES

Adam, W. and K. Mieth (1968) Okonomische Ein Schatzung des Dasselfliegen Bekampfungsprogramms des Bezirkes Potsdam. Monatshefte fur Veterinarmedizin 22:924-928.

Bauer, G. (1968) Problemas de la crea de gando vacuno de carne en el tropico de Latinomerica (Bolivia) y medidas que hemos adoptado para solucionarlos. II Conf. Anual de Ganado de carne en America Lativa. University of Florida, Gainesville.

Berth, A. (1975) The return of medic. CIMMYT Today 3:1-16.

Blair, R. and D. W. Knight (1973) Recycling animal wastes. Feedstuffs 43:32.

Bogert, L., G. M. Briggs, and D. H. Calloway (1973) Nutrition and Physical Fitness. Philadelphia: W. B. Saunders.

Bradin, A. W. H. and I. W. McDonald (1970) Disorders of grazing animals due to plant constituents. Pages 381-391, Australian Grasslands, edited by R. M. Moore. Canberra: Australian National University Press.

Brown, L. R. (1974) In the Human Interest. New York: W. W. Norton.

Bundie, E. (1974) Can animals compete for world grain supplies? Feedstuffs 46:16, 18, 70.

Burton, G. W., R. H. Hart, and R. D. Lowry (1967) Improving forage quality in Bermuda grass by breeding. Crop Science 7:329-332.

Butz, E. L. (1975) Looking ahead ± 25 years. Feed Management 26:118.

Byerly, T. C. (1966) The role of livestock in food production. Journal of Animal Science 25:552.

Carpenter, T. E. (1976) A Linear Programming Model for Brucellosis Eradication. Proceedings, International Symposium on New Techniques in Veterinary Epidemiology and Economics, University of Reading, Reading, England.

Carpenter, T. E. and B. R. Heron (1975) Benefit-cost Study of Brucellosis Program. A Report on the Bovine Brucellosis Eradication Program in California. Department of Food and Agriculture, Health, and Industrial Relations, State of California, Sacramento.

Caton, D. D. (1970) Growth in Demand for Feed Grains. USDA Economic Report, No. 63. U.S. Department of Agriculture, Washington, D.C.

Cattle Tick Control Commission (1973) The Cattle Tick in Australia--Enquiry by the Cattle Tick Control Commission. Department of Public Health, Canberra, Australia.

Childs, A. H. B. and C. G. Grom (1964) Balanced farming with cattle and coconuts. East African Agriculture and Forestry Journal 29:206-207.

Cockrill, W. R. (1971) Economic loss from poultry disease--world aspects. British Egg Marketing Board Symposium 7:3-24.

Collins, P. (1975) Conserving genetic resources. Nature 258:184.

Consultative Group on International Agricultural Research, Technical Advisory Committee (1976) Priorities for International Support to Agricultural Research in Developing Countries, Agenda Item 6. Rome: Food and Agriculture Organization of the U.N.

Couch, J. R. (1972) Feeding poultry manure to animals. Feedstuffs 44:24.

Council for Agricultural Science and Technology (1975) Ruminants as Food Producers Now and for the Future. Special Publication No. 4.

Cunha, T. J. (1974) The future of animal agriculture. Feedstuffs 46:96, 98, 110-111.

Cunha, T. J. (1975a) The place of livestock in meeting human food needs. Feedstuffs 47:23, 27-28.

Cunha, T. J. (1975b) Can the animal industries survive? Feedstuffs 47:8.

Dinius, D. A. and C. A. Baille (1976) Chemical intake stimulation and growth of steers. Journal of Animal Science 43:319.

Duncan, A. (1975) Economic aspects of the use of organic materials as fertilizers. Organic Materials as Fertilizers. Rome: Food and Agriculture Organization of the U.N.

Ellis, P. R. (1972) An Economic Evaluation of the Swine Fever Eradication Programme in Great Britain: Using Cost-Benefit Analysis Techniques. Study #11. Department of Agriculture, University of Reading, Reading, England.

Euzeby, J. A. (1974) Helminthic diseases of domestic ruminants and horses in France. Pages 148-151, Helminthic Diseases of Cattle, Sheep and Horses in Europe, edited by G. N. Urquhart and J. Armour. Glasgow: Robert MacLehose and Co.

Fontenot, J. P. and K. E. Webb, Jr. (1974) The value of animal wastes as feeds for ruminants. Feedstuffs 46(14):48.

Fontenot, J. P. and K. E. Webb, Jr. (1975) Health aspects of recycling animal wastés by feeding. Journal of Animal Science 40:1267.

Food and Agriculture Organization of the U.N. (1962) Animal Health Yearbook. Rome: FAO.

Food and Agriculture Organization of the U.N. (1970) Animal Production Yearbook, 1970. Vol. 23. Rome: FAO.

Food and Agriculture Organization of the U.N. (1971) Agricultural Commodity Projections, 1970-1980. Vol. II. Rome: FAO.

Food and Agriculture Organization of the U.N. (1974) Assessment of the World Food Situation: Present and Future. Item 8 of the Provisional Agenda. Rome: FAO.

Food and Agriculture Organization of the U.N. (1975) Animal Production Yearbook, 1975. Vol. 28. Rome: FAO.

Food and Agriculture Organization of the U.N. (1976) Report of the Expert Consultation on International Buffalo Research Needs. Los Banos, Philippines.

Gimeno, E. J. and F. Salces (1967) Incidencia economica de la fiebre aftosa en la Republica Argentina. Bulletin de l'Office Internationale des Epizooties 68:549-553.

Goodwin, R. F. W. (1971) The economics of enzootic pneumonia. Veterinary Record 89:77-81.

Hodgson, H. J. (1976) Forage crops. Scientific American 234(2):60-75.

Horner, M. R. (1970) Economics of parasitic disease. Journal of Parasitology 56:427-428.

Johnston, B. F. and P. Kilby (1975) Agriculture and Structural Transformation: Economic Strategies in Late-Developing Countries. New York: Oxford University Press.

McCallon, B. R. (1973) Prevalence and Economic Aspects of Anaplasmosis. Proceedings, Sixth National Anaplasmosis Conference, Las Vegas, Nevada.

McCallon, B. R. (1976) Economic Implications of Brucellosis Eradication. Proceedings, International Symposium on New Techniques in Veterinary Epidemiology and Economics, University of Reading, Reading, England.

McGregor, R. C. (1973) The Emigrant Pests--A Report to Dr. Francis J. Mulhern, Administrator, Animal and Plant Health Inspection Service. Marketing and Consumer Services, U.S. Department of Agriculture.

Nadeau, J. D. (1966) Importance du controle des maladies animales dans l'efficacite des production. Canadian Veterinary Journal 7:142-147.

National Research Council (1974) A Nationwide System for Animal Health Surveillance. Washington, D.C.: National Academy of Sciences.

National Research Council (1975) The Effect of Genetic Variance on Nutritional Requirements of Animals. Washington, D.C.: National Academy of Sciences.

National Research Council (1976a) Urea and Other Nonprotein Nitrogen Compounds in Animal Nutrition. Washington, D.C.: National Academy of Sciences.

National Research Council (1976b) Agricultural Production Efficiency. Washington, D.C.: National Academy of Sciences.

Novakowski, N. S. and V. E. F. Solman (1975) Potential of wildlife as a protein source. Journal of Animal Science 40:1016.

Oloukun, S. B. (1976) An Appraisal of the Anti-C.B.P.P. Program in Nigeria. Proceedings, International Symposium on New Techniques in Veterinary Epidemiology and Economics, University of Reading, Reading, England.

Oltjen, R. R. (1969) Effects of feeding ruminants non-protein nitrogen as the only nitrogen source. Journal of Animal Science 28:673.

Oltjen, R. R., T. S. Rumsey, and P. A. Putnam (1971) All-forage diets for finishing beef cattle. Journal of Animal Science 32:327.

Ott, E. (1964) Cellulose and Cellulose Derivatives: A Monograph. New York: Interscience Publishers, Inc.

Oyer, E. B. (1976) Constraints on Increasing Agricultural Production in the Tropics: Research and Implementation Needs. Report to the National Science Foundation, Cornell University Experiment Station, Ithaca, N.Y.

Perkins, D. (1969) Agricultural Development in China, 1368-1968. Chicago: Aldine Publishing.

Peter, A. P., E. E. Hatfield, F. N. Owens, and U. S. Garrigus (1971) Effects of aldehyde treatments of soybean meal on in vitro ammonia release, solubility and lamb performance. Journal of Nutrition 101:605.

Power, A. P. and S. A. Harris (1973) A cost-benefit evaluation of alternative control policies for foot-and-mouth disease in Great Britain. Journal of Agricultural Economics 24:573-600.

Pritchard, W. R. (1966) Increasing protein foods through improving animal health. Proceedings of the National Academy of Sciences 56:360-369.

Reid, J. T., K. L. Turk, and R. Anrique (1975) Comparative Efficiency of Animals in the Conversion of Feedstuffs to Human Foods. Presented at Rockefeller Foundation Symposium, Future Role of Animals in Food Production, New York, N. Y.

Reid, W. M. and L. Kowalski (1970) Economics of coccidiosis in poultry production. Journal of Parasitology 56:279-280.

Ruthenberg, H. (1971) Farming Systems in the Tropics. London: Oxford University Press.

Schwabe, C. W. (1969) Veterinary Medicine and Human Health. Baltimore: Williams & Wilkins.

Scott, M. L. (1975) Proceedings, 1975 Cornell Nutrition Conference. Ithaca, N.Y.: Cornell University.

Scrimshaw, N. S., D. I. C. Wang, and M. Milner (1975) Summary and Research Recommendations. Washington, D.C.: National Science Foundation.

Shapiro, K. H. (1976) Efficiency and Modernization in African Agriculture: A Case Study in the Geita District, Tanzania. Nairobi: East African Literature Bureau.

Sharman, E. C. and J. D. Lamont (1974) The Viscerotropic Velogenic Newcastle Disease Eradication Program in Southern California. Proceedings, XV World Poultry Congress, New Orleans, Louisiana.

Singh, A. (1975) Use of organic materials and green manure as fertilizers in developing countries. Organic Materials as Fertilizers. Rome: Food and Agriculture Organization of the U.N.

Sprague, G. F. (1975) Agriculture in China. Science 188:549.

Stevens, A. J. (1971) Economic loss from poultry disease in Great Britain. British Egg Marketing Board Symposium #7.

Tracey, M. V. (1975) The Future of Animal Production from the Point of View of Food Technology. Proceedings, Third World Conference on Animal Production, Melbourne, Australia.

U.S. Department of Agriculture (1968) Evaluation of Program Alternatives for Mastitis Abatement in Dairy Cattle. Agricultural Research Service. Washington, D.C.: U.S. Government Printing Office.

U.S. Department of Agriculture (1970) Model: Tuberculosis Eradication. Agricultural Research Service. Washington, D.C.: U.S. Government Printing Office.

U.S. Department of Agriculture (1973a) Agricultural Statistics. Washington, D.C.: U.S. Government Printing Office.

U.S. Department of Agriculture (1973b) Economic Research Service Report. Washington, D.C.: U.S. Government Printing Office.

U.S. Department of Agriculture (1974) The World Food Situation and Prospects to 1985. Foreign Agricultural Economic Report No. 98. Washington, D.C.: U.S. Government Printing Office.

University of California Food Task Force (1974) A Hungry World: The Challenge to Agriculture. Division of Agricultural Sciences, University of California.

VanDemark, N. L. (1976) Potential increases in food supply through research in agriculture. Increased Productivity from Animal Agriculture. Report to the Science and Technology Policy Office, National Science Foundation.

Van Horn, H. H., T. J. Cunha, and R. H. Harms (1972) The role of livestock in meeting human feed needs. Biological Science 22:710.

Van Keulen, H. and C. T. de Wit (1975) Actual and Potential Herbage Production in Arid Regions. University of Wageningen, Wageningen, The Netherlands.

Van Voorhoeve, J. J. C. (1974) Organic Fertilizers: Problems and Potential for Developing Countries. World Bank Fertilizer Study, Background Paper No. 4. Washington, D.C.: Office of the Economic Advisor, International Finance Corporation. In: Duncan (1975).

Wanasinghe, D. C. (1971) Economic losses due to mastitis. Ceylon Veterinary Journal 19:124-125.

Ward, G. M. and D. Seckler (1975) Protein and energy conservation of poultry and fractional animal waste. Feedstuffs 47:467-474.

Warwick, E. J. and E. H. Cobb (1975) Genetic variation in nutrition of cattle for meat production. In: National Research Council (1975).

Watt, B. K. and A. L. Merrill (1950) Composition of Foods--Raw, Processed, Prepared. U.S. Department of Agriculture Handbook No. 8. Washington, D.C: U.S. Government Printing Office.

Wells, K. F. (1970) Foot-and-mouth disease: eradication and preventive measures in Canada. PAHO Scientific Publications 196:76-81.

Weston, R. H. and J. P. Hogan (1973) Nutrition of Herbage-fed Ruminants. Pages 233-268, Pastoral Industries of Australia, edited by G. Alexander and D. B. Williams. Sydney, Australia: Sydney University Press.

Whyte, R. O. (1975) The Animal Industry Potential in Monsoonal and Equatorial Asia. Paper presented at the Asian Productivity Organization Symposium on Diversification in Agriculture--Livestock and Poultry Production, Tokyo.

Wilham, R. L. (1976) Genetics of fat content in animal products. Fat Content and Composition of Animal Products. Washington, D.C.: National Academy of Sciences. In: National Research Council (1976).

Wittwer, S. H. (1975) Food Production and Supply: Priorities and Needed Outputs. Food Technology 29:28.

BIBLIOGRAPHY

Ayala, P. O. (1970) Planning of a foot-and-mouth disease control program. PAHO Scientific Publications 196:41-57.

Barat, S. K. (1975) Hides, skins and animal by-products. World Review of Animal Production 14:20-25.

Barfoot, L. W., J. F. Cote, J. B. Stone, and P. A. Wright (1971) An economic appraisal of a preventative medicine program for dairy herd management. Canadian Veterinary Journal 12:2-10.

Becton, P. (1976) Symposium: biological agents causing infections in dairy cattle. Journal of Dairy Science 59:1163-1165.

Bens, R. J. (1971) The economics of preventive medicine and swine production. Canadian Veterinary Journal 12:186.

Berg, A. (1973) The Nutrition Factor: Its Role in National Development. Washington, D.C.: The Brookings Institution.

Beveridge, W. I. B. (1960) Economics of animal health. Veterinary Record 72:810-815.

Borsella, J. (1970) Foot-and-mouth disease campaign in Argentina: results, benefits, and projections. PAHO Scientific Publications 196:58-65.

Bram, R. A. (1975) Tick-borne livestock diseases and their vectors, 1. the global problem. World Review of Animal Production 16:1-5.

Branagan, D. and J. A. Hammond (1965) Rinderpest in Tanganyika: a review. Bulletin of Epizootic Diseases of Africa 13:225-246.

Callow, L. L. (1974) Epizootiology, diagnosis and control of babesiosis and anaplasmosis, relevance of Australian findings in developing countries. Bulletin de l'Office Internationale des Epizooties 81:825-835.

Campbell, R. S. F. (1976) Veterinary training for the tropics with particular reference to the Australian experience. World Review of Animal Production 17:16-21.

Carpenter, T. E. (1976) Economic Losses Associated with Anaplasmosis in Cattle. Department of Food and Agriculture, Health and Industrial Relations, State of California, Sacramento.

Chu, H. P. and J. Rizk (1972) Newcastle disease--a world poultry problem. World Review of Animal Production 2:33-43.

Clark, F. L. (1968) Food habits as a practical nutrition problem. World Review of Nutrition and Dietetics 9:56-84.

Cockrill, W. R. (1964) The profession and the science: international trends in veterinary medicine. Advances in Veterinary Science and Comparative Medicine 9:251-325.

Cockrill, W. R. (1974) The Husbandry and Health of the Domestic Buffalo. Rome: Food and Agriculture Organization of the U.N.

Cockrill, W. R. (1976) The Buffaloes of China. Rome: Food and Agriculture Organization of the U.N.

Delgado, M. V. (1970) Foot-and-mouth disease campaign in Venezuela: results, benefits and prospects. PAHO Scientific Publications 196:69-75.

Dobbins, C. N. (1969) Mastitis losses. Modern Veterinary Practice 50:38-41.

Dorwart, R. A. (1959) Cattle disease (rinderpest?) prevention and cure in Brandenburg, 1665-1732. Agriculture History 33:79-85.

Ellis, E. M. and H. E. Kendall (1964) The public health and economic effects of vesicular stomatitis in a herd of dairy cattle. Journal of the American Veterinary Medical Association 144:373-380.

Ellis, R. (1975) The movement of live animals. Health aspects of world trade in animals and animal products. World Review of Animal Productivity 16:5-12.

Ferguson, W. (1969) Periodicity of epidemics and cost-benefit of vaccination programmes. Veterinary Record 85:420-421.

Food and Agriculture Organization of the U.N. (1970-1975) Animal Health Yearbook. Rome: FAO.

Food and Agriculture Organization of the U.N. (1970-1975) Animal Production Yearbook. Rome: FAO.

Food and Agriculture Organization of the U.N. and World Health Organization (1975) The Veterinary Contribution to Public Health Practice. Report of a Joint FAO/WHO Expert Committee on Veterinary Public Health. WHO Technical Report Series #573.

Gardner, R. L. and R. G. Edwards (1968) Control of the sex ratio at full term in the rabbit by transferring sexed blastocysts. Nature 218:346-349.

Gordon, R. F. (1976) The economics of disease on the poultry industry. Veterinary Record 80:101-107.

Groot, H. (1970) Epidemiology of the epizootic form of Venezuelan equine encephalitis and its impact on the economies and health of the nations of the Americas. PAHO Scientific Publications 196:58-65.

Grunsell, C. S., R. H. C. Penny, S. R. Wragg, and J. Allcock (1969) The practicability and economics of veterinary preventive medicine. Veterinary Record 84:26-41.

Hansel, W. (1967) Control of the ovarian cycle in cattle. A review. Australian Veterinary Journal 43:441.

Herschler, R. C., C. Miracle, B. Crowl, T. Dunlap, and J. W. Judy (1964) The economic impact of a fertility control and herd management program on a dairy farm. Journal of the American Veterinary Medical Association 145:672-676.

Hodgson, R. E. (1971) Place of animals in world agriculture. Journal of Dairy Science 54:442-447.

Hugh-Jones, M. E. (1976) Bovine Brucellosis Eradication Model for the United Kingdom. Proceedings, International Symposium on New Techniques in Veterinary Epidemiology and Economics, University of Reading, Reading, England.

Hugh-Jones, M. E., P. R. Ellis, and M. R. Felton (1975) An Assessment of the Eradication of Bovine Brucellosis in England and Wales. Study #19, Animal Health Group, Department of Agriculture and Horticulture, University of Reading, Reading, England.

Inskeep, E. K. (1973) Potential uses of prostaglandins in control of reproduction cycles of domestic animals. Journal of Animal Science 36:1149.

Ishikawa, S. (1971) Changes in the structure of agricultural productivity in mainland China. Agrarian Policies and Problems in Communist and Non-Communist Countries, edited by W. A. Jackson. Seattle: University of Washington Press.

Jahnke, H. E. (1974) The Economics of Controlling Tsetse Flies and Cattle Trypanosomiasis in Africa Examined for the Case of Uganda. Ifo-Institut fur Wirtschaftsforschung, Weltforum Verlag, Munchen.

Johansson, I., B. Lindke, and F. Pirschner (1974) Cause of variation in the frequency of monzygous and dizygous twinning in various breeds of cattle. Herditas 78:201-234.

Johnston, B. F. and J. W. Mellor (1961) The role of agriculture in economic development. American Economic Review 4:566-593.

Johnston, J. H. (1975) Public policy on cattle tick control in New South Wales. Review of Marketing and Agricultural Economics 43:3-39.

Kafel, S. (1975) Exporting animals and meat from developing countries, the major impediments. World Review of Animal Production 14:15-19.

Kaplan, M. M. (1966) Social Effects of Animal Diseases in Developing Countries. Agricultural Series #3. Institute of Agriculture, University of Minnesota.

Kiddy, C. A. and H. D. Hafs, eds. (1971) Sex Ratio at Birth--Prospects for Control. A Symposium. Champaign, Ill.: American Society of Animal Scientists.

Kverno, N. B. and G. C. Mitchell (1976) Vampire bats and their effect on cattle production in Latin America. World Review of Animal Production 17:16-21.

Leech, F. B. (1961) Food losses through animal disease. Proceedings of the Nutrition Society 20:20-24.

Leech, F. B., M. E. Davis, W. D. Macrae, and F. W. Withers (1960) Disease, Wastage and Husbandry in the British Dairy Herd. Report of a National Survey in 1957-58, Fisheries and Food. Ministry of Agriculture, London.

Looslie, J. K., V. A. Igenuga, and G. M. Babatunde (1974) Animal Production in the Tropics--Proceedings, International Symposium on Animal Production in the Tropics. Ibadan, Nigeria: Heinemann Educational Books Limited.

MacEvoy, M. G. (1974) Establishment and management of pastures in coconut plantations. Extension Bulletin, ASPAC Food & Fertilizer Technology Center (Asian and Pacific Council).

Mack, R. (1971) The great African cattle plague epidemic of the 1890s. Tropical Animal Health and Production 2:210-219.

Mahler, H. (1976) World Health Organization and the new economic order. WHO Chronicle 30:215-222.

Maurer, F. D. (1975) Livestock, a world food resource threatened by disease. Journal of the American Veterinary Medical Association 166:920-923.

McCallon, W. (1971) Current status of economic analysis of animal health programs. Fourth Inter-American Meeting on Foot-and-Mouth Disease and Zoonoses Control, Lima, Peru.

McCauley, E. H. (1974) The contribution of veterinary service to the dairy enterprise income of Minnesota farmers: production function analysis. Journal of the American Veterinary Medical Association 165:1094-1098.

Morris, R. S. (1969) Assessing the economic value of veterinary services to primary industries. Australian Veterinary Journal 45:295-300.

Morris, R. S. (1969) Mastitis control within a preventive medicine programme. Victorian Veterinary Proceedings 1968-69:56-57.

Morris, R. S. (1969) The economic evaluation of a dairy preventive medicine programme. Victorian Veterinary Proceedings 1968-69:59-60.
Morris, R. S. (1971) Economic aspects of disease control programmes for dairy cattle. Australian Veterinary Journal 45:358-363.
Morris, R. S. (1975) The economics of animal disease control. 19th Annual Conference of the Australian Agricultural Economic Society.
Morris, R. S. (1975) The integration of economic and epidemiological methods in the study of animal disease. Meeting of the Scientific Advisory Committee to the Pan American Foot-and-Mouth Disease Centre, Rio de Janeiro.
Morris, R. S. (1976) Animal health information systems. Proceedings, International Symposium on New Techniques in Veterinary Epidemiology and Economics, University of Reading, Reading, England.
Morris, R. S. and D. C. Blood (1968) The profession and agricultural economics. Correspondence. Veterinary Record 83:475-476.
Morris, R. S. and D. C. Blood (1969) The economic basis of planned veterinary services to individual farms. Australian Veterinary Journal 45:337-341.
Morrow, D. A. (1966) Analysis of herd performance and economic results of preventive dairy herd health programs, I and II. Veterinary Medical Journal 61:474-483, 577-582.
Mulhern, F. J. (1970) Repercussions of the occurrence of foot-and-mouth disease in a disease-free area. PAHO Scientific Publications 196:90-96.
Mullenax, C. H. and B. B. Norman (1968) A systematic approach to the resolution of livestock production problems in Colombia. Agricultura Tropical 24:605-615.
Muriithi, I. E. (1973) Disease control and agricultural extension services. Bulletin of Epizootic Diseases of Africa 21:477-483.
National Research Council (1966) A Historical Survey of Animal Disease Morbidity and Mortality Reporting, Publication #1346. Washington, D.C.: National Academy of Sciences.
National Research Council (1974) African Agricultural Research Capabilities. Washington, D.C.: National Academy of Sciences.
National Research Council (1975) Enhancement of Food Production in the United States. Washington, D.C.: National Academy of Sciences.
National Research Council (1975) World Food and Nutrition Study: Interim Report. Washington, D.C.: National Academy of Sciences.

Nazlioglu, M. (1967) Economic losses caused by foot-and-mouth disease in Turkey and sanitary measures taken. Bulletin de l'Office Internationale des Epizooties 68:533-540.

Odenh'hal, S. (1970) A Preliminary Report on the Ecology of Cattle in Rural West Bengal. Papers and Proceedings, 11th Technical Meeting, International Union for Conservation of Nature and Natural Resources. Vol. I. New Delhi, India.

Oduye, O. O. (1975) Bovine cutaneous streptothricosis in Nigeria. World Review of Animal Production 16:13-18.

Omerod, W. E. (1976) Ecological effect of control of African trypanosomiasis. Science 191:815-821.

Pagot, J. R. and H. Serres (1974) Livestock and veterinary medicine institute for tropical countries. World Review of Animal Production 9:34-38.

Pritchard, W. R. (1968) Importance of animal disease in the economic development of countries of the hemisphere. PAHO Inter-American Meeting on Foot-and-Mouth Disease and Zoonoses Control, Washington, D.C.

Pritchard, W. R. (1969) Intensification of Animal Production in the World Food Problem. A Report of the President's Science Advisory Committee, Vol. II. Washington, D.C.: U.S. Government Printing Office.

Pritchard, W. R. (1976) Animal disease constraints to world food production. Journal of Theriogenology 6:305-312.

Robson, J. R. K. (1972) Malnutrition: Its Causation and Control, Vol. I. New York: Gordon and Breach.

Roe, R. T. and R. S. Morris (1976) The integration of epidemiological and economic analysis in the planning of the Australian eradication programme. Proceedings, International Symposium on New Techniques in Veterinary Epidemiology and Economics, University of Reading, Reading, England.

Rogers, L. R. (1972) Economics of replacement rates in commercial beef herd. Journal of Animal Science 34:921-925.

Ross, J. G. (1970) The economics of Fasciola hepatica infections in cattle. British Veterinary Journal 126:13-15.

Rowson, L. E. A., R. A. S. Lawson, and R. M. Moor (1971) Reproduction of twins in cattle by egg transfer. Journal of Reproduction Fertility 25:261.

Rowson, L. E. A., R. M. Moor, and R. A. S. Lawson (1969) Fertility following egg transfer in the cow; effect of method, medium and synchronization of estrus. Journal of Reproductive Fertility 18:517.

Salisbury, G. W. and R. H. Hart (1975) Functional integrity of spermatozoa after storage. BioScience 25:159-165.

Salisbury, G. W. and N. L. VanDemark (1961) Reproductive Physiology and Artificial Insemination of Cattle. San Francisco and London: W. H. Freeman and Co.

Schwabe, C. W. (1968) Animal diseases and world health. Journal of the American Veterinary Medical Association 153:1859-1863.

Schwabe, C. W. (1970) Diseases in Animals and Man's Well-being. University of Saskatchewan, University Lectures, #24.

Schwabe, C. W. and R. Ruppanner (1972) Animal diseases as contributors to human hunger problems of control. World Review of Nutrition and Dietetics 15:185-224.

Scott, J. T., Jr. (1970) The hog cholera eradication program: What are its costs and benefits to hog producers? How does it affect other special groups? What are the economic effects of society as a whole? Illinois Research 12:8-9.

Siefert, G. W. (1971) Variations between and within breeds of cattle in resistance to field infestations of the cattle tick (Boophilus microplus). Australian Journal of Agricultural Research 22:159-168.

Smith, L. E., Jr., G. D. Sitton, and C. K. Vincent (1973) Limited injections of follicle stimulating hormone for multiple births in beef cattle. Journal of Animal Science 37:523.

Smithcors, J. F. (1964) The development of veterinary medical science. Some historical aspects and prospects. Advances in Veterinary Science and Comparative Medicine 9:1-34.

Steelman, C. D. (1976) Effects of arthropod parasites on domestic livstock production. Annual Review of Entomology 21:155-178.

Streenan, J. M. and D. Beehan (1974) Egg transfer in the cow: pregnancy rate and egg survival. Journal of Reproductive Fertility 41:497.

Task Force on Medicine and Public Health (1967) Education and World Affairs: The Professional School and World Affairs. Albuquerque: University of New Mexico Press.

Taylor, S. M. (1974) The cost of liver fluke in Northern Ireland. Agriculture in Northern Ireland 49:264-268.

Trejos, A. and J. F. Williams (1970) The problem of hydatidosis in the Americas. PAHO Scientific Publications 196:122-126.

Tremblay, R. H. (1969) Economic evaluation of the rinderpest eradication campaign in West Africa. U.S. Department of Agriculture and U.S. Agency for International Development. Washington, D.C.: U.S. Government Printing Office.

Turner, H. (1968) The Effect of Selection of Lambing Rate. Proceedings, Symposium on Physiological Reproduction, Stillwater, Oklahoma.

U.S. Department of Agriculture (1965) Losses in Agriculture. Agricultural Handbook #291. Agricultural Research Service. Washington, D.C.: U.S. Government Printing Office.

U.S. Department of Agriculture (1969) Economic Aspects of Agricultural Development in Africa: A Selective Reading List of Reports and Studies Concerning 40 African Countries during the Period 1960-1969. Washington, D.C.: U.S. Government Printing Office.

U.S. Department of Agriculture (1970) A Program Planning Budgeting Model for the Eradication of Trichinosis of Swine in the United States. Consumer and Marketing Service, and Agricultural Research Service. Washington, D.C.: U.S. Government Printing Office.

U.S. Department of Agriculture (1975) Supplement to Statistical Bulletin #547. Washington, D.C.: U.S. Government Printing Office.

World Health Organization (1970) Consultations on the Socioeconomic Consequences of Zoonoses and Their Control. Geneva, Switzerland.

World Health Organization (1972) Report of Consultations on Socioeconomic Aspects of Zoonoses. Reading, England.

Wragg, S. R. (1970) The economics of intensive livestock production. Veterinary Record 86:33-37.

Report of Study Team 3

AQUATIC FOOD SOURCES

STUDY TEAM 3

John E. Bardach, CHAIRMAN, Hawaii Institute of Marine Biology and East-West Center
Robert C. May, LEAD ANALYST, Hawaii Institute of Marine Biology
Harvey R. Bullis, Jr., National Oceanic and Atmospheric Administration
James A. Crutchfield, Jr., University of Washington
Harold L. Goodwin, Bethesda, Maryland
John E. Halver, University of Washington
Harlan C. Lampe, University of Rhode Island
John C. Marr, Mardela Fisheries, Ltd.
George M. Pigott, University of Washington
Eddie W. Shell, Auburn University
Lucian M. Sprague, International Bank for Reconstruction and Development
Kenneth E. F. Watt, University of California, Davis

ACKNOWLEDGMENTS

We wish to thank the following persons for participating in various meetings of this study team: J. B. Glude, National Marine Fisheries Service; C. P. Idyll, National Oceanic and Atmospheric Administration; J. E. Johnston, The Rockefeller Foundation; E. R. Pariser, Massachusetts Institute of Technology; and H. H. Webber, Groton BioIndustries Development Co.

Valuable comments on the draft report of this study team were provided by some of the above-named individuals, as well as by: W. H. L. Allsop, International Development Research Centre; F. T. Y. Christy, Resources for the Future; J. A. Gulland, Food and Agriculture Organization of the U. N.; P. Helfrich, University of Hawaii; J. Liston, University of Washington; J. H. Ryther, Woods Hole Oceanographic Institution; Z. H. Shehadeh, International Center for Living Aquatic Resources Management; and M. A. Steinberg, National Marine Fisheries Service.

In addition, the following persons kindly responded to written inquiries on specific topics or met with this study team, its chairman, or lead analyst: J. R. Benemann, University of California, Berkeley; J. R. Calaprice, University of California, Santa Barbara; L. R. Donaldson, University of Washington; M. S. Doty, University of Hawaii; M. Fujiya, Freshwater Fisheries Research Laboratory, Tokyo; T. Gjedrem, Agricultural University of Norway; C. L. Hubbs, Scripps Institution of Oceanography; J. E. Huguenin, Groton BioIndustries Development Co.; R. Moav, Institute of Animal Science, Bet-Dagan; M. Nomura, Kanagawa International Fisheries Training Center, Yokosuka City; W. J. North, California Institute of Technology; C. E. Purdom, Fisheries Laboratory, Lowestoft; O. A. Roels, University of Texas Marine Science Institute; G. N. Rothwell, The Oceanic Institute; and A. Suda, Fisheries Agency of Japan, Tokyo.

Besides persons specifically mentioned, the study team received helpful advice on various subjects from many scientists and others involved in fisheries and aquaculture too numerous to mention individually.

We also wish to thank the Technical Advisory Committee (TAC) of the Consultative Group on International Agricultural Research for permission to refer to the Report of the TAC Subcommittee on Aquaculture. Finally, we wish to thank the staffs of the Hawaii Institute of Marine Biology, in particular, M. Kalaiwaa; the Open Grants Division of the East-West Center; and the World Food and Nutrition Study, without whose assistance the report of this study team could not have been produced.

TABLE OF CONTENTS

INTRODUCTION

FISH AS FOOD

Aquatic animals, predominantly fish, make up about 26 percent of people's total animal protein intake, excluding milk (Sprague and Arnold 1972, Pimentel et al. 1975). Fish consumption exceeds that of beef as well as of other domesticated animal categories taken singly. In addition, fishmeal is an important component of poultry and mammalian stock feed.

Fish are by far the most important source of animal protein in the tropics, e.g., Southeast Asia (Pantulu 1976), where possibly even a billion people rely predominantly on fish for animal protein. Besides figuring prominently in the external trade of some tropical countries, aquatic foods are important in other ways. First, aquatic products are nutritionally equivalent in protein to the meat of avian or mammalian stock, with a full complement of essential amino acids, and are low in saturated fat. Aquatic foods also are high in essential minerals and are culturally acceptable in many areas plagued by malnutrition where introduction of other animal food might be difficult. Second, fish can be elaborated into products that are combined easily with vegetable products (this also applies to fish hydrolysates for milk substitutes, i.e., weaning foods). Third, the quantity of aquatic food now harvested from oceans, lakes, rivers, and fishponds can be increased in the tropics as well as in the temperate zone, and wastage, which is great, can be reduced sharply. Fourth, aquatic productivity can be increased beyond the levels that presently prevail in natural ecosystems.

Aquatic plants require special comment. Macroscopic aquatic plants, of which kelp is a familiar example, do not directly contribute to meeting nutritional needs for protein or calories, though they may supply important trace minerals. However, their use in industrial products and condiments makes them economically important. Most aquatic plants are microscopic algae which can be high in protein and therefore potentially valuable as food. But their production for use in human nutrition presents great technical, economic, and sociocultural problems. Thus for the foreseeable future animal protein will remain the major contribution of aquatic food sources to human nutrition.

Because of the ecological and evolutionary characteristics of aquatic environments and species, a substantial portion of the potential foods from the world's waters will continue to elude direct human control. Important factors are the motile or migratory nature of most stocks, the competition among many species for the same food, and the high fecundity and mortality rates of fish during their early stages. These factors, coupled with our lack of mastery over the aquatic environment, have necessitated managing the fish of the sea and most lakes through influencing the harvesters rather than the production base. In addition, fish are common property resources with all of the institutional problems such a resource status implies, belonging to no one and at the same time to everyone. Yet we are now endeavoring to increase direct control over aquatic stocks and/or their production base through management that is in some ways akin to that prevalent in animal husbandry; this approach is aquaculture in the broadest sense.

PRESENT AND FUTURE AQUATIC FOOD PRODUCTION

The latest available estimates (FAO 1975b) place the total world food production from fresh and saltwater in 1974 at 69.8 million tons, whales excluded. About 12 million tons of this amount is from fresh- and the rest from saltwater. Animals other than fish, i.e., molluscs and crustaceans, make up about 7 million tons, or 10 percent of the total. Included predominantly but not exclusively in the freshwater production is 5 million tons from aquaculture.

The world fish catch rose steeply between 1948 and 1969 (see Figure 1). Since then the rate of increase has slowed substantially, and the world catch appeared to level off between 1969 and 1974. Gulland (1971) states that for a while world catches may change but little and surely at a slower pace than in the third quarter of the present century. The rapid rise in fisheries production after World War II has been explained by (1) replenishment of stocks due to reduced fishing activities during hostilities; (2) building of new and modern fishing vessels, with fishing above sustained yield levels in certain areas; (3) discovery and rapid utilization of certain stocks of small schooling fishes (e.g., Peruvian anchovies); and (4)

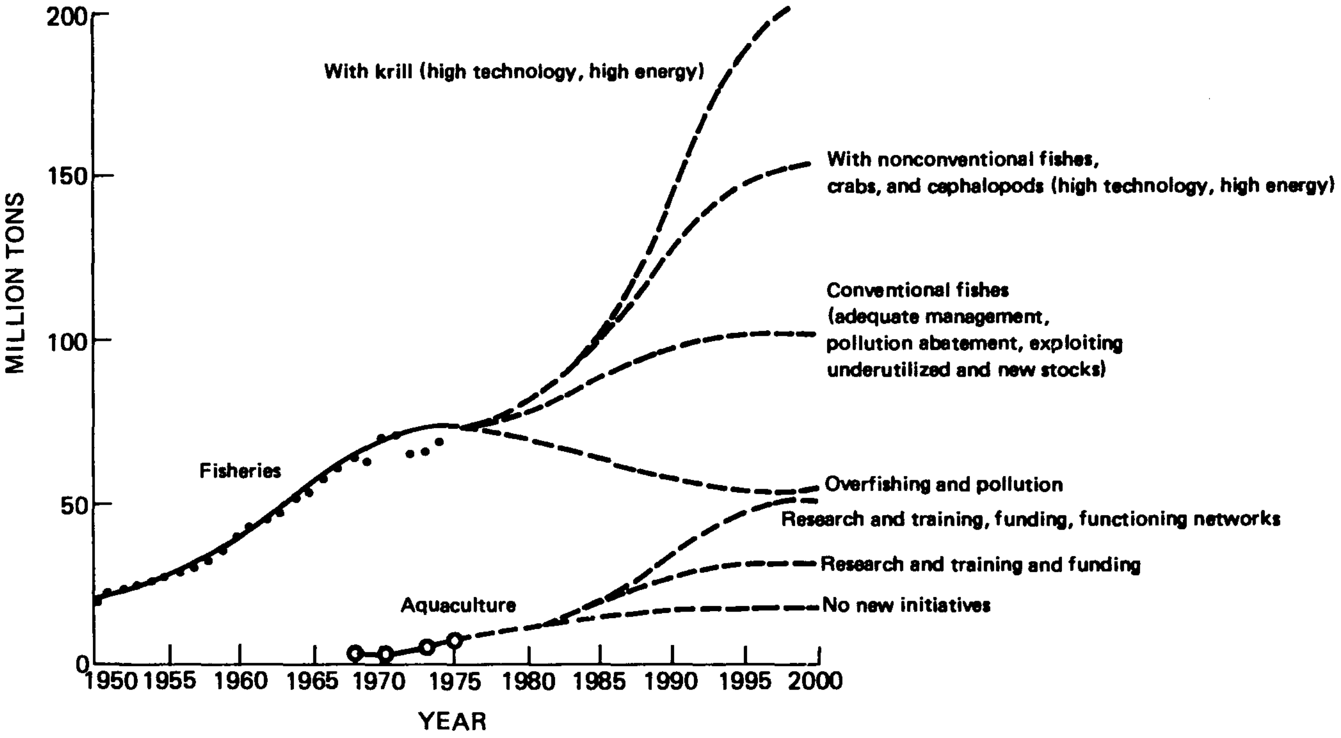

FIGURE 1 Actual and projected world fish catch, 1950-2000.

SOURCES: Fisheries statistics, FAO (1950-1974); fisheries projections, FAO Technical Conference on Fishery Management and Development, 1973; and aquaculture statistics and projections, Pillay (1976).

emergence of some nations as important world fish producers (e.g., Peru, U.S.S.R., South Korea, Taiwan).

By contrast, U.S. fisheries have grown little during the last 20 years, with sporadic exceptions in certain species such as tunas (U.S. Department of Commerce 1975). Fish consumption in the United States has increased commensurately with the population increase, but for economic reasons (e.g., high labor costs) fish imports rather than increases in the domestic catch have met the expanded demand for fish for direct human consumption as well as for animal feeds. Consequently, except for tuna and shrimp fisheries, U.S. fish capture technology has not developed as effectively as that of other technologically advanced nations. Perhaps as a result of the U.S. marketing system with its high sanitary standards and ubiquitous use of refrigeration, the country has substantial capabilities in fish processing technology. Significantly, the United States, with many other coastal nations, has declared a 200-mile extended economic zone. The consequences may be a rise in U.S. fishing activity, especially in view of the large stocks in the expanded waters (U.S. Department of Commerce 1975). While some species among these stocks are not traditionally consumed in the United States, techniques for their processing and marketing are available.

The world fish catch is made up only in part of traditional table fish, which are generally large carnivorous animals. The other main portion of the marine catch is made up of small schooling fishes largely reduced into fishmeal, oil, and solubles which mostly find their way into animal feed, with some ancillary, minor industrial uses. About 21 million tons of the total 69 million tons were so used in 1974. In 1970, before the decline of the Peruvian anchovy catch, nearly 26 million tons of the 70 million tons total were used for reduction. It is often advocated (Borgstrom 1974, Sprague and Arnold 1972) that direct food use of much or some of this portion is desirable on ecological and nutritional, if not eventually economic, grounds. The fact remains, however, that the spatiotemporal distribution of these fish (large schools in certain places and seasons), coupled with present technological constraints, make such use less practical than may appear at first glance. Nevertheless, technologies must be developed to permit an increasing direct consumption of this portion of the world catch, a necessity that is addressed in this report.

Largely because of differential ocean fertilities, the developing countries, located mainly in tropical and some near-tropical portions of the world, furnished only about 43 percent of the total marine catch, or 30 million tons, in 1974 (FAO 1975b). The tropics, however, are the site of about 70 percent of the world's aquacultural production (Pillay 1976). Aquacultural production, although it appears to have grown substantially in the past few years (about 17 percent per year), is still relatively small. In fact, it supplies only 5 million tons, i.e., less than 10 percent of the world's total fish production. These figures probably reflect a real increase in aquaculture and also an improvement in Food and Agriculture Organization (FAO) statistics.

Estimates of the potential for increasing aquatic food production, especially in the case of capture fisheries, are hampered by a number of uncertainties. Appraisals of the magnitude of fish stocks vary widely, and Gulland (1971:Figure 1) stresses that quantum increases are possible only through the capture of presently unused resources (krill, squid, and midwater fishes). Were these tapped, which would be possible only with high technology and high energy inputs, the present global fish catch of 70 million tons might go up to 200 million tons (see Figure 1), with estimates ranging as high as 400 million tons (Idyll 1970). If this were to happen, the effects on the malnourished populations of the world would be indirect at best. Some harvest of tropical squid populations may be an exception to this statement.

More germane to the task of this study team are estimates of increases that are possible within the next few decades by expanding the fisheries for pelagic (open sea) and demersal (bottom-associated) fishes in the tropics. Sprague and Arnold (1972) estimate that these two categories would yield eventually about 48 and 42 million tons respectively worldwide. Drawing on Gulland (1971) and on estimates provided by this study team, we estimate that there are 20 to 30 million tons within geographic reach of malnourished nations that could be harvested in addition to the present catch. Some of these fish would undoubtedly best be made into fishmeal, albeit with the advances and therefore savings advocated here, while the rest would enter direct human consumption. Fishing-related operations, from landing the quarry on the boat to bringing it to the plate or even into the bag of fishmeal, are extremely wasteful. Foremost attention must be paid therefore to waste-eliminating technology which promises gains equal to those of extending fishing ranges and/or grounds.

Pollution has taken its toll of fisheries mainly in the north temperate regions with inland seas (Baltic, Mediterranean, the Seto Inland Sea of Japan). Estuaries and bays are the most seriously affected sites. In the tropical and/or developing countries, the International Oceanographic Commission of the United Nations Educational, Scientific, and Cultural Organization (UNESCO 1976) finds industrial pollution relatively scarce and states that "The pollutants of primary concern [in the tropics] are bacteria, oil residues, pesticide residues and organic matter from sewage." Little information exists on the behavior of pollutants in warm marine environments but pollution, once begun, can quickly reduce local stocks of food fishes and can pose public health hazards. The developing countries lack the scientific personnel necessary for pollution work. They also often lack an awareness of the potential ill-effects of industrial waste and of massive sewage discharges into rivers and the sea on aquatic food production (fisheries and aquaculture). These discharges and even oil spills are expected to increase in the tropics as countries develop (UNESCO 1976) and will require increased monitoring if not abatement to prevent declines in actual and potential fish harvests in many sites (Figure 1).

Presently, aquaculture is confined largely to fresh- and brackishwaters but has the potential, though largely unrealized, of mariculture and the ranching of aquatic animals in seas, lakes, and reservoirs. The expansion potential of aquaculture is largely in the tropics, where it flourishes more than in the temperate zone even now. It has been estimated that aquacultural production can grow fivefold to tenfold by the year 2000 or thereabouts (Pillay 1976:Figure 1). Thus adding the perhaps conservative estimates from fisheries (20 to 30 million tons) and aquaculture (30 million tons), conventional aquatic food increases in the tropics would amount to 50 to 60 million tons by the year 2000. This figure implies that in the tropics a near threefold increase of present aquatic food sources, from about 30 million tons to 80 to 90 million tons whole weight, exvessel or pond, theoretically is possible, even without having recourse to new technologies. These new technologies, especially artificial upwelling, could increase tonnages even further, in the long run by considerable amounts.

GOALS AND ORGANIZATION OF THIS REPORT

The goal of our recommendations is to optimize, through a mix of science, technology, and organizational inputs, increases in aquatic food production and availability at reasonable costs, with the expectation of good results for the developing nations. This will be accomplished through appropriate

U.S. activities within an international framework with the assumption that important spinoffs also will be realized for U.S. aquatic food production and availability.

The possible increases in aquatic food production are predicated on research advances on two broad fronts. First are assemblages of research projects based on science and technology, treated in this report as research profiles. (In Table 1 each profile is assigned a priority and given an estimated degree of success in both the short and long term.) Second are long-range research programs that deal specifically with the institutional and policy aspects of aquatic food production. These stress broad frameworks for research implementation and training. These matters are treated in a later section. Programs of this nature are essential for fisheries because of their common property nature. This has no counterpart in agriculture. Furthermore, national and international (legal) concepts of much of the resource and its base (i.e., the sea), including the important areas of pollution control and international aspects of marine research, are now subject to redefinition in the United Nations (the U.N. Conference on the Law of the Sea).

Table 1. Priorities and probable degree of success of research profiles

Profile	Priority*	Probable degree of success (percent) Less than 15 years	 Greater than 15 years
1. Multispecies Fisheries Management	2	40	60
2. Improved Catch Utilization	1	80	90
3. Improved Fish Location	3	30	80+
4. Biotechnical Gear Development	3	50	75
5. Aquaculture	1	80	90
6. Artificial Upwelling Aquaculture	2	0	80+

*1 = highest priority, 3 = lowest.

Profile 1

MULTISPECIES FISHERIES MANAGEMENT

Fish stocks that can be exploited more heavily, and that are adjacent to the developing countries, include populations of groundfish, best taken by bottom or midwater trawling, and of small, shoaling pelagic species, efficiently captured by purse seines. The catch normally consists of dozens of different species, with wide variations in market value. In tropical waters these factors combine to create potentially severe management problems. Economic incentives to take the most profitable species will cause serious problems in the future because of side effects on other species which are not currently profitable but promise large food supplies in the future. Imperfect market organization can account for the lack of economic incentives to harvest these latter types. Providing protection against depletion while market development work is undertaken is even more important in this instance.

Large multispecies stocks are found within the 200-mile economic zone now claimed by the United States. Hence the possible expansion of U.S. fisheries based on these stocks, and the obligation imposed on the United States to manage these stocks whether harvested by U.S. flag carriers or by others under joint agreements, make this research of paramount importance to the United States and other countries.

RESEARCH NEEDS

Assessment of multispecies fishery stocks is accompanied by an analysis of the dynamics of the principal, commercially interesting populations and includes at least preliminary work on interactions of these stocks under fishing pressure. Previous and ongoing work by the United States, U.S.S.R., Japan, and FAO on the theory of multispecies fisheries underscores the complexity of the functional relations involved and of data requirements. Nevertheless, even first approximations of interspecies interactions are highly useful in planning investment in fisheries and management programs for the future.

Given the complexity of multispecies stocks, especially in the tropics, it would be highly desirable to formulate simple principles that can be applied by managers to keep resources reasonably well managed. This would include defining minimum data requirements to permit adequate management and improved utilization of the mixed species involved. We recommend therefore that one or more developed multispecies fisheries for which reasonably adequate data are available be studied in detail.

It is expected that these mission-oriented efforts will be paralleled by ongoing work in many centers to develop more sophisticated models (and corresponding data systems) that will make fuller use of modern computer capability. Feedback channels must be established between these two parallel lines of work.

IMPACT

The results of this research should be available in five years, and have an effect on food production within 10 years, if national and international institutional frameworks exist and are made effective. Improvements in processing technology could enhance the effect.

This research is essential to understanding the multispecies stocks exploited by trawling, which are estimated to be capable of supporting an increase of 20 million tons worldwide, with at least 7 million tons in the tropics. If purse seining and midwater trawling also are used, the increase could be 30 million tons. Improved understanding of multispecies stocks would help avert declines in fisheries yields, which could come about if exploitation continues without a sound basis for management.

Exploitation of multispecies stocks is based on reasonably mechanized harvesting technologies, and therefore is not conducive to high labor use, but is conducive to raising incomes. Assuming, for example, that Indonesian waters are capable of yielding an additional 2 to 3 million tons through well-managed fisheries expansion, and that one fisherman produces 50 tons per year, 40,000 to 60,000 new jobs would result from expanded fisheries. Several times this number of new jobs will result from associated processing and marketing activities. An increase of 2 to 3 million tons round weight is equivalent to .28 to .42 million tons of protein (using 14 percent as a conversion factor; Pimentel et al. 1975). The 20 million tons worldwide figure (round weight) translates to 2.8 million tons of protein, or nearly half of the fish protein used for direct human consumption in 1975 (Pimentel et al. 1975).

Improved understanding of multispecies complexes is expected to permit improved conservation of marine ecosystems; this includes conservation of presently utilized living resources as well as rational utilization of still-unexploited resources.

One area that this research would affect would be the United States, where improved knowledge of multispecies fisheries would enable rational management of stocks occurring within the newly claimed 200-mile economic control zone. Another area would be Southeast Asia; a third, the west coast of Africa; and a fourth, Central America. In the foreign areas mentioned, a major portion of the stocks is exploited by gear of limited selectivity so that the problem of multispecies fishery management is pressing and unavoidable. Research conducted in the United States should enable transferring technology to the other areas.

This research has a high probability of success, but successfully applying it depends on institutions. The combination of this research with improved processing technology most likely would have the greatest effect on urban rather than rural populations.

IMPLEMENTATION

The National Oceanic and Atmospheric Administration (NOAA) and selected U.S. university and state fisheries organization scientists should participate in this research. In order to assure technology transfer, a team leader would organize recurrent work and/or training sessions in both the data acquisition and analysis phases, with selected fishery scientists from the developing and high-income countries and FAO included.

We and outside consultants both agree about the value of this research but find it difficult to recommend a "best" location where the study could be carried out. In view of the emphasis on complex multispecies stocks that are characteristic of the tropics, the U.S. fishery in the Gulf of Mexico is one possible candidate, with work to be coordinated by the Southeast Fisheries Center. Given the cooperation of the FAO/U.N. Development Programme (UNDP) South China Sea Fishery Development and Coordinating Program of the Philippine government, and of the International Center for Living Aquatic Resources Management (ICLARM), the

South China Sea is another possible site, and the Gulf of Thailand a third.

Depending on the site chosen, data acquisition and analysis should take three to five years. If the research is executed in the United States, existing priorities for this type of research in the Department of Commerce would have to be elevated and pertinent efforts of the National Marine Fisheries Service (NMFS) would have to be coordinated nationally and with Mexico and FAO. If the research were executed within the framework of the South China Sea Program, FAO would take the lead and the United States should send at least three experts for five scientist-years each. The total cost of the project would be $2.5 million, including data acquisition.

Profile 2

IMPROVED CATCH UTILIZATION

Fresh fisheries products are highly perishable. Considerable amounts of captured and cultured fish are lost from spoilage and lack of adequate processing and preservation in addition to normal processing waste. In small-scale rural fisheries, where frequently no preservation technologies are applied, losses of up to 40 percent of the initial wet weight of the fish are believed to occur (Day 1976). In large industrial operations such as the Peruvian anchovy fishery, shipboard deterioration may account for the loss of massive tonnages of fish flesh. By improving preservation and processing technologies or applying current technologies, a portion of the 60 percent or more of the world fish catch that now ends up as animal feed or waste could be used for direct human consumption (Pigott 1976). Suitable technologies could also allow using part or all of the shrimp fisheries by-catch, projected to reach 10 to 20 million tons per year by 1985 (FAO 1975a:77).

Table 2 shows the estimated waste from the world catch currently being discarded or used for low-grade animal feed. This estimate, based on a knowledge of processing methods, is believed to be conservative concerning processing plant waste. Of the 24.4 million tons of estimated waste, at least one-half could be made available with certain changes in present plant operations. Most of the 7.8 million tons of freezing waste and the 2.1 million tons of canning waste should be available since these operations are normally carried out in medium-size to large-size central plants. Conservative estimates are that 10 million tons of waste could be diverted into higher use categories with relatively minimal effort.

The research activities recommended here are largely adaptive research pertaining to existing technologies or technologies that are nearly perfected. There is less "knowledge gap" research involved than in certain other areas of aquatic food production.

Successful application of this research, however, would nearly double the amount of fish protein available for human consumption. Saving fish through various processing methods was an early invention and has undergone improvement through time. Changes and improvements in these methods are now underway in many locations, e.g., Thailand (The Asian Institute of Technology in Bangkok), Japan, and the United States. Present adaptive research lacks focus, however, and would benefit from planned coordination, establishment of effective information transfer channels, and regional extension facilities. As we mentioned in the Introduction, processing technology is one area in which the United States has substantial capabilities.

RESEARCH NEEDS

Research on technological improvements in catch utilization must proceed at two levels, and in many cases the end results will complement one another. The modern fishing fleets and processing plants of the high-income countries have sophisticated means of handling mass quantities of fish, even though efficiency from the standpoint of utilization often is minimized. Some developing nations also have such fleets (e.g., Thailand). In these developing countries, technologies must be developed to segregate large volumes of catch into more uniform raw materials and to upgrade utilization through better preservation techniques and practices.

In contrast, many developing countries require more rudimentary technologies to upgrade local fish utilization from artisanal (low technology) fisheries. Extensive development of this area eventually will result in larger and more sophisticated commercial entities. This will be especially true of aquaculture, which in some locations could develop into large central growing areas requiring the most modern processing technology. Hence the aims of small-scale and more industrial fisheries-oriented research are compatible in both the high-income and developing countries.

Below we identify high priority research that should be supported by the United States. The work required under the various categories is interrelated, making worldwide coordination of research activities most desirable.

Table 2. Estimates of waste in the processing of fishery products, 1974

Processing method	Proportion of world catch in 1974[a] (percent)	(million tons)	Estimated amount utilized[b] (percent	(million tons)	Estimated waste (million tons)
Fresh	30.0	21.0	50[c]	10.5	10.5
Reduction	29.0	20.3	90[d]	18.3	2.0
Freezing	18.5	13.0	40[e]	5.2	7.8
Curing	11.5	8.0	75[f]	6.0	2.0
Canning	10.0	7.0	70[g]	4.9	2.1
Miscellaneous	1.0	0.7	100	0.7	0
TOTAL	100.0	70.0		45.6	24.4

[a] FAO (1975b).

[b] Estimated percent utilized is the amount going to the market or user where there is slight opportunity to reclaim further waste for processing. Exact figures are not available; our estimates are based on knowledge of processing techniques, and in all cases the amount wasted was estimated conservatively.

[c] Fresh fish are prepared in several manners for market, ranging from whole fish to finished fillets and steaks. A relatively small percentage is sold as whole fish, whereas a large amount is sold headed and gutted. A headed and gutted fish will average a yield of about 75 percent. A large

portion of the fresh fish are sold in a prepared state ranging from a 20 to 30 percent yield as fillets to as much as a 50 to 60 percent yield as steaks. In small-scale fisheries, fish tend to be eaten whole, but loss from direct spoilage before reaching the consumer may approach 50 percent. Hence an estimated 50 percent yield for utilized fresh fish is probably conservative, leaving 50 percent or 10.5 million tons as processing and/or spoilage waste.

[d] The use of "industrial fish" for reduction to oil and animal feed takes approximately the same amount of the world catch as does fresh fish. An estimate of 90 percent utilization is high since the large operations in the warmer climates lose considerably more than 10 percent of the raw material through spoilage and inefficient processing. Note, however, that reduction has the highest percentage utilized among the five major processing methods.

[e] The freezing of fish has increased in recent years at a much faster rate than any other method of processing for human consumption. Since most frozen fish are processed in commercial plants, the waste is readily available. Furthermore, most frozen fish are sold as fillets, blocks, or other forms that yield 20 to 35 percent from the raw material. A 40 percent utilization in this category would result in 60 percent or 7.8 million tons of highly nutritious waste that is centrally available. Some of this material is currently being sold for cheap animal food, but much of it could be upgraded to high-grade animal or human food.

[f] Most fish are headed and gutted prior to curing so that an estimate of 75 percent utilization should be quite accurate. However, much of the 2 million tons of waste will be in small plants or communities where large concentrations of waste will not result.

[g] Approximately two-thirds of a raw fish is used for canning. Waste from canneries is normally concentrated in large volumes so that much of the estimated 2.1 million tons should be available for further processing.

Improved Use of Industrial and By-catch Fish

To improve the use of industrial and by-catch fish, we must: (1) upgrade a fair to substantial portion of the industrial fish catch to human food; (2) use presently discarded by-catches; and (3) improve the efficiency of raw material utilization, thereby minimizing waste.

These research objectives can be accomplished by:

- Improving and developing systems of shipboard preprocessing, pickup and transfer of fish on the high seas, stabilization of fish (both on shipboard and on shore), and transport of raw materials.
- Developing mechanization techniques for sorting fish into desired groups of specific size and/or shape for shipboard or shore operations.
- Developing high-speed facilities for heading and gutting fish that are normally limited to fishmeal because of the inability to process large amounts before deterioration sets in.
- Developing techniques for extracting high quality fish proteins to be used as food supplements. Refinements must be made in existing techniques and the engineering technology necessary to assure success on commercial scales must be developed.

Improved Use of Fish Utilized for Direct Human Consumption

This research objective could be accomplished by (1) developing unitized modules that can be placed quickly on fishing vessels to convert them for different fisheries, (2) eliminating waste in certain commercial operations through in-plant changes, and (3) upgrading waste to "secondary raw materials" which can be converted into usable or higher quality products.

Some approaches to this research are:

- Adapt present knowledge to modernize materials-handling techniques to prevent spoilage and reduce waste in all phases of fish catching and processing.
- Adapt and improve available machinery and procedures for removing fish flesh from processed carcasses or acceptable industrial or by-catch fish.
- Develop acceptable formulated foods using deboned fish flesh as a source of protein.
- Develop unitized modules so that a vessel can handle and preprocess different raw materials. For example, one module could have all of the machinery

and facilities required for heading and gutting fish while another might have a deboning and block freezing capability.

Improved Fish Use in Small-scale Fisheries

The two research objectives here are to assist in a reduction of waste from small-scale fisheries, particularly those in warm climates, and to increase marketing possibilities through product development.

Developing cured products based on minced fish muscle which can be stored at room temperature is one approach to this problem. Another is the development of packages and packaging techniques to allow transport and storage of the above products without loss to vermin. An example of such a product would be a formulated dried fish cake which could be reconstituted and prepared like salt-fish. Developing low-cost, sanitary cooling and/or ice production emphasizing cooling by energy sources such as solar and wind power is still another approach. Improving the efficiency of small-scale, traditional ice manufacture should be pursued as well. Such developments will help reduce spoilage and allow fishermen to land fish in good condition.

In addition to the specific research needs described above, we wish to call attention to the importance of the following two areas in relation to small-scale fisheries.

Crucial Role of Extension Work

A major need in small-scale fisheries is the implementation of education and extension programs to show rural fishermen how to use the desirable handling practices for fish after capture, including the importance of sanitation and the use of ice and onshore water supplies. Such programs cannot be considered research, but they are fundamental to applying successfully the results of the research recommended here for small-scale fisheries as they are for other small-scale food production endeavors. These programs would fulfill the need for attention to extension and problems of technology transfer. Such extension programs can and should begin immediately so that target populations will be in a position to make effective use of the research results.

Influencing Taste Preferences

Although fish are avidly consumed in most of the developing world, in some areas, particularly in Central and South America, there are formidable cultural obstacles to fish consumption. In such instances, the use of new products may be necessary to allow the introduction of fish protein into local diets, but we believe that social and psychological studies on methods of influencing taste preferences also can play an important role in increasing fish consumption.

IMPACT

The research described here should take 5 to 10 years, and extension work in the developing countries should begin immediately. The advances advocated here will have a multiplicative effect since increases in catch made possible by other advances (e.g., improved management of multispecies fisheries, improved stock location, increased aquacultural productivity) will magnify the effects of improvements in processing technology.

If all of the research projects presented were carried out and their results applied widely, possibly more than 30 million tons of fish could be added to the amount of fish available for human consumption by the year 2000 (Figure 2). Assuming that the relative proportions of the various fishery products are the same in 2000 as in 1974, 13 million tons of the 30 million tons would come from the use of waste in directly consumed fish, 5 million tons from a 50 percent use of the shrimp by-catch, and 14.5 million tons from upgrading to direct human consumption 50 percent of the fish presently used for reduction. However, a substantial portion of these gains would occur in industrialized fisheries, with the direct nutritional benefits accruing mainly to the more affluent sectors of society.

Added to this 30 million tons would be savings realized from eliminating fresh fish waste, mainly in small-scale fisheries. Processing technologies recommended here will increase the availability of high quality animal protein to the rural poor by reducing spoilage losses and allowing storage and transport of fisheries products to areas remote from the site of landing. It is believed that at least 5 million tons could be saved for direct human consumption in this way. Developing methods that would combine extracted fish protein with local staples can contribute significantly to the nutritional well-being of the

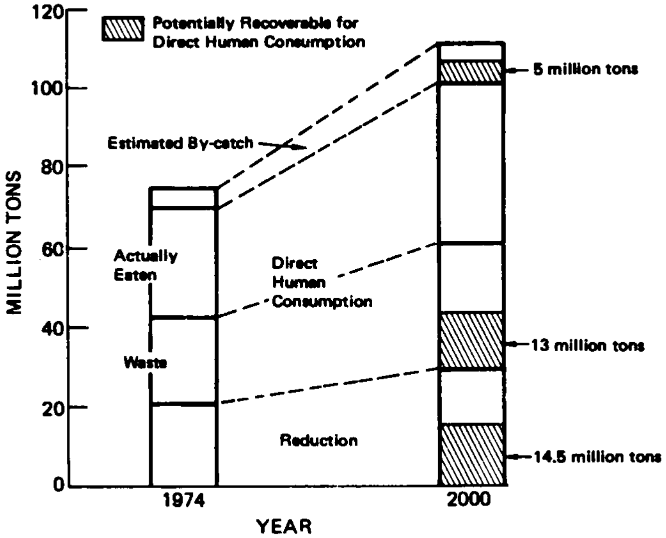

FIGURE 2 Fish catch for 1974 and estimated potential for 2000, and estimate of fishery products potentially recoverable for direct human consumption through processing improvements.

rural poor if adequate attention is given to product acceptability. Also, turning even a part of the present industrial fish catch to direct human consumption will be a positive contribution.

Much of the research recommended here can benefit U.S. fisheries by reducing waste and enabling utilization of at least part of the presently discarded by-catch. The net result will be an increase in the availability of domestically caught fish on the U.S. market and a decrease in imports. The expansion of U.S. fisheries, which may occur as a result of the newly declared 200-mile economic control zone, would make this research all the more relevant to the United States.

IMPLEMENTATION

The research we recommend can best be carried out by creating three centers for the development of processing technology and by linking each center with a consortium of U.S. universities. These centers would serve as sites for the research we have described and would play a vital role in promoting the badly needed extension work in fish handling. We recommend that one center be established in each of three regions, the centers to be chosen from those listed below.

- -- Southeast Asia: Iloilo, Philippines, Southeast Asian Fishery Development Center, Aquaculture Department; Bangkok, Thailand, Technology Laboratory, Thai Department of Fisheries and/or Kasetsart University; or Penang, Malaysia, Universiti Sains Malaysia.
- -- Latin America: Vera Cruz, Mexico, University of Vera Cruz; or Santos, Brazil, Instituto de Tecnologia de Alimentos (ITAL).
- -- Africa: Accra, Ghana, Oceanographic Institute; or Lagos, Nigeria, Federal Fishery Station.

Each center would require eight professional staff members and 12 technicians. Personnel plus facilities and operating costs would mean a total cost of $16 million per center for a five-year period, or $48 million for all three centers. Although we recommend the simultaneous establishment of these three centers to achieve the maximum short-term effect, the program could begin at a single center, with the other centers phased in at later dates.

In addition to the centers, we recommend that a 130-foot to 200-foot vessel be outfitted with equipment for conducting simple processing operations on fishery products. This vessel should include a classroom, laboratory, and other amenities required to make it an effective means of transferring technology. Training courses and demonstrations could be conducted on this vessel, and it could be moved about within a region and even among regions. Technical input from the National Marine Fisheries Service would be highly desirable. Funding should be multinational, with considerable support from the U.S. Agency for International Development (AID). The project should be coordinated by FAO and the vessel should fly a U.N. flag. It would have certain similarities to the medical ship "Hope."

Profile 3

IMPROVED FISH LOCATION

Considerable potential exists for expanding the catch of tropical fisheries. Undertaking this effort could mean large increases, as demonstrated by Peru's fisheries for directly consumed fish. Fisheries can, in fact, be expanded significantly in many developing countries without depleting stocks. For instance, it is not generally appreciated that in Peru between 1970 and 1973 the catches of species other than anchovy (i.e., species consumed directly as human food) increased by 150 percent, from 200,000 to 500,000 tons. Furthermore, it is estimated that in Peru the catch of most pelagic species other than anchovy could be increased still further, an important catch of squid could be taken, the catch of bottom and nearshore species could be increased, and inland resources could yield more both through exploitation of wild stocks and through extensive and intensive cultivation (FAO 1976a).

In addition to the possibility of expanded large-scale fisheries, there are many productive but currently unexploited nearshore environments in the tropics which cannot be exploited by any means other than small-scale or artisanal fisheries. These fisheries offer direct nutritional benefits to the malnourished rural poor. Needless to say, increased levels of exploitation should be coupled with management measures to avoid overharvesting.

Fisheries development involves research in many areas, ranging from stock assessment to boat and gear development to port construction. This profile stresses the strong capabilities and comparative advantages of the United States in the application of sophisticated, science-based technology to fish location, running the gamut from the assessment of broad oceanic regions to fish finding on a scale meaningful to the individual fisherman.

RESEARCH NEEDS

Expanding catches presupposes the ability to locate aggregations of fish, but the inordinate expense of searching to locate fish is a problem. The National Marine Fisheries Service has used satellites to detect indicators of productivity and fish presence, such as areas of upwelling, convergence and divergence, river inflow effects, water mass discontinuities, and temperature differences (one-quarter mile survey grid portions can be scanned). This technology could be applied to large-scale and small-scale surveys of areas in the U.S. extended economic zone with potential for expanded fisheries as well as in the tropics, especially in areas of upwelling. The need for ground truth acquisition indicates that a satellite program should be closely coordinated with national, or preferably regional, fisheries investigations. More conventional remote sensing (multispectral photographic surveys from aircraft), also developed by the United States, should have short-term application, whereas satellite technology may have considerable potential for long-term payoffs. Recent and ongoing developments in microcircuitry no doubt will increase the usefulness of satellite data and improve benefit-cost ratios as time passes by improving image definition and data analysis while cutting time requirements and costs of information processing.

Fishermen also would benefit from the development of a hydroacoustic system that functions effectively in the shallow water areas where so much tropical fishing takes place. Such a development is a prime research subject, inasmuch as existing sonar devices encounter severe problems with surface and bottom reflections in shallow water.

In short, the research needs are to improve satellite photography and associated data interpretation and adapt them to fisheries systems, and to develop through microcircuitry, sonar-based, small fish finders that can be used on a great variety of craft and that work well in shallow water.

IMPACT

The impact of this short-term to medium-term research can be realized in less than 15 years.

Increases in production that might result from this research are related to the potential increases discussed in the Introduction, i.e., 20 to 30 million tons. The main effect of this research, however, will be in increasing efficiency. Any effects on the developing countries would come about through transferring technology that would be developed largely if not totally in the United States. The probability of success is considered high, and the results of this research could have an influence on all fisheries--industrial, semi-industrial, and small scale. The methods developed could be applied equally well to U.S. fisheries, including those in the extended economic zone.

IMPLEMENTATION

Large-scale Resolution

This technology transfer program is composed of five distinct phases: (1) planning and coordination, (2) system acquisition and implementation, (3) training, (4) cooperative investigation, and (5) consulting.

Planning and Coordination

This phase would be completed before the others are initiated. It would include evaluating available expertise and facilities, training needs, fishery needs, and system requirements, and identifying an appropriate fishery to demonstrate the role of satellite technology for solving local fishery problems. This one-year phase would require three scientist-years and $100,000 (salaries and travel expenses).

System Acquisition and Implementation

All hardware and software requirements will be satisfied during this phase. It is anticipated that the principal output of this phase would be a satellite data analysis system complete in every respect except for a receiving system. This phase would last six months to one year and would require one scientist-year and $350,000 (salaries and electronic equipment).

Training

All training material and procedures will be developed during this phase. Training will be provided in areas related to experimental design, data analysis, computer programming, and system operation. Some special training must be provided through U.S. universities. This phase would last one year in an intensive form and one year in a periodic form; it would require four scientist-years and $145,000 (salaries and materials).

Cooperative Investigation

A cooperative investigation to demonstrate the application of satellite technology to problems of fishery harvest and management would be conducted during this phase. Emphasis would be on allowing a country to conduct most of the investigation including selection of specific areas and stocks. Technical assistance from the United States would be limited to implementation and some coordination of efforts. This one-year phase would require four scientist-years and $200,000 (salaries, supplies, and equipment).

Consulting

This phase would be devised to monitor the developing country's program in satellite application technology and to provide assistance when required. It also would enable the transfer of new analytic techniques and procedures to the developing country as they become available. This five-year phase would require one scientist-year and $50,000 per year (travel and so forth).

Summary

Optimistically, programs to transfer fishery-related satellite technology to the developing countries could be completed in three to five years at a cost of approximately $750,000 to $1 million. Approximately $50,000 per year for five DOCUMENT additional years will be required for technical assistance and coordination. AID, with temporary assignment of competent NMFS personnel, might be a source of funds and implementation. South China Sea and Indian Ocean programs of FAO should be included.

A U.S. effort is ongoing in this field, especially in the southeast U.S. fishery sector. Work also could be undertaken in the Northern Indian Ocean, the Persian Gulf, and the area in the southwest Pacific extending in latitude from the Moluccas to the Solomon Islands and in longitude from the Caroline Island Basin to the Arafura Sea and Coral Sea Basin.

Small-scale Resolution

This work, to be undertaken in the United States for three years, would require cooperation between the National Aeronautics and Space Administration (NASA) and NMFS in specific applications, and U.S. industry in software development. Nine scientist-years of applied biology and engineering skills also would be required. The National Research Council should coordinate the personnel and funding for this project. The cost would be $1 million (industry contributions not included).

The entire program on improved fish location may be accomplished by an outlay of $2 million, a conservative estimate that assumes additional industry funding.

Profile 4

BIOTECHNICAL GEAR DEVELOPMENT

Insight into the behavior and senses of fish species to be contained or captured can lead to efficient and energy-saving harvesting and containment methods. With the exception of handlining from the shore, catching fish requires an expenditure of energy, both in going to where the fish are and in gathering them. The research described here is aimed at reducing the energy costs of the gathering process, as well as the costs of containing fish in aquacultural situations. These developments will become especially important as fishing nations realize that operating a fishing boat can represent an expenditure of 20 times the energy contained in the catch (Pimentel et al. 1975).

RESEARCH NEEDS

We need to know more about the effects of sensorily perceived environmental changes on fish behavior in order to fashion attractants and containment mechanisms. Knowledge also is needed about the use of reproduced biological sounds as attractants or repellents, and the use of acoustic floors under purse seines, bubble curtains, and chemical attractants. Table 3 summarizes the potential uses of various selective biological barriers (not attractants).

Another possible application is derived from research for the U.S. Navy on the "sound signatures" of ocean species. This work has resulted in a sound catalogue of scores of Atlantic fish species. Buoy systems, if established in the tropics for other purposes, might be equipped with passive receptors to telemeter information on local fish stocks.

In many parts of the developing world, offshore drilling platforms remain even after the oil they are bringing to the surface has been exhausted. Various modes of attraction and shelter modification are possible to convert these platforms into effective fish concentration devices.

IMPACT

Use of the methods and instruments to be developed by this research would necessitate a certain amount of technological sophistication. In acquiring these methods, however, use should be made of fishermen in many developing countries who are knowledgeable about local fish habits and have skills that can be exploited to capture fish. From this partnership between the developing and high-income countries, beneficial effects would accrue to both. The high-income countries might learn a good deal about the characteristics of tropical fishes, and the developing countries might acquire simple technologies that require technical input not previously available. Of special importance is the fact that the new ocean regimes may result in increased partnerships between the high-income and developing nations rather than unilateral exploitation.

Gear based essentially on fish habits and characteristics will probably be more acceptable to technologically less skilled fishermen than complicated, engineering-based capture methods. Relative ease of technology transfer is one of the virtues of this research. For example, the reactions of fishes to a broad spectrum of sounds or special visual signals might be used. Scents could be used as fish appetizers or highly effective "lures" through combinations of attractants and so forth.

This research would require 10 to 15 years, and its potential effect is considered medium term. Combining the technologies developed with conventional fishing gear could greatly magnify the effect. Some production increases are envisaged from this work, but the main advance would be savings in the energy requirements of capturing fish and hence increases in the incomes of fishermen. The results of this research could be applied globally in both fisheries and aquaculture.

Since the program encompasses a number of species and capture/culture situations, the overall probability of success is difficult to evaluate. Present information virtually guarantees success with certain species. Ecological assessment, however, would be important to prevent depletion of resources through too effective capture methods. U.S. fisheries and aquaculture would benefit, as well as those of other countries.

Table 3. Summary of barrier elements to contain fishes

Type of barrier	Previous use as repellant or barrier	Effectiveness	Effective with respect to	Mechanisms involved	Selecttivity	Potential as a barrier element	Remarks
Light (white)	Yes	Good	Species	Not understood	Fair	Fair	. Usually used as attractant
Color effects	Not intentionally	Fair	Species	Not understood	Fair	Fair/good	. Distinct color effects, so more repellant than others . Contradictory results on which colors produce which effects and reasons for these effects
Electric barrier	Yes	Excellent	Length Species	Understood	Good	Excellent	. Best suited to barring large predators . Fright reaction may be exploitable, with the

							use of very little electric power
Acoustic barriers (biological sound)	Yes	Excellent	Species	Possibly understood	Good	Excellent	. Boundaries likely to be indistinct
Bubble curtain	Yes	Very good	Size Species	Possibly understood	Unknown	Very good	. Effectiveness is limited in currents, turbid water, and at night
Physical restraint	Yes	Excellent	Size Species	Understood	Very good	Excellent	. Best known . May be limited by sea, wind, current, and ship damage
Chemical (olfactory)	Yes	Good	Species Age Sex	Possibly understood	Good/ excellent	Good/ excellent	. Potential largely unknown . May prove the most selective

Source: Huguenin (1968).

IMPLEMENTATION

Selected U.S. university, government, and private research organizations should participate in this research. This effort would require a 10-year project with a team of two engineering and two biology scientists and a minimum of four technicians in addition to supplies, equipment, and so forth. A lead institution and scientist should be identified. Joint programming with the developing countries would be mandatory and could be brokered through ICLARM (initiated by the Rockefeller Foundation and incorporated as a nonprofit organization in the Philippines). The cost would be $5 million. The National Academy of Sciences/National Research Council (NAS/NRC) should approach the RANN program (Research Applied to National Needs) at the National Science Foundation (NSF) and NMFS/Sea Grant for funding; international/private nonprofit donors (the Consultative Group on International Agricultural Research, Ford, Carnegie, etc.) should be considered as additional funding sources. Since results appear applicable to the developing countries, intern training through AID, NOAA, or other international programs also should be considered.

Profile 5

AQUACULTURE

Aquaculture is defined as the growing of aquatic animals and plants in salt or freshwater. It encompasses a spectrum of management inputs, ranging from complete control over the life cycle of animals in highly artificial containment systems, to semi-intensive culture, to extensive systems with limited care bestowed on the organisms raised. These organisms are predominantly fish; molluscs and crustaceans are of secondary importance in most aquaculture production. Aquaculture produces high-grade animal protein which is regarded most commonly as a cash crop but which in certain instances serves as subsistence protein.

The rationale of aquaculture is to accelerate the energy and materials flow through the growing system or the animal grown to enhance organic production of a desired kind over that which would be possible in "unimproved" nature. Hence materials must be supplied from the outside, with fertilizer, feed, and labor the main recurrent inputs and water supply, containment structures, and the like as the main fixed inputs. Feed and fertilizer loom high among the input costs--in the range of 25 to 40 percent of production costs. There are some possibilities of using tidal or runoff advection of nutrients, plankton as food, and recycling schemes and unconventional fertilizers (sewage, organic wastes, nutrient-rich deep ocean water).

Aquatic animals are better food converters than birds and mammals, even to the extent that fish incorporate twice the amount of protein as do chickens for the same amount of calories supplied (Smith 1976). This relative advantage stems from fish not having to maintain a warm body temperature and having certain advantages in deriving their support from a dense medium.

Also, most aquatic animals grow faster in warm than in cold water; therefore, aquaculture is eminently suited for the tropics. In fact, 70 percent of the present world aquaculture production of about 5 million tons comes from the People's Republic of China and the world's tropical regions. Aquaculture, highly significant in Asia, is gaining renewed importance in Africa and is beginning to develop in Latin America.

Whereas in capture fisheries a pronounced dichotomy exists between artisanal and more industrialized fishing, ongoing aquaculture enterprises in the tropics are predominantly small scale and rural, with direct benefits to needy rural populations. Some vertically integrated, large-scale aquaculture enterprises are beginning to develop and may gain in importance, especially as these frequently furnish export crops. Such enterprises also will play a useful role in the training of operators of medium-sized aquafarms and of government extension workers, although scientific inputs, from the more fundamental to the applied, will be derived by and large from university or government research centers.

The major biotechnical components in aquaculture are providing enough young animals to stock ponds or other culture facilities; supplying adequate diets to assure growth of the animals at reasonable cost; and improving the genetic suitability of cultured animals to particular culture conditions. Of extreme importance for the future are selective breeding and genetic upgrading of characteristics such as vigor, disease resistance, growth rate (Figure 3), and taste. It is important to note, however, that fish farmers hardly have begun to breed aquatic animals. More attention to genetic selection probably will pay off handsomely if the other parameters of domestication also are pursued. Feed, based on the nutritional requirements of the species reared, becomes increasingly important as farming methods intensify. Management techniques also must be keyed into the process of genetic improvement of the species.

The primary technical bottlenecks to intensifying and expanding large-scale aquaculture include the lack of knowledge about the nutrient requirements for proper, efficient feed formulation and a lack of nutrient data on feedstuffs that could be used as fish feed ingredients. Equally important is the lack of an adequate larval food to rear newly hatched larvae up to seed fish size for distribution to growout areas for intensive or extensive culture. These bottlenecks can be overcome by an integrated, massive, orderly scientific research effort to yield tremendous dividends in the development of efficient, effective "fish for food" production industries.

Many variants of aquaculture rely on husbanding simultaneously several compatible species (polyculture). Yields of 10,000 kilograms/hectare/year of several species of Indian and Chinese carps grown in

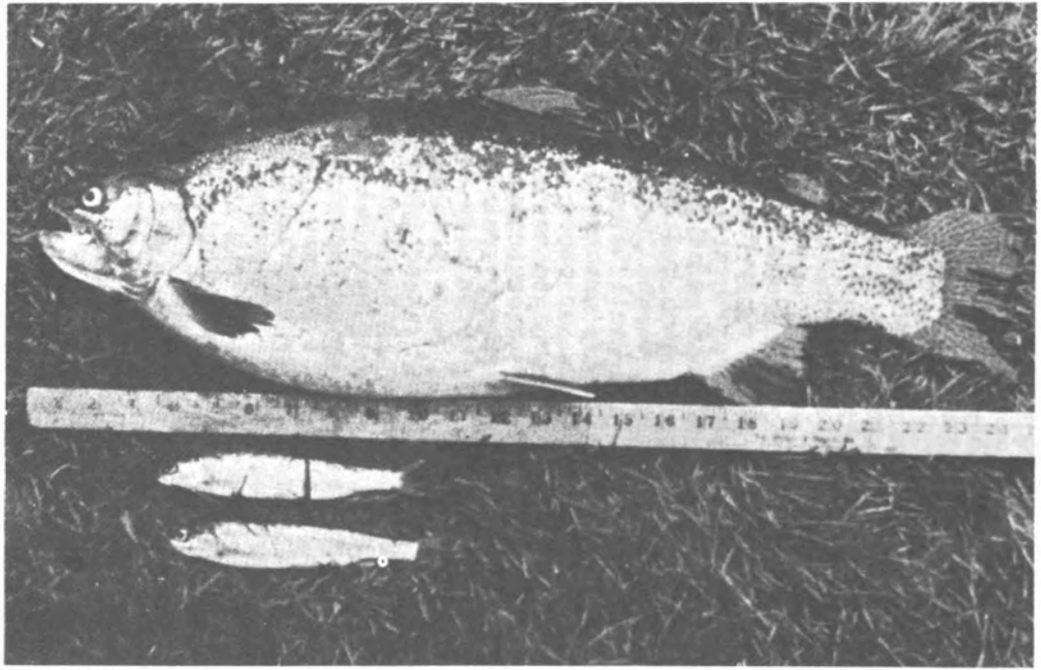

FIGURE 3 Wild and mass-selected, hatchery-fed rainbow trout at the University of Washington School of Fisheries, Seattle. All three fish are two years old, and the large one is a result of over 30 years of selective breeding paired with special feeding. It illustrates what may be achieved with some species by simultaneous attention to practical genetics and nutrition.

Photograph courtesy of Lauren Donaldson, Professor Emeritus, University of Washington, Seattle.

one pond have been reported from experiments with relatively modest inputs (Chaudhuri et al. 1975). Visitors to aquaculture communes in the People's Republic of China tell of annual yields as high as 20,000 kilograms/hectare. Combinations of aquatic animal with land animal husbandry, or of wet plant crops with fish culture also are possible. The practice is not in need of long-range research inputs but is the subject of adaptive research and extension. It is ongoing in many countries.

Aquaculture can and does compete with other land and water uses. Thus evaluation of potentially competitive uses of land and water must precede the establishment of new aquaculture installations. Such evaluations should take into consideration the advisability of ecologically sound uses which do not actually or potentially compete with other land or water uses (Pantulu 1976). For example, aquaculture may be successful on certain types of land that are entirely unsuitable for agriculture and thus may provide a means of turning otherwise unproductive land into an important source of high quality protein.

Aquaculture has been concerned largely with growing aquatic organisms from very small to marketing sizes. Another approach, occasionally practiced successfully, involves producing young fish or other aquatic animals in hatcheries, releasing them into natural bodies of water at a small size, and harvesting them after they have grown to a marketable size by using as food the natural productivity of the water body into which they were released. This approach has been an outstanding success in the case of salmon "ranching," which makes use of the natural proclivity of salmon to return to the same streams in which they were released after feeding in the ocean for varying lengths of time. Other instances of successful release programs are restricted mainly to freshwater environments, although recent claims have been made for success in releasing some marine species (Hanamura 1976). The concept of release or "partial rearing" can include setting up feeding stations in lakes or reservoirs, and even selectively removing and replacing fish in a given body of water.

It is possible that marine fishes in the warmer zones of the globe may be suited to release programs but too little is known about their habits at present. Only a more detailed look will tell whether such an operation would work in biological or economic terms. We should not forget that selective breeding, as well as postnatal behavior modifications (imprinting), permit us to influence migration patterns and distances, perhaps even routes. Research along those lines promises a handsome payoff.

A subject that deserves special mention is the possibility of stocking freshwater fishes in large lakes and manmade reservoirs such as those in Africa, where increased fish production could be crucially important to the landlocked malnourished.

RESEARCH NEEDS

Research needs for international aquacultural development have been considered by various bodies in the past. Perhaps the most comprehensive assessment of these needs was made by the Aquaculture Subcommittee of the Technical Advisory Committee (TAC) of the Consultative Group on International Agricultural Research (CGIAR). The subcommittee's recommendations (CGIAR, TAC 1974) were reiterated at the FAO/UNDP Regional Workshops on Aquacultural Planning in Africa, Asia, and Latin America in 1975 as well as at the FAO Technical Conference on Aquaculture (FAO 1976b). The present recommendations therefore draw heavily on the report of the TAC subcommittee. The TAC report stresses that much aquacultural development work is already in progress in many developing nations. Some of it is singularly successful, but as a whole the development lacks coordination as well as regional focusing (for elaboration see excerpts from the TAC report on regional research centers and research networks for aquaculture under "Implementation" below).

Because of regional differences in species complexes, ecological conditions, and consumer preferences, aquacultural research must be conducted regionally, paying attention to culture systems and species complexes of importance in each major region, rather than establishing one central international station. Regional centers with networks of outreach stations are called for below, each concentrating on its appropriate culture systems and species groups as identified by the TAC subcommittee. We endorse this approach strongly and in the present recommendations concentrate on one region, South and Southeast Asia, which is acknowledged to be a region with the greatest effort (and interest) in aquaculture and with a longstanding tradition of freshwater and brackishwater aquaculture. We believe that this region is the logical, initial focal point for assistance from the United States and the most likely region to feel an early effect from our efforts. It is hoped that success in this one region will lead to later involvement in Africa and Latin America, but in view of the lack of trained personnel we consider it unrealistic at this time to recommend concentration on these other regions.

The TAC subcommittee has identified needed research in each region. We recommend that, as work in South and Southeast Asia progresses, efforts to train scientists and extension personnel in aquaculture progress quickly enough to enable phased implementation of programs in Africa and later in Latin America. The report of the TAC Subcommittee is an authoritative and adequate summary of the relevant culture systems and research problems to guide this implementation and requires no further elaboration here (see Table 4, extracted from the TAC subcommittee report [CGIAR, TAC 1974]).

The culture systems and species complexes of importance in South and Southeast Asia are (1) polyculture of carps in ponds and other impoundments, (2) pond culture of milkfish and grey mullets, and (3) pond culture of shrimps and prawns.

The carp culture system in South and Southeast Asia relies mainly on the following species: grass carp, *Ctenopharyngodon idella*; silver carp, *Hypophthalmichthys molitrix*; bighead, *Aristichthys nobilis*; catla, *Catla catla*; rohu, *Labeo rohita*; mrigal, *Cirrhina mrigala*; common carp, *Cyprinus carpio*; and tawes, *Puntius gonionotus*.

The pond culture of milkfish and grey mullets is mainly practiced in the brackishwater environment, though these fish are sometimes also acclimated to freshwater. The species concerned are milkfish, *Chanos chanos*; and grey mullets, *Mugil cephalus*, *M. dussumieri*, *M. belanak*, and *M. tade*.

Shrimp and prawn culture, which is still in an early stage of development, involves a number of species, but the more important are: giant freshwater prawn, *Macrobrachium rosenbergii*; shrimps, *Penaeus monodon*, *P. merguiensis*, *Matapenaeus brevicornis*; and *P. japonicus* and *P. orientalis*, which are also important in certain areas.

Among the high priority research problems that should be addressed in the networks, we have identified the following as being particularly appropriate for contributions from the United States.

Breeding and Associated Requirements

Seed Production

The objectives of research in seed production would be:

-- to ensure adequate and reliable seed supplies independent of natural sources and to extend the period of seed availability,

-- to enable domestication of species presently used in aquaculture,
-- to enable domestication of additional species of promise for aquaculture,
-- to make genetic selection and hybridization possible.

Factors governing the reproduction of the target species, carps, milkfish, mullet, and penaeid shrimp, should be studied. These factors include: reproductive physiology; nutrition of brood fish, larvae, and juveniles; environmental factors (water conditions, photoperiodicity, space, etc.); behavioral responses (stress, crowding, shock, sex segregation, etc.); and parasites and diseases.

Genetic Selection and Hybridization

Carps, mullet, and prawns should be studied for genetic selection and hybridization. This investigation would: determine genetic variabilities within species; identify characters for selection experiments; and study the genetic nature of desirable characteristics (growth, disease resistance, dressed weight, etc.).

Nutrition, Food, and Feeds

The objectives of research in this area would be to develop economical and nutritionally efficient feeds based on locally available materials, and to optimize food production in ponds.

The species complexes to be studied are carps, milkfish, mullet, prawns, and penaeid shrimp. The nutritional requirements of these species in the various life history stages should be determined and appropriate feeds formulated. The availability of adequate, inexpensive feed ingredients, including substitutes for conventional animal proteins used in fish feeds, also should be determined. Potential feed ingredients must be analyzed and an international fish feedstuffs data bank established. Furthermore, a survey should be made of the factors affecting production of natural food organisms in ponds, including fertilization and pasture management (polyculture).

Table 4. Program summary of culture systems and problems by regions

Region	Problems / System	Breeding, seed production	Nutrition, feeds	Genetics, selective breeding
Asia and Oceania	Carp culture in ponds	Reproduction physiology (S) Larval rearing methods (S)	Nutrition requirements (S) Food and feeds (S)	Select for suitable traits (L) Hybridization (L)
	Milkfish and mullet in brackishwater ponds	Reproduction physiology (S) Larval rearing methods (S)	Production of food in ponds (S) Nutrition requirements (S) Feed development (S)	Genetic variation (L)
	Shrimp culture	Reproduction physiology (S) Larval rearring methods (S)	Nutrition requirements (S) Food and feeds (S)	Genetic variation and trait selection (L)
Africa	Mullet in brackishwater ponds	Reproduction physiology (S) Larval rearing methods (S)	Nutrition requirements of all stages (S) Food and feed production (S)	
	Tilapia in freshwater		Nutrition requirements (S) Feed production (S)	Hybridization (S) Growth and sterility (S)
	Catfish in fresh and brackishwater ponds	Reproduction physiology (S) Extend breeding season (S)	Nutrition requirements (S) Development of feeds (S)	Select for growth and disease resistance (L)
	Catfish cage culture			
	Shrimp in ponds	Reproduction physiology (S)	Nutrition requirements (S) Feeds (S)	Select for desirable traits (L)

Culture systems intensification	Aquaculture engineering	Aquafarm management	New species selection
Densities (S) Stocking rates(S) Polyculture (S)	Installation equipment, pond design(S)	Physico-chemical factors (S) Metabolites (S) Economics (S)	
Polyculture (S) Densities (S) Stocking/ cropping (S)	Pond design, installation construction techniques (S)	Physico-chemical factors (S) Diseases, predators, economics (S)	
Densities (S) Stocking/ cropping (S)	Hatchery design (S) Pond installation (S) Raceways (L)	Predators (S) Physico-chemical factors (S) Economics (S)	
Densities (S) Stocking/ cropping (S) Metabolites (S)	Design and construction of ponds (S)	Physico-chemical factors (S) Diseases (L) Economics (L)	
Polyculture (S) Stocking/ cropping (S)	Food design(S)	Economics (S) Culture unit size(S)	
Densities (S) Polyculture (S) Stocking/ culture (S)	Site selection (S) Pond design(S)	Physico-chemical factors (S) Economics (S)	Screen new species (L)
	Design suitable cages(S)	Diseases (L) Economics (S)	Screen new species (L)
Densities (S) Stocking/ cropping (S)	Pond design(S)	Economics (S) Predators (S) Physico-chemical factors (S)	

Table 4. (Continued)

Region	Problems / System	Breeding, seed production	Nutrition, feeds	Genetics, selective breeding
Latin America	Aqua-range farming: Cichlids, Sciaenids, Characids	Reproduction physiology (S) Larval rearing (S) Breeding (S)		
	Mullet in brackishwater	Reproduction physiology (S) Larval rearing methods (S)	Nutrition requirements of all stages (S) Food and feeds (S)	
	Shrimp in ponds	Reproduction physiology (S) Larval rearing methods (S)	Nutrition requirements (S) Feeds (S)	
	New Amazon species	Reproduction physiology (L) Seed production (L)	Nutrition requirements (L)	

(S) Problems likely to yield applicable results in the short term; further research may lead to refinements.
(L) Results expected in the longer term.

Source: CGIAR, TAC (1974).

Culture systems intensification	Aquaculture engineering	Aquafarm management	New species selection
	Feeding and harvesting techniques (S)		Screen new species (L)
Metabolites (S) Cropping/stocking (S)	Food design and construction (S)	Physico-chemical factors (S) Diseases (L) Economics (S)	
Metabolites (S) Cropping/stocking (S) Polyculture (S)	Food design (S)	Physico-chemical factors (S) Diseases (L) Economics (S)	
		Define parameters (L)	Screen and select species (L)

Aquaranching

Aquaranching of Anadromous or Otherwise Migratory Species

Research objectives in this area would be to determine which regional species in the tropics are suitable for aquaranching by virtue of predictable migratory patterns, and to undertake pilot-scale aquaranching operations for the chosen species. This research could be undertaken by:

- surveying anadromous and otherwise migratory species of South and Southeast Asia (and gathering life history information on species chosen for further investigation);
- conducting experiments on induced breeding and larval rearing;
- investigating the possibility of chemical imprinting;
- studying parasites and diseases;
- assessing the effects of release programs, including tagging studies and benefit-cost appraisals.

Aquaranching of Nonmigratory Species

The objectives of research in this area would be to determine which regional species in the tropics are amenable to intensified aquaranching with additional feeding, and to increase the productivity of inland and inshore waters by providing partial nutrition to the selected stocked species.

Investigations that should be undertaken in connection with this research are:

- a study of the conditioned feeding responses of species selected for release;
- a study of the efficacy of sonic or other cues in attracting released fish to feeding stations;
- exploration of suitable sites in lakes, reservoirs, or coastal lagoons;
- an ecological study of the carrying capacity of the environment and the effects of nutrient additions;
- benefit-cost studies of the intensification of aquaranching.

IMPACT

Most impacts will be short to medium term, generally within 15 years after program initiation.

The effect of the genetic work, however, is primarily of a long-term nature (greater than 15 years), although some gains are expected from this work in the short term (Table 5).

The research described here is expected to contribute to the sixfold increase to 30 million tons predicted for world aquaculture by the year 2000 (Pillay 1976). Exact figures for production increases from the specific lines of research cannot be given, but it can be stated firmly that without these research efforts the 30-million-ton figure will never be attained. The effects of this research will take the form of increased employment and protein availability to undernourished rural populations in Southeast Asia, and also of significantly increased income in the case of the crustacean culture systems. Aquaranching has potential in inland lakes, reservoirs, and river systems in proximity to malnourished populations, and such developments recommended here for South and Southeast Asia may have important implications for the severely malnourished landlocked populations of Africa and Latin America.

This research is clearly aimed at the developing world, and benefits to the United States may be primarily of a secondary and indirect nature. However, crustaceans, especially freshwater prawns, which are among the species proposed for study, are being now commercially cultured in the United States and have been identified by the U.S. government as high priority species groups for development in this country. In view of the large volume of high-priced crustaceans imported into the United States, improvement in culture techniques for them will benefit the United States economically, as well as provide a high quality, fresh seafood of high consumer appeal. Research developments in fish culture, such as improved feeds, improved genetic strains, and methods for aquaranching, could prove valuable to the United States in many ways, including providing impetus to efforts to develop aquaculture in the southeastern United States (see the NOAA Aquaculture Plan [U.S. Department of Commerce 1976] and NSF/Massachusetts Institute of Technology Protein Resources Study [Waslien et al. 1977]).

IMPLEMENTATION

AID partnership with land-grant and sea-grant universities, which is envisioned under Title XII of the Foreign Assistance Act of 1961, as amended, is one of the appropriate vehicles for implementing the international and regional research proposed here. Subprojects should be administered as grants awarded to

Table 5. Impact timing and degree of success of research projects

Research area	Cost ($ millions)	Years		Impact timing[a]	Probability of success[b]
		Scientist	Technician		
Breeding, etc.[c]	22.3	160	320	S & L	90
Nutrition[d]	11.0	100	200	S	90
Aquaranching[e]	3.3	10	20	S & L	70
TOTAL	36.6	270	540		

[a] S = impact short range (<15 years); L = impact long range (>15 years).
[b] Assuming full implementation of the research projects outlined in this report.
[c] Duration: selective breeding, 20 years; seed supply, 10 years.
[d] Duration: 10 years.
[e] Duration: 10 years.

U.S. universities and regional research institutions on a basis of a 60/40 division of funding between AID and international funding agencies. Most of the funding should be directed toward solving defined objectives and tasks (as indicated above), and about 40 percent of the international funding should be reserved and allocated in response to research program proposals identified and submitted by the regional research centers. In order to accomplish the goals set forth, in line with the spirit and expressed intent of Title XII, the research could well be carried out jointly by the universities and the developing country institutions named below, with emphasis on deployment of U.S. expertise on site in the developing country. Scientists in the developing countries should be involved as much as possible, and the developing country institutions would be strengthened through this process and through concurrent emphasis on practical education and on-site training. Inasmuch as regional research institutions have to be strengthened and international funding is involved, and as interregional coordination is mandatory, the international dimensions of research planning (task schedule review, etc.) should be conducted through the close cooperation of the United States with the international funding agencies (CGIAR, the Agricultural Development Council [ADC], etc.). ICLARM is recommended as a practical coordination vehicle.

Personnel requirements, project durations, and estimated funding requirements are listed in Table 5. These figures are estimated and subject to refinement.

Regional Research Centers and Research Networks for Aquaculture

The TAC Aquaculture Subcommittee states (CGIAR, TAC 1974), concerning execution of aquaculture research:

> None of the existing research centres in the developing world and few elsewhere have a truly multidisciplinary, highly trained staff and the facilities required for the necessary mission and systems-oriented research capable of producing the results essential for the rapid progress of aquaculture. There is also no centre or organization anywhere in the world designed to carry out long-range interdisciplinary research needed to underpin scientific aquaculture along the lines indicated in the programme. The formidable constraints to centralisation of research have already been recognized.

Similarly, there is a serious insufficiency (nationally, regionally and internationally), of trained research personnel capable of implementing a comprehensive programme which is a prerequisite to the development of aquaculture.

In view of these shortcomings and recognizing the interdisciplinary nature of research effort required; the need for institutional, financial and other support; the differences in ecological conditions, species available for culture, as well as socio-economic conditions; the Sub-committee supports the conclusion of the Spoleto meeting that investigations on the major problems of aquaculture have to be organized _regionally_. The Sub-committee therefore recommends the strengthening of selected national institutions as regional centres for research, closely linked to a network of national outreach stations.

With these considerations in mind, we recommend the following regional centers and networks of outreach stations where the latter can be identified. The possible future expansion of the networks in the three regions is indicated by suggesting the countries that are developing requisite basic facilities for effective participation:

1. _South and Southeast Asia_. A regional center is recommended in India at the Central Inland Fisheries Research Institute, Barrackpore and Cuttack (for freshwater aquaculture); and in the Philippines at the Brackishwater Aquaculture Centre, SEAFDEC Aquaculture Department, Iloilo. Outreach stations/nations should be Indonesia: Brackishwater Aquaculture Centre, Japara near Semarang, Java and Research Institute for Inland Fisheries, Bogor, Java; Thailand: Bangkhen Inland Fisheries Station, Bangkok, or National Inland Fisheries Institute; and a station to be selected in Malaysia. We can expect future expanded linkages in Bangladesh, Fiji, Hong Kong, Korea, Nepal, Singapore, and Vietnam.
2. _Africa_. The regional center south of the Sahara should comprise the Freshwater Fish Culture Station, Ministry of Agriculture, Ibadan, Nigeria, and the Brackishwater Fish Culture Station at Buguma, Nigeria. Outreach stations should be in the Central African Republic at the Fish Culture Research Station, Landjia, Bangui; in the Ivory

Coast at the Inland Fisheries Research Station, Bouake; in Madagascar at the Fish Culture Station, Perinet; and in Uganda at the Kajansi Experimental Station, Fisheries Department. Future expanded linkages will be in Cameroon, Ghana, Kenya, Mauritius, Zaire, and Zambia. In North Africa and the Middle East the following research institutions from developing countries participating in the General Fisheries Council for the Mediterranean (GFCM) Cooperative Programme of Research on Aquaculture (COPRAQ) are proposed: Institute of Inland Fisheries and Fish Culture, El Xanatir, Elkhaira, Egypt; the Fish Culture Research Station, Dor, D.N., Hof Hacarmel, Israel; and the Institut National Scientifique et Technique d'Oceanographie et de Peche (INSTOP), Salambo, Tunisia. Expanded future linkages will be in Iran, Lebanon, and Syria.

3. Latin America. The regional center should comprise the Fish Culture Research Station, Pentecoste, Fortaleza, Brazil, in association with the Instituto Nacional de Pesquisas da Amazionia, Manaus, and the Brackishwater Aquaculture Station, Natal, Brazil. Outreach stations will be in Colombia at the Fish Culture Station, University of Caldas, Manizales; in El Salvador at the Fish Culture Station, Santa Cruz Purillo; and in Mexico at the Fish Culture Station, El-Zarco, D.F. Future expanded linkages will be in Guyana, Venezuela, and Trinidad.

Profile 6

ARTIFICIAL UPWELLING AQUACULTURE

BACKGROUND AND POSSIBILITIES

The thermal differential between tropical (and perhaps subtropical) surface and deep waters is about 20°C with the cooler water found below 400 meters. The possibility of exploiting this thermal gradient to produce electricity (OTEC, Ocean Thermal Energy Conversion) is presently being explored by the U.S. Energy Research and Development Administration (ERDA), sea-grant and U.S. universities, and U.S. industry. The technology also is being investigated by CNEXO (Centre National pour l'Exploitation des Oceans, of France) and is being considered in Japan and Germany. The deep water contains between 20 and 30 times the nitrogen (mainly NO_3) and roughly 10 times the phosphate that is found in surface waters. Thus deep water nutrients represent probably the most abundant and possibly the cheapest fertilizer source available, which could be used to stimulate the production of marine plants if raised to the surface. It has also been postulated that one could combine an OTEC system with the manufacture of nitrogen fertilizer (Kohl 1976).

We have consulted a number of distinguished scientists and engineers concerning the potential of upwelling aquaculture. Consequently, we believe that aquaculture utilizing artificial upwelling is promising if it is developed as a component of thermal energy conversion systems. Upwelling aquaculture by itself (i.e., not in conjunction with OTEC), while technically feasible, is likely to be marginal at best because of the high technology required. The latter would be made available largely through OTEC development(s), but would be difficult to justify for aquaculture alone. In fact, OTEC systems may have several components: power generation, aquaculture, nitrogen fertilizer manufacture, and even desalination. When planned in site-specific and need-specific combinations, these systems may be cost effective.

According to proponents of the method, 10 km^2 of growing space and 4.5 x 10^7 liters/minute of upwelled water (the amount required by a 100-megawatt sea thermal power plant) would theoretically produce 300,000 tons annually of molluscan shellfish meat. This estimate is based on very optimistic extrapolations from small-scale experiments (Roels et al. 1976). If no special aquaculture installations were undertaken in connection with the OTEC plant, discharged water could produce a small but possibly significant local nutrient enrichment and perhaps a fishery. If the route of intensive aquaculture were chosen, problems of processing and distribution associated with the production of such magnitude of shellfish (transporting, processing, marketing of the meat, disposing of shells) will certainly arise. The engineering development recommended here must also include assessment of localized environmental side effects. Once the system exists, however, there is potential for producing large amounts of protein cheaply. For this reason, the subject is relevant to the present study.

A range of possible OTEC-aquaculture combinations exists, from large to medium size, and from intensive husbandry in containers to the management of a fishery generated by the input of primary nutrients. Depending on whether the plant is shore-based or floating, the primary producers (plants) in the aquaculture system may be brackish- or saltwater algae. Culture of any of the two can produce a high plant biomass per shallow unit growing volume (Waslien 1977; J. H. Ryther 1973, personal communication, Woods Hole Oceanographic Institution). The algae may be elaborated into industrial products such as algal colloids, or protein food additives, or serve as food for animals low in the food chain such as filter feeding molluscs. Again, these several kinds of algae may be grown in connection with one OTEC plant depending on location, proximity to cities, industries, and so forth.

The engineering exigency will exist to prevent or to delay by containment or other means the sinking of nutrient-rich water, which is still cold even though somewhat warmed by the process of producing electricity through heat exchange with the surface water.

It must be stressed that the development of upwelling aquaculture, like the development of OTEC power itself, is a major engineering undertaking requiring highly sophisticated technology. Therefore it should be done in the United States, preferably with the cooperation of other advanced nations that show interest in the scheme (France, Japan, and, of late, West Germany).

IMPACT

The building of a prototype OTEC plant will depend on the direction of U.S. energy policies. Provided such a pilot facility is built to demonstrate feasible power production at economies of scale, it would contribute to such a demonstration if one were to undertake from the beginning parallel development of associated beneficial technologies such as aquaculture, desalination, and nitrogen fertilizer production. We strongly recommend that OTEC-associated aquaculture facilities be developed concurrently with power production engineering and feasibility studies. As mentioned, these facilities require high technology inputs and will initially be built in the United States and/or other high-income nations. It should be possible to automate power productions sufficiently so that transfer to developing country sites could be considered. Then there would be a substantial number of sites in the mid-latitudes with depths of more than 500 meters within 30 kilometers of land (Figure 4). Several of these have potential shore sites with steep slopes accessible to deep water permitting the development of shore-based installations; others appear better suited for floating, nearshore plants. In any case, the production of large amounts of shellfish or fish proteins appears possible near several areas that now suffer from malnutrition. For this production to have a significant direct effect on the nutrition of these areas, processing and marketing modes must be developed that will make increased protein available to the rural and urban poor (see Profile 2).

The effects of this research would be long term as prototype OTEC plants are not likely to be on line before 1985, if then. A small pilot development planned soon for French Polynesia may be an exception to this statement and underscores the urgency of international cooperation in this field.

Assuming for realism's sake that postulated protein production figures (Roels et al. 1976) are not likely to be attained on a sustained basis and that a 100-megawatt plant may produce 100,000 instead of 300,000 tons of filter feeder animal meat per year, and assuming that by the year 2000 or thereafter there could be 20 to 30 such power plants in existence, the resulting amount of flesh in the round would be 2 to 3 million tons. Some of this aquatic animal flesh may be produced in the vicinity of large cities and therefore serve crucial needs.

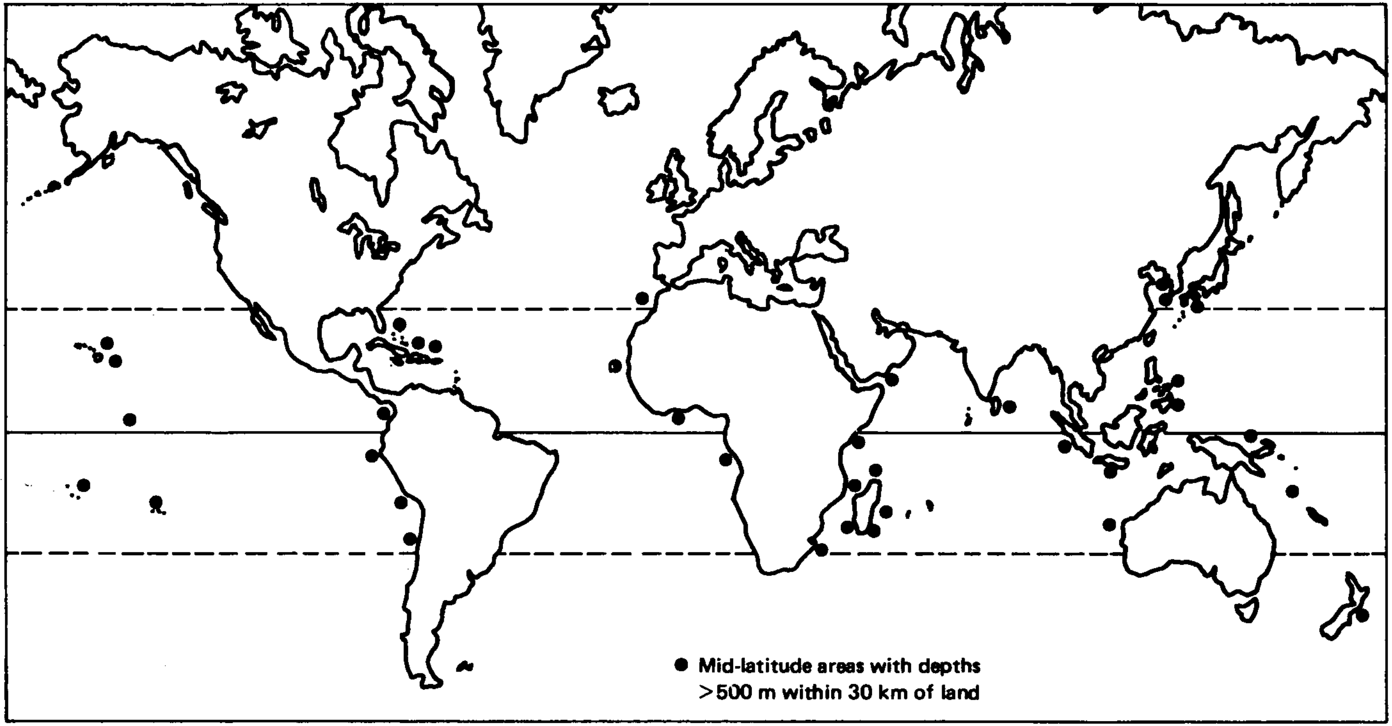

FIGURE 4 Sites in the mid-latitudes with depths of more than 500 meters within 30 kilometers of land.

RESEARCH NEEDS

To examine and to project design characteristics of these aquaculture structures and to integrate these into OTEC design and prototype testing operations are important research needs. Prototypes should be constructed of floating containers, devices to bring about optimal utilization of sinking thermal exchange water. These should emphasize fixtures to delay sinking or otherwise extract the nutrient-rich water through biotechnologies.

IMPLEMENTATION

Selected institutions now pursuing OTEC planning should undertake this research. (For a complete list of experts and institutions involved in this planning, see Kohl [1976]). Prominent institutions are the Carnegie Mellon Institute of Technology, University of Texas, Scripps Institution of Oceanography, and University of Hawaii; federal agencies involved are ERDA and NSF/RANN; and among private industries, Lockheed has shown substantial interest in OTEC planning.

As far as division of labor and location are concerned, ERDA or a successor agency should be enjoined through NAS/NRC to take the lead in forming a multidisciplinary working group for the implementation of this research. Aside from OTEC designers and engineers, persons and agencies interested in marine plant bioconversion, in algae production from enriched effluents, in aquacultural engineering, and in molluscan shellfish culture should be involved. This list is indicative but not exhaustive.

The task force should initially examine all possible modes of OTEC-associated aquaculture with production and other economic considerations to be included in the effort as soon as possible.

ERDA is now the most appropriate agency to take the lead in funding. Funds should also come from other quarters in the federal government inasmuch as prototype development of OTEC is part of the federal responsibility related to the development of a long-range U.S. energy policy. Pilot facilities will have to be established requiring fairly substantial funding (an estimated $5 million), even for aquaculture prototype constructions. As an alternative it may be possible to relate the aquaculture portion to already existing small-scale upwelling facilities such as that at St. Croix (Virgin Islands) or that now in the planning stage by CNEXO in French Polynesia. Collaboration with France and other high-income nations appears not only possible but highly desirable and could considerably reduce the U.S. expenditure.

It is estimated that five scientist-years with associated technician teams would be required. If prototype testing of both OTEC power and aquaculture product generation appears encouraging, funding for aquaculture could and should be incorporated into the cost of developing the total system.

LONG-RANGE PROGRAM NEEDS

INSTITUTIONAL FRAMEWORK FOR FISHERIES

Historically, the common property nature of fisheries has created major management problems. Regional fisheries agreements frequently have failed to achieve the desired regulatory effects, and overfishing followed by the collapse of fisheries sometimes has occurred. This "tragedy of the commons" stems from the economic incentives that lie in exploiting a common property resource, and from a concomitant inability to realize through individual action the joint interest inherent in maintaining the optimal yield of a fishery rather than overharvesting it. The extended jurisdiction of coastal states to include a 200-mile economic control zone--which has occurred already in many parts of the world and which will become essentially universal, with or without specific endorsement by the U.N. Conference on the Law of the Sea--will alter the situation by placing virtually all exploited stocks (with the exception of high seas tunas and a few others) within the control of individual nations or groups of nations. The common property condition, however, will persist in those numerous situations where stocks are shared by two or more nations.

Research Needs

Institutions are the keys to solving fisheries problems and as such are themselves legitimate subjects for research. We strongly believe that research on institutions is of fundamental importance in fisheries. This research must be carried out by both social scientists and fisheries scientists and should address at least the following issues:

-- Coastal states must realize the potential for better national management of fisheries in order to preserve present catch levels, let alone expand catches.

- Institutional arrangements must deal with the ecological realities of fish stocks with habitats crossing national boundaries.
- The past tendency to view exploited fish populations in isolation must be replaced by a view of these fish as part of systems heavily influenced by land-use patterns and the pollution resulting therefrom, which may have regional impacts.
- Scientific research by outsiders within economic control zones will be severely curtailed or made more difficult than before. Means of permitting the high-income nations to contribute to the formulation of new fisheries management theories and techniques for the tropics should be sought. These means should be consistent with the new role assumed by the developing nations in formulating regional management measures through extended coastal state jurisdiction.
- The design of regional fisheries research and management organizations, particularly in areas adjacent to the developing nations, is a research problem of paramount importance. These organizations should grow out of regional needs and be integrated with parallel organizations dealing with nonfisheries marine research (pollution, mineral extraction, transportation, weather, climate, and coastal zone land use). At the same time, the importance of national bodies and, in particular, national personnel needs (especially at the middle management level) must be recognized (for treatment of the key problem of personnel training, see the next section).

Implementation

The first five issues above should be analyzed in depth in specific regions where the full range of complications inherent in multinational fishery management are encountered, and where solutions are of pressing importance to the nations involved. Southeast Asia (South China Sea) and Northwest Africa (east central Atlantic) are logical choices for these studies. In both cases, opportunities for increased production from latent resources and severe overexploitation of others are evident; distant water and local, small-scale fisheries are in conflict. These conflicts could well be exacerbated under extended economic zones as new joint venture arrangements are sought. The need for management has run far ahead of the scientific knowledge and data base required to do the job, and different national development policies are, in some instances, on direct collision courses.

Two task forces should undertake detailed, comparative field studies of alternative institutional and legal arrangements for management in these regions. Each group should include as a nucleus a resource economist, an expert in fisheries management planning, and a fisheries scientist with particular expertise in stock assessment and population dynamics. The team might also require, for varying periods of time, the aid of legal, political science, and other specialists. Strong attempts should be made to include personnel from FAO and from countries in the study regions, if possible.

Each group would be expected to delineate as fully as possible the biological, economic, distributional, and social effects of feasible management systems in the study region, and to relate these effects to information system requirements.

Upon completion of the regional studies, a comprehensive comparative analysis and review should be undertaken at an extended working session including members of both teams and experts from both the high-income and developing countries to examine possible modes of cooperation and implementation.

Resources for the Future, Inc. would be the logical agency to coordinate these studies. It has an established program in ocean resources management and excellent in-house capability and contacts with outside experts. The new Resources Systems Institute of the East-West Center in Honolulu, Hawaii is another possible lead agency. Complementary work could be undertaken by the Law of the Sea Institute (Hawaii), the Ocean Management Institute (Rhode Island), and other qualified organizations. Funding should be sought primarily from private agencies, particularly the Ford and Rockefeller foundations, with additional support from the federal government.

Impact

Nonresolution of these problems requiring social and natural science inputs could lead to overfishing, to political tensions, and perhaps to clashes at sea. An overall decline in fish production (see Figure 1) is a likely result, especially in the tropics where several high-income nations now deploy distant water fleets and where there is a need for new institutional, conservation-oriented management measures.

The conclusion of a recent paper by Christy (1976) puts these matters succinctly:

It is clear that the changes occurring in the law of the seas will dramatically affect the patterns of exploitation of fisheries and of the distribution of their benefits. It is not clear, however, that the effects, in the short run, will be beneficial. If the institutions for distribution and management of fisheries cannot adjust rapidly enough to deal with the changes, it is conceivable that the world will experience a significant decline in the catch of marine fishes. This could occur through the failure of regional bodies to reach acceptable agreements on the allocation of benefits or to adopt, impose, and enforce effective regulations. In addition, the temptation of the Soviets and other distant-water countries to reject the claims to 200 miles will increase if the regional bodies are weakened by internal conflict. The net result could be severe depletion of the stocks in the regions where stocks are widely shared.

In order to avoid such an outcome, the regional institutions will have to acquire a high degree of authority. Whether or not they will do so will depend upon how the states balance off their perceptions of the needs for authoritative bodies against their reluctance to relinquish any of their sovereignty.

The deliberation at the UN Conference on the Law of the Sea could do much to improve perceptions of the importance of regional approaches to shared stocks. But the delegates of the coastal states seem to be too beguiled by apparent increases in wealth from extended jurisdiction to give much attention to the problems that will come with their new rights.

Eventually, the transition will be past and orderly and effective systems for distribution and management will come into effect. But it may not come until after the benefits have become so dissipated that there is little to lose by granting the necessary authority to the regional bodies.

PERSONNEL

Training Needs

Individuals need to be trained, especially in the developing countries, to serve as: administrators, with skills in resource economics; research managers, also with these skills; researchers; and extension personnel at several levels.

The educational basis, certainly for the first three but probably also for the top level of the fourth category, is a college curriculum such as does not now exist, even in the high-income countries. The fisheries curriculum of the University of the Philippines or the planned network of Indonesian universities dealing with aquatic resources (one university for oceanography, one for fisheries, one for coastal zone management) approaches basic educational needs for these personnel categories, but they are still far off the mark. This level of training should be local, i.e., national.

The curriculum we suggest should integrate special disciplinal information from biology, oceanography, ecology, engineering, economics, political science, regional sociology and anthropology, business administration and law, as well as computational and a modicum of modeling and simulation skills.

After the initial degree, one advanced degree is advisable. Long-term (five-year) assignments of a substantial number of teams of expatriate experts to national or regional teaching and research institutions are envisaged so that there are far fewer postgraduate missions abroad and more advanced degrees given in the developing countries. Present U.N. technical agency measures in this regard are unsatisfactory; Agricultural Development Council and perhaps to some extent International Development Research Centre (IDRC) stances are better but still insufficient.

Instruction should be shared by staffs from the United States and other nations, but it must be stressed that the planning of such an endeavor, if responsibly approached, is a most challenging matter and one that requires top-level personnel and long-term commitments. This effort should be facilitated by Title XII of the Foreign Assistance Act.

Staffing

Staffing regional and national research centers in the past has been a major concern when research networks have been proposed. Lateral movement (see below) is at least a partial solution to this problem. Creating international research teams is highly desirable, and putting teams to work on different types of problems (such as food technology, seed production, feed research, and breeding) together in one location should have a salutary effect on research.

Scientists in the high-income countries are working on problems directly related to fisheries and aquaculture in the tropics; these include food technologists, endocrinologists, geneticists, and nutritionists. Finding a way to tap these scientists' expertise for the benefit of the developing countries could speed development of aquatic food sources in these regions. We strongly urge that methods be devised for linking scientists in the high-income countries with scientists in the developing countries without transplanting the former on a permanent basis. Such methods could include sending scientists from the high-income countries to the developing countries for short periods of time each year but on a five-or-more-year basis, perhaps along the lines suggested by Djerassi (1976). This would raise the level of scientific sophistication of scientists in the developing countries and transfer the most recent results of advanced nations to the tropical countries.

Lateral Movement of Specialists

Research and development activities in aquatic food production are largely multidisciplinary in nature. Expertise in certain fields could be tailored to serve the needs of aquatic foods research and development missions. Poultry geneticists can become fish geneticists; in fact, all of the few such fish experts have backgrounds in mammalian or avian sciences. A similar argument applies to nutritionists, engineers, soil scientists, population ecologists, food technologists, etc. who would have to be retrained to deal with aquatic life forms. In most cases, such retraining can be accomplished in a few months to a year. Manuals, special courses, and selected course sequences of existing courses could be devised for each category, if not for each individual. This again would require applying the talent of the most experienced senior experts in the aquatic production and food sciences fields. We suggest therefore that experts be identified who can act singly or as a panel to advise the developing countries that want to retrain technical personnel to become effective in aquatic food production and development. These experts need not all be chosen from the United States. The same rationale probably could be applied to other multidisciplinary fields in the area of food and nutrition.

REFERENCES

Borgstrom, G. (1974) Focal Points. A Global Food Strategy. New York: Macmillan.

Chaudhuri, H., R. D. Chakrabarty, P. R. Sen, N. G. S. Rao, and S. Jena (1975) A new high in fish production in India with record yields by composite fish culture in freshwater ponds. Aquaculture 6:343-355.

Christy, F. T., Jr. (1976) Problems for the Management and Distribution of International Fisheries During the Next Decade. Submitted to the American Society of International Law.

Consultative Group on International Agricultural Research, Technical Advisory Committee (1974) Aquaculture Research Programme: Report of the TAC Subcommittee on Aquaculture. DDDR/IAR/74/25 Restricted.

Day, C. (1976) Small-scale fisheries: the problems and the opportunities. Fishing News International 15(3):33, 35-36, 39.

Djerassi, C. (1976) A modest proposal for increased north-south interaction among scientists. Bulletin of the Atomic Scientists 32(2):56-60.

Food and Agriculture Organization of the U.N. (1950-1974) Yearbook of Fishery Statistics. Rome: FAO.

Food and Agriculture Organization of the U.N. (1975a) Proposals for Action. World Food Conference. Rome: FAO.

Food and Agriculture Organization of the U.N. (1975b) Yearbook of Fishery Statistics. Vol. 38 (for 1974). Catches and Landings. Rome: FAO.

Food and Agriculture Organization of the U.N. (1975c) Yearbook of Fishery Statistics. Vol. 39 (for 1974). Fishery Commodities. Rome: FAO.

Food and Agriculture Organization of the U.N. (1976a) Peru. FAO Fishery Country Profile. Rome: FAO.

Food and Agriculture Organization of the U.N. (1976b) Summary Report. FAO Technical Conference on Aquaculture, Kyoto, Japan.

Gulland, J. A. (1971) The Fish Resources of the Ocean. Surrey, England: FAO, Fishing News (Books) Ltd.

Hanamura, N. (1976) Advances and Problems in Culture-based Fisheries in Japan. FAO Technical Conference on Aquaculture, Kyoto, Japan.

Huguenin, J. E. (1968) Selective Biological Barriers: A Preliminary Feasibility Study. Department of Ocean Engineering, Massachusetts Institute of Technology. Report 70-10.

Idyll, C. P. (1970) The Sea Against Hunger. New York: Crowell.

Kohl, J., ed. (1976) Energy from the Oceans, Fact or Fantasy? Conference proceedings, Center for Marine and Coastal Studies, North Carolina State University.

Pantulu, V. R. (1976) Role of Aquaculture in Water-resource Development--A Case Study of the Lower Mekong Basin Project. FAO Technical Conference on Aquaculture, Kyoto, Japan.

Pigott, G. M. (1976) New approaches to marketing fish. Pages 1-38, New Protein Foods, Vol. 2, Technology, edited by A. Altschul. New York: Academic Press.

Pillay, T. V. R. (1976) The State of Aquaculture, 1975. FAO Technical Conference on Aquaculture, Kyoto, Japan.

Pimentel, D., W. Dritschilo, J. Krummel, and J. Kutzman (1975) Energy and land constraints in food production. Science 190:754-761.

Roels, O. A., S. Laurence, L. van Hemelrijck, and A. F. Amos (1976) Potential mariculture yield of floating sea thermal power plants. Part 1--General statement. Pages 47-52, Kohl.

Smith, R. R. (1976) Nutrient Utilization by Fish. Proceedings of the First International Symposium on Feed Composition, Animal Nutrient Requirements, and Computerization of Diets, Logan, Utah.

Sprague, L. M. and J. H. Arnold (1972) Trends in use and prospects for the future harvest of world fisheries resources. Journal of the American Oil Chemists' Society 49(8):345A-350A.

United Nations Educational, Scientific, and Cultural Organization, Intergovernmental Oceanographic Commission (1976) A Comprehensive Plan for the Global Investigation of Pollution in the Marine Environment and Baseline Study Guidelines. IOC Technical Series #14. Paris: UNESCO.

U.S. Department of Commerce (1975) National Plan for Marine Fisheries (review draft). National Marine Fisheries Services, National Oceanic and Atmospheric Administration.

U.S. Department of Commerce (1976) NOAA Aquaculture Plan. Prepared by the Office of Sea Grant, National Marine Fisheries Service, National Oceanic and Atmospheric Administration.

Waslien, C., B. Kok, J. Meyers, and W. J. Oswald (1977) Photosynthesic single cell protein. NSF/MIT Protein Resources Study, edited by N. Scrimshaw and M. Milner.

ISBN 0-309-02647-4