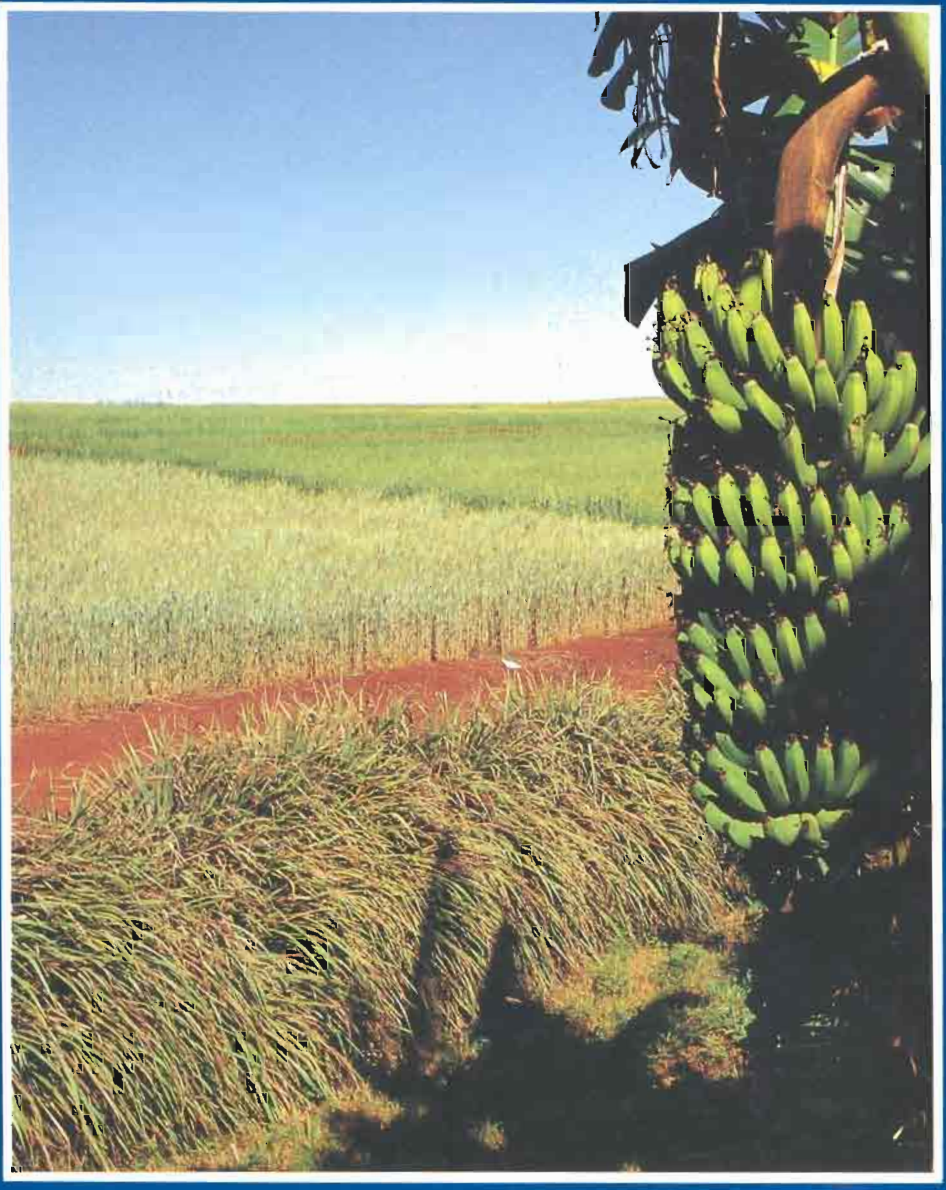
Wheat Production Constraints in Tropical Environments

A.R. Klatt, technical editor



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On the cover: Wheat and bananas in adjacent fields in the state of Paraná, Brazil (Photo by Gene Hettel)

Wheat Production Constraints in Tropical Environments

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A.R. Klatt, technical editor

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The International Maize and Wheat Improvement Center (CIMMYT) is an internationally funded, nonprofit scientific research and training organization. Headquartered in Mexico, the Center is engaged in a worldwide research program for maize, wheat, and triticale, with emphasis on food production in developing countries. It is one of 13 nonprofit international agricultural research and training centers supported by the Consultative Group on International Agricultural Research (CGIAR), which is sponsored by the Food and Agriculture Organization (FAO) of the United Nations, the International Bank for Reconstruction and Development (World Bank), and the United Nations Development Programme (UNDP). Donors to the CGIAR system are a combined group of 40 donor countries, international and regional organizations, and private foundations.

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Acknowledgments

It takes many peole to organize a conference of this type, especially one that has been as successful as this meeting. We owe a great deal of thanks to the following people: first to Dr. Yookti Sarikaphuti, director general of the Department of Agriculture of Thailand, for his continued support for wheat research and Thai wheat researchers; also to Dr. Ampol Senanarong, deputy director general for research within the Department of Agriculture, for officially opening the conference and his support for wheat research in Thailand; to Dr. Nakorn Nalampang, dean of the Faculty of Agriculture of Chaing Mai University and his staff for their assistance and excellent cooperation in making preparations for this conference; to Dr. Phattakun Chandhanamutta, National Wheat Coordinator, for his continued support and participation in the wheat research efforts of Thailand; and to all the scientists and Thai wheat cooperators who assisted with the preparation for this conference.

Special thanks also go to Dr. Boriboon Somrith, director of Upland Crops at the Phrae Rice Research Center, for demonstrating that wheat can be grown in paddy fields in Thailand. He and his staff deserve special congratulations for the accomplishments they have achieved in wheat research in the last 3 years. Also, we want to commend them on their new logo for the Center, which has rice on one side and wheat on the other. Maybe wheat does have a future in Thailand!

Warm gratitude also goes to Major Pian Chansuebsri and his staff at the Agriculture Training Center at Lampang. Obviously he has put together a team of dedicated scientists who are doing excellent research on wheat. Their efforts should make wheat a commercial crop in Thailand in the near future.

Also special thanks goes to the entire Thai wheat program involving scientists from the Department of Agriculture, Kasetsart University, Chiang Mai University, and the Agriculture Extension Service for their continuous support and for their efforts in arranging this conference. We also recognize two individuals, Dr. Dumrong Tiyawalee of Chiang Mai University and Dr. Vitoon Khunthicula from the Department of Agriculture at Samoeng, for their foresight to realize that wheat production could be important to Thailand. They have been conducting wheat research for the last 20 years and we are certain that their efforts have had an impact on the current wheat research program in Thailand.

Appreciation also goes to Janet Keyser of Washington. D.C., and Gene Hettel, CIMMYT science writer/editor, for their development and editing of these proceedings.

We are also indebted to the United Nations Development Programme (UNDP) for its financial support of this conference and the continued funding for this type of work in a project entitled, Development of Wheat Varieties for Marginal Areas.

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Preface

The international conference on Wheat Production Constraints in Tropical Environments was held in Chiang Mai, Thailand, January 19-23, 1987. This was the second major conference addressing the problems associated with introducing wheat into the warmer environments of the world. Eighty-three participants from 26 countries in Asia, Africa, and North and South America attended.

Following the presentation of 25 invited papers discussing the major constraints that confront wheat growing in these nontraditional areas, breeding, pathology, and agronomy discussion groups identified future research objectives, established priorities, and identified areas for international cooperation.

Obviously, progress has been made in the 2½ years since the first conference in Mexico, but additional efforts are still required if wheat is to become a commercial crop in warmer environments.

These proceedings are a companion piece to *Wheats for More Tropical Enviroments: Proceedings of an International Symposium*, CIMMYT 1985.

Grateful acknowledgement is given to the United Nations Development Programme (UNDP), our Thai hosts, and the growing team of international cooperators working on these constraints for making this valuable conference possible.

Arthur R. Klatt
Technical Editor

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Welcome to the Conference on Wheat Production Constraints in Tropical Environments

Ampol Senanarong, Deputy Director General, Department of Agriculture, Thailand

It is my privilege to welcome you to the conference on Wheat Production Constraints in Tropical Environments. This conference is a follow-up to the tropical wheat workshop held in Mexico in September 1984. Its main purpose is to bring together wheat researchers from various countries that have been doing research on developing wheats and wheat technology for the more tropical environments. It is an honor that CIMMYT and UNDP consider Thailand an appropriate place to hold a conference with so many distinguished delegates.

Traditionally, Thailand is a food-producing country. An estimated 35 million people, about 70% of the Thai population, are engaged in agriculture and agriculturally related activities. Sixty percent of the land cultivated in Thailand is planted to rice. Thailand is currently the largest rice exporter in the world, having recently accounted for 4 million tons, which is about one-third of worldwide trade.

Bread was first introduced to the taste of Thai urban life by the bakery house of the Oriental Hotel in Bangkok about a century ago. The consumption of wheat in various forms has gradually built up in a conservative manner. Currently, the annual per capita consumption is 145 kg for rice and 2.5 kg for wheat. Wheat consumption now is double the figure of 25 years ago. At this level, we have to spend about US $20 million to import wheat.

Many factors complicate the distribution of wheat, including people's tastes, desires, and traditions. Wheat has to survive in a cultural as well as a physical environment. Wheat experiments in Thailand were first conducted in northern Thailand in 1934. Some adapted varieties have emerged from introduced materials. However, the crop has not yet taken farmers' preference because of production and research constraints. Our recommended wheat varieties are 20 years old. There is a national cooperative yield trial to evaluate new varieties for their adaptation and yield potential. A number of the newly introduced varieties look very promising and yield substantially well.

Another field of interest is wheat agronomy in rainfed upland and irrigated lowland after bunded rice. The development of local-use technology for wheat has been started and looks encouraging. Some small farmers have expressed an interest in wheat cultivation after being shown how to convert whole wheat grain into flour and products that can be consumed at home or sold to neighbors.

The national wheat breeding and production program is a cooperative activity among the Department of Agriculture, Chiang Mai University, and Kasetsart University. The other principal cooperating institutions include the Department of Agricultural Extension, the Office of Agricultural Economics, and

CIMMYT. Such a coherent effort has revived the wheat program tremendously. The Ministry of Agriculture and Cooperatives has projected a target of 20,000 hectares in the current 5-year plan.

At this prestigious moment, I thank CIMMYT and UNDP for sponsoring the conference, and I hope it will offer practical findings and set a framework for research priorities.

I also wish all delegates a happy stay in Chiang Mai, an old city of 700 years, yet undivided. Do not let the remnant city wall barricade your pleasure and enjoyment.

Thank you very much.

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Keynote Address: The Potential for Expanding Wheat Production in Marginal and Tropical Environments

B.C. Curtis, Director, Wheat Program, CIMMYT, Mexico

The main purpose of this conference on Wheat Production Constraints in Tropical Environments is to bring together wheat researchers from countries that have been doing research on developing wheats and wheat technology for the warmer nontraditional environments. This meeting is a follow-up to the tropical wheat workshop held in Mexico, September 24-28, 1984 (4), and will concentrate on research findings in the interim period and other topics pertinent to tropical wheat environments.

Why Expand Wheat to Nontraditional Areas?

Wheat is already grown across a wide range of environments around the world. In fact, it has the broadest adaptation of all the cereal crop species. More land is already devoted worldwide to the production of wheat than to any other commercial crop—about 232 million ha.

Some may then ask why we are trying to expand wheat production into nontraditional areas, especially in light of the fact that following the 1986 harvest, much of North America, Europe, China, and India had great excesses of wheat and other cereal crops. In many places, this bountiful harvest was stored on the ground for lack of any better alternative. Presently, the export market is weak, prices are depressed, and wheat stocks held by the major producing countries amount to almost 125 million tons! A recent World Bank report (3) stated, "The world has ample food. The growth of global food production has been faster than the unprecedented population growth of the past 40 years—yet many poor countries and hundreds of millions of poor people do not share in this abundance. They suffer from a lack of food security, caused mainly by a lack of purchasing power."

However, I can assure you that these "apparent" surpluses are merely transitory. Sooner or later, grain scarcities will return. At an International Agricultural Trade Research Consortium meeting last month at the International Maize and Wheat Improvement Center (CIMMYT), economist Robert Herdt of the Rockefeller Foundation said that within 10 years, we will again be in a period of grain scarcity.

Exploding population in the developing world necessitates the continued work of increasing cereal production. Early in 1986, the population of this planet reached 5 billion. Between 1990 and 2000, the developing countries will add a whopping 828 million more people to the world's population—more than three times the current population of the United States. By the year 2000, only 4729 days away from today, January 19, 1987, an additional 1.2 billion people will live on this earth.

The birth rate at the end of the century will be 4.5 new hungry mouths every second. Ninety percent of these new people will be born in the Third World. Developing nations, which already account for three-fourths of the world's population, will be growing at least three times faster than the developed nations at the end of the century. The International Food Policy Research Institute (IFPRI) expects that the proportion of the population of developing countries living in urban areas will increase from about 30% in 1980 to about 44% by the year 2000 (2). This is a massive demographic shift, without precedent in human history.

In addition, wheat consumption has continued to increase worldwide during the 1980s, especially in the developing world. According to Per Pinstrup-Andersen (2), the main driving factors are urban population growth, rising incomes, income distribution, relative prices, and taste — all leading to a higher per capita wheat consumption, with increases of 4 to 5% annually in some countries, well above population growth. Bread is becoming a staple food for more and more people in the tropics. There is a strong desire to substitute wheat bread for other cereal-based foods, a phenomenon found in most higher-income developing countries. Bread is a preferred commodity. For many developing nations, this has led to an increased dependency on wheat imports and the accompanying foreign exchange drain.

Wheat production in developing countries has increased at an average pace of 5% per year (1975-84). However this production has been very unevenly distributed, with traditional wheat-growing countries taking the biggest share (China, India, Turkey, Argentina, Pakistan). This indicates that many farmers in environments that are less favorable did not participate in the productivity gains of wheat made worldwide. These environments include the marginal areas and the warmer regions of the world (that is, between 23°N and 23°S latitudes).

Traditional wheat-growing countries in the developing world have increased yields, but have also expanded wheat areas into less favorable environments, that is, the more tropical regions of peninsular India, Bolivia, the formerly forested areas of Parana state in Brazil, and Paraguay. In addition, countries lying entirely in the tropics have initiated wheat research for their circumstances—Brazil (Sao Paulo, Minas Gerais, and Mato Grosso states), Ivory Coast, Nigeria, Cameroon, Madagascar, Dominican Republic, Colombia, the Chaco region of Bolivia and Argentina, Thailand, the Philippines, Sri Lanka, and Indonesia, to name a few.

Initiation of Tropical Wheat Research

Much attention has been given by scientists to developing wheats suitable for climates that are cooler than the crop's original habitat in the Middle East, and agronomic practices to realize the yield of such varieties have been greatly refined and adapted to modern inputs. Likewise, in recent years, yields have been increased in the temperate climates similar to the Middle East, largely through the development of semidwarf varieties resistant to the prevalent diseases. These varieties, commonly referred to as HYVs (High Yielding Varieties), combined with new technology, such as chemicals and fertilizers, and, under some circumstances, new irrigation facilities and mechanization, have greatly increased production. These varieties are now grown on about 50.7 million ha in developing countries, including China, as of the 1982-83 crop year (1).

However, until 1982, little effort had been made specifically to broaden the genetic variability of wheat for the more marginal areas and warmer climates and their environmental stresses, although production areas have expanded towards the equator over recent years (Figure 1). The total potential wheat area in the tropics is estimated to be between 3 and 4 million ha in nearly 60 countries (Table 1). These countries can be divided into basically two types of environments—1) high temperatures, dry, short crop season, few disease problems, and 2) high temperatures, more humid, short crop season, significant disease problems.

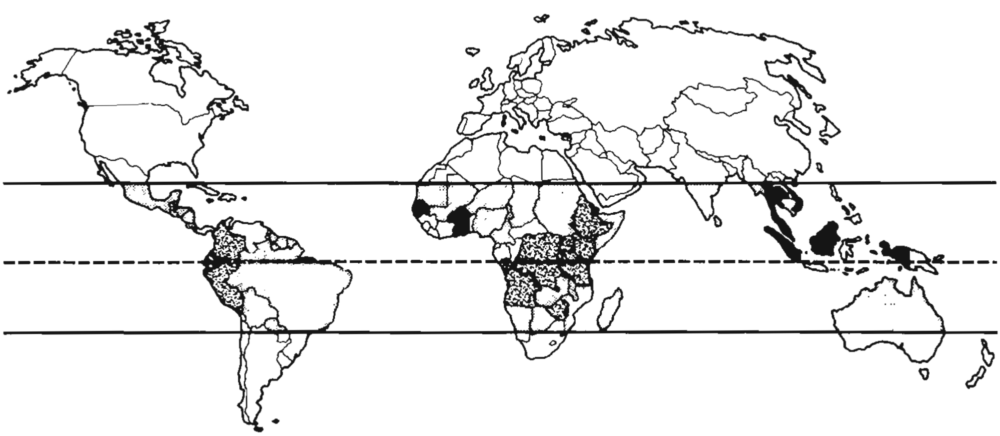
Starting in the late 1970s and early 1980s, many of these countries began requesting from CIMMYT wheat germplasm capable of producing acceptable and reliable yields in tropical climates.

One donor responded and in his keynote address to the 1984 symposium, Wheats for More Tropical Environments, Mr. W.T. Mashler, senior director for the Division for Global and Interregional Projects of the United Nations Development Programme, said that in the late 1970s, he and the UNDP recognized the need to fund a project to aid in the development of wheats to fit into the nontraditional, more tropical areas. This led to a 5-year UNDP-funded project, which started on July 1, 1982. In this project, CIMMYT has aimed to develop improved wheat germplasm suitable for these warmer subtropical areas with cooperating research institutions in many developing countries.

What Has Been Accomplished So Far

The project's overall goal has been to develop high-yielding, disease-resistant, semidwarf wheats with proven performance in target countries. Specific objectives have included:

- Development of wheat germplasm with the following characteristics:
  - wide adaptation with high yield potential,
  - photoperiod insensitivity,
  - improved heat tolerance,



commercial production | commercial production above 1500 m | experiments

Figure 1. Wheat production in the tropics.

— high tillering ability,

— high hectoliter weight,

— different maturity classes to fit the range of environments,

— semidwarf stature and strong straw to withstand lodging,

— acceptable milling and baking quality, and

— resistance to leaf rust, *Helminthosporium* spp., *Fusarium* spp., and *Alternaria triticina*;

- Exchange of information through conferences and workshops; and

- Training of young scientists in countries of marginal areas that are setting up research programs.

Progress is being made on all of these objectives through:

- Shuttle breeding—the growing of alternate generations after crossing in environments diverse for several of the required characters;

Table 1. Countries and areas that could potentially benefit from the development of wheats with better adaptation to marginal areas

Environment I: High temperatures, dry, short crop season, few disease problems	Environment II: High temperatures, more humid, short crop season, significant disease problems
Coast of Mexico	Costa Rica
Northern Venezuela	Dominican Republic
Coast of Ecuador	Guyana
Coast of Peru	Eastern Colombia
Eastern Bolivia	Southern Brazil
Northwestern Paraguay	Southeastern Paraguay
Northern Argentina	Central Cameroon
Southern Mauritania	Central African Republic
Northern Senegal	Congo
Central Mali	Eastern Zaire
Burkina Faso	Zambia
Northern Ghana	Uganda
Central India	Ethiopia
Niger	Tanzania
Northern Nigeria	Mozambique
Northern Cameroon	Malawi
Chad	Madagascar
Sudan	Northeastern India
Somalia	Nepal
Saudi Arabia	Bangladesh
Oman	Burma
PDR of Yemen	Thailand
Yemen	Vietnam
United Arab Emirates	Laos
Southern Pakistan	Kampuchea
	Southern China
	Indonesia
	Philippines

- Multilocation testing—to facilitate the identification of suitable parental material for crosses as well as to make suitable material available to interested national programs;

- Training and conferences—to build up a network of scientists familiar with research in a completely new crop through workshops and conferences as well as formal training courses; and

- Funding of necessary research equipment—to permit newly trained scientists to be efficient in their work for an often not yet commercially grown crop.

All project activities are being carried out as proposed. Segregating generations have been exchanged between Mexico and specific areas or "hot spots" known for disease occurrence and/or environmental stress. Specific international nurseries for fusarium, helminthosporium, and heat tolerance, including lines superior for the respective characters, have been established and distributed annually to interested national programs. Flow-back of reliable data has been used to plan further crosses and refinement of breeding research approaches.

Two conferences, several workshops, sponsoring of visiting scientists to Mexico and between national programs, in-country training courses, and formal training in Mexico have contributed to creating a core of researchers familiar with the problems of growing wheat in warmer environments and the techniques for the development of potential solutions.

These activities have contributed toward the overall goal of development of suitable germplasm and capable national staff to use it. Progress has been made in most of the project's breeding objectives.

Let me point out some specific areas that CIMMYT has been involved in to broaden the genetic variability of wheat for the marginal and warmer environments.

Screening techniques
CIMMYT pathologists have developed techniques to obtain reliable information about scab and helminthosporium resistance. These include inoculation techniques, production and storage of inoculum, standardization of disease reaction readings, and identification of hot spots, that is, suitable environments for screening inside Mexico as well as in other countries, such as China and Brazil for scab, and Bangladesh, Brazil, and the Philippines for helminthosporium.

Intensive crossing
CIMMYT breeders have started intensive crossing on the basis of previous information and have continued this with more confidence as information from cooperating countries has been returned with growing reliability. Lines from initial crosses, based on limited information about their adaptation and performance in target environments, have reached international nurseries within the last year.

Germplasm for specific disease and stress purposes being developed through shuttle breeding with cooperative countries is now only part way through its development, since alternating generations in two countries allow only one generation per year, due to the logistics of international seed shipment. These materials will require additional cycles of selection and subsequent testing before they are ready for release in the respective countries.

Training of local researchers
Local reseachers have received training to handle a completely new crop for their areas. In countries that are just starting to do research on wheat, this includes basic knowledge of breeding and agronomic practices, selection criteria, diagnosis and scoring of diseases, and seed handling and storage. Unfortunately, turnover of local staff in nontraditional wheat countries is high because often a lifetime career on a noncommercial crop is not possible and researchers prefer "safer" jobs if they become available. I must point out that a threshold number of researchers trained in wheat is still to be achieved in many national programs. CIMMYT has trained numerous young researchers. Training officers have visited tropical areas and have included relevant aspects from these environments in their curricula.

Development of management practices
CIMMYT agronomists are assisting in research to develop suitable management practices in cooperation with experiment stations and farmers in target areas. The initial problem in the nontraditional areas has been the research and extension workers' total unfamiliarity with wheat. So much attention has been, and is being, focused on in-country training, both formal and informal. Now that some research and extension workers have achieved a reasonable level of competence, soil management practices, fertility management, weed control techniques, and integrated methods of disease control are being addressed, both on experiment stations and farmers' fields.

Wide crosses
The CIMMYT wide cross program continues to make interspecific and intergeneric crosses to transfer needed genes from alien genomes into wheat. Hopefully these will contribute to the improvement of characters important in warm climates.

Other activities
CIMMYT's commitment to the development of germplasm for the warm and nontraditional wheat environments is reflected in the following activities:

- An associate scientist position has been created to work on heat tolerance and helminthosporium resistance inside Mexico.
- A staff pathologist is working part-time in Mexico on scab.
- Wide crosses are being made for hot climate characters, as I mentioned earlier.
- There has been intensive cooperation on many levels with Chinese, Brazilian, and Mexican scientists where scab is the main disease.
- A large cooperative program with Brazilian institutions has been initiated to further promote tolerance to acid soils and aluminum toxicity, which are widespread in tropical soils.
- CIMMYT wheat research teams have been placed here in Thailand and in Paraguay.
- Some screening work for saline soils, an increasing problem in tropical irrigation systems, is being done.

- Agronomists have been based in Southeast Asia and East Africa in order to develop suitable agronomic practices for these environments, and soon another agronomist is expected to be based in Latin America for the warmer areas.

- A large number of policy makers and research administrators have visited Mexico or other countries relevant to wheat for marginal areas.

- Several national program scientists have visited Mexico and other countries to study problems of growing wheat in marginal areas.

Other benefits
One important reason for CIMMYT's emphasis on wheat germplasm development for nontraditional areas lies in the expected high spinoff of this activity for traditional areas and/or stress areas of a different kind than ones dealt with for tropical wheat. For example, the diseases of hot climates are present in traditional wheat areas too, although with less pressure; but they do show up after genetic control of traditional diseases has been achieved. Also terminal heat tolerance is important for areas such as South Asia, the Mediterranean Basin, and Latin America where high temperatures occur frequently.

The Potential for Tropical Wheat

After working on wheat for warmer environments for a number of years now, we have shown that there is good potential for growing it commercially in some areas. We have also found that the variability exists to further increase productivity and dependability of production under these conditions. However, before we can realize the potential of producing wheat in the tropics, there are still a number of things that must be done.

What needs to be done
For the future, we need to integrate the achievements realized thus far and bring them closer to farmers' reach and adoption. Our specific goals include the following.

Germplasm recombination—Germplasm improved over the last 5 years for single characters such as wide adaptation, photoperiod insensitivity, heat tolerance, tillering ability, earliness, semidwarfism, acceptable industrial quality, and resistance to leaf rust, helminthosporium, and fusarium has to be recombined for the needs of the principal wheat environments in the warmer areas to withstand the relevant hazards.

New breeding objectives—Some new breeding objectives that have been recently identified as important must receive additional attention. These include the foot rots caused by a variety of fungi, waterlogging tolerance, and tolerance to saline soils.

Study of agronomic practices—Agronomic practices appropriate to farmers' circumstances and existing cropping practices must be intensively researched. Major areas include seedbed preparation methodology to reduce the turnaround time and consequent moisture loss, waterlogging avoidance on heavy paddy soils, irrigation and fertilizer technology, weed, disease, and insect control with an emphasis on integrated approaches, and improved threshing methodology. Attention must also be given to postharvest technology aimed at preserving viability of wheat seed stored at the farm level.

How to accomplish these goals
To accomplish our goals, we need to continue activities in the following areas.

Breeding—Breeders will have more parental lines available that have been improved through crossing over the last 5 years. As I have already stated, future hybridization must involve character combination according to the needs of actual and potential growing areas in warmer climates.

Information will be collected and distributed about genetic variability for new characters that have posed problems for national programs, such as foot rots, bacteria, waterlogging, and some insects.

Shuttle breeding within Mexico as well as with national programs in the Southern Cone of South America and Southeast Asia will be an important means to identify germplasm with the desired combination of characters, because only in this way can segregating generations become exposed to different types of stresses.

Testing and exchange—Special international nurseries for heat tolerance, drought, scab, helminthosporium, and acid soils will provide a means for germplasm distribution to interested countries. An increasing number of entries will be the result of crosses made for these environments, rather than existing lines that proved superior during screening.

Direct exchange of lines developed on a national level from locally made crosses or from local selections of F_2 populations from Mexico will take place from a nursery initiated by breeders in South and Southeast Asia 2 years ago. There are plans to broaden this nursery to include lines from all national programs interested in such direct exchange of local germplasm.

Development of agricultural practices—Crop management is more critical in hot climates where a small error can result in very large yield losses relative to comparable errors in temperate climates. For this reason, precise crop management techniques must be developed to exploit the superior yield potential of better adapted lines as they become available. Research will center on soil management, fertility maintenance, disease control, harvesting and threshing techniques, and appropriate small-farm equipment.

Training and conferences—In order to teach extension workers and farmers with confidence, we hope to increase the number of trained reseachers as well as strengthen the experience of trained researchers through in-service training, support for visiting scientists, regional workshops, and a conference that will address global wheat problems and research progress.

Who Will Benefit?

Farmers in various types of warm environments and other nontraditional areas will benefit from this work. Improved varieties are one of the cheapest inputs for a reliable and high-yielding crop and appropriate agronomic practices help to achieve the optimum utilization of the normally poor resources at the disposal of farmers.

Farmers who are already attempting to grow wheat but are experiencing a wide range of yields due to hostile climate and diseases, will realize benefits the most quickly through higher and more reliable or stable yields. Farmers in areas where wheat is still not a crop will have a new option to increase food output during the cool and dry season through the introduction of high-quality cereals that adapt to many cropping patterns; especially where short duration, water-use efficiency, and/or low labor input are important. Farmers will gain from breeding progress in wide adaptation, yield potential, and disease resistance. The same farmers will reap extensive benefits from the new crop management techniques derived from the increased attention given to agronomic research.

For resource-poor farmers, wheat offers high flexibility due to its potential dual purpose for the farm economy. In years when food is in short supply, it can be used for the farmer's family; in years with abundant staple food, it can be considered a cash crop that is relatively easy to handle, store, and transport.

On the national level, cultivation of wheat offers the benefit of foreign exchange savings.

Ultimately, millions of people, as well as national economies in subtropical and tropical countries, can confidently be expected to benefit—provided germplasm and crop management technology can be developed that is acceptable to farmers.

The Next 5 Days

Briefly, I have outlined what we have accomplished and what research still needs to be done to develop wheats for warmer environments. Over the next 5 days, we will hear more details from more than 30 researchers from around the world.

This conference has been divided into four sessions:

1) Characterization of tropical wheat environments

2) Constraints associated with rice-wheat rotations

3) Constraints to wheat cultivation in nonirrigated areas

4) Discussion groups according to discipline (breeding, pathology, and agronomy) to identify future research objectives, establish priorities, and identify areas for international cooperation

I look forward to hearing these presentations and participating with you in the coming days.

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4

Characterization of Tropical Wheat Environments: Identification of Production Constraints and Progress Achieved

South and Southeast Asia

D.A. Saunders, Wheat Program, CIMMYT, Bangkok, Thailand

Abstract

In the more tropical countries of this region, such as Thailand, the Philippines, and Indonesia, there is increasing interest in domestic wheat production. At this early stage of genotype and management development, wheat cannot be expected to compete with adapted traditional crops. Rather, it should be promoted as an additional crop in rotations in which there is a crop void during the cool, dry season. This can occur for various reasons in rainfed upland or rice paddy situations. In the former, on-farm yields of up to 2.5 t/ha, and in the latter, up to 5 t/ha, have already been recorded.

Further yield increases can be expected from improved germplasm (by selection of segregating populations in target environments) and crop management techniques. More timely seeding, improved water management, weed and disease control, increased fertilizer efficiency, and more appropriate threshing techniques will result in substantial yield gains.

Input costs are a major factor in the farming communities throughout the region and, in some areas, fertilizer use, in particular, is tending to decrease due to commodity market price pressures. In some areas, fertilizers are never used. There is a potential danger that fertility depletion by the additional wheat crop may result in a reduction of yield in the subsistence crop of rice or maize.

In South and Southeast Asia, approximately 33 million hectares are sown to wheat in India, Pakistan, Bangladesh, and Burma. Of this, an estimated 7 million hectares are sown to wheat below the Tropic of Cancer, principally following rice, in India and Burma.

In the more tropical countries such as Thailand, the Philippines, and Indonesia, there is increasing interest in domestic wheat production to at least partially substitute for the increasing wheat importations. In Burma and Bangladesh, wheat production is contemplated in the more tropical southern regions.

This review will center mainly on recent experiences in the more tropical countries, but reference will be made to the more temperate areas of the region as basic similarities exist, particularly in relation to the rice-wheat rotation.

Target Areas for Wheat Growing

Some climatological characteristics of three current target areas are shown in Figure 1. Northern Thailand, represented by Chiang Mai, has the longest dry season and coolest temperatures. Wheat is sown from October to December depending on the farming system. In the Cagayan Valley of Luzon, Philippines (Tuguegarao), the peak rainfall is in November, normally in the form of

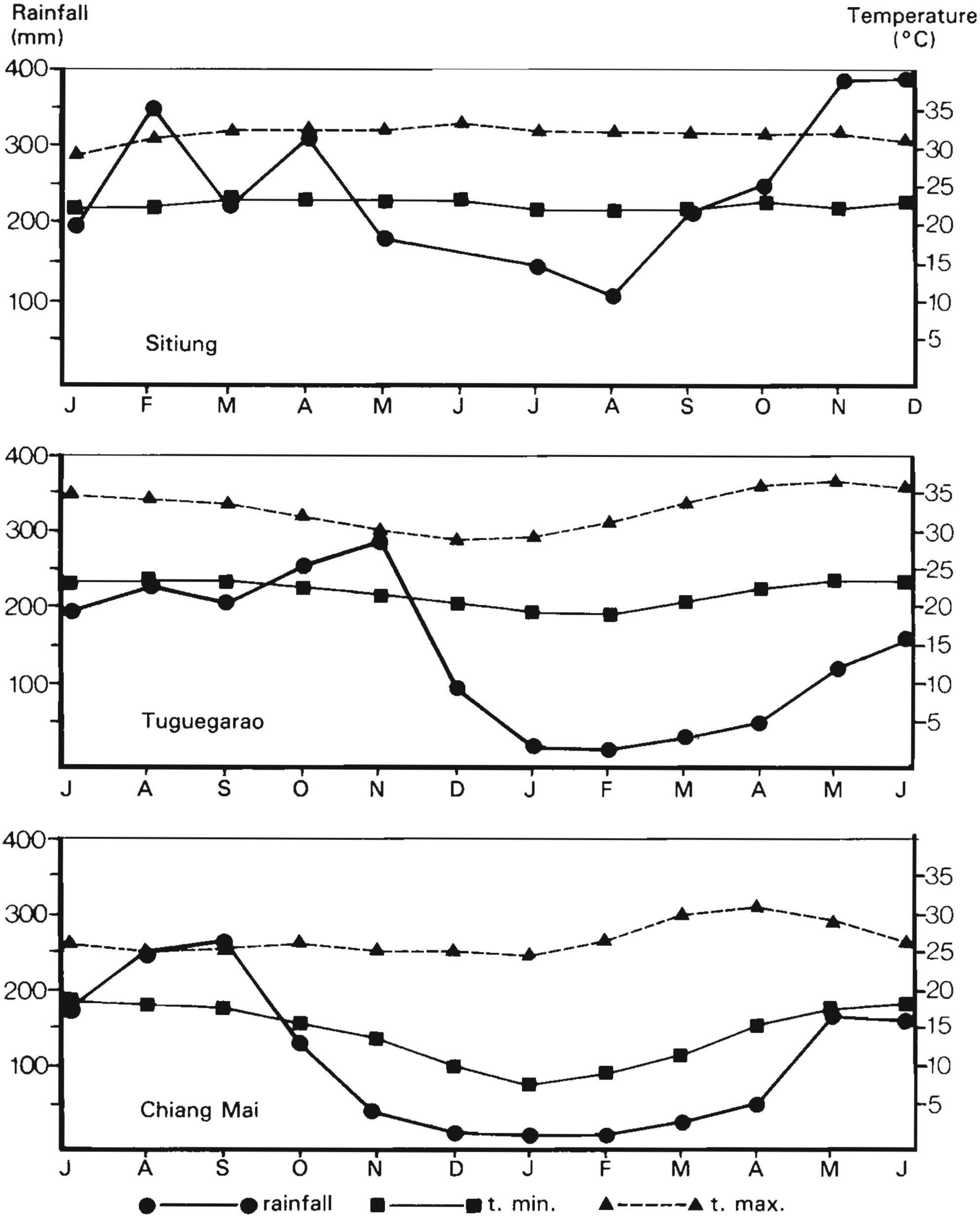

Figure 1. Climatological characteristics of three wheat target areas in Southeast Asia, Chiang Mai (northern Thailand), Tuguegarao (northern Philippines) and Sitiung (western Sumatra, Indonesia).

typhoons, which typically delay rice harvest and the subsequent seeding of the wheat crop. Wheat in the past few seasons has normally been sown in late December. Sitiung, representing the lower altitude areas of western Sumatra has virtually no variability in temperature throughout the year, August being the driest month (approximately 100 mm on average). This area is highly experimental and research is aimed at establishing the wheat crop in April-May to harvest in August.

As rainfall and temperatures increase, diseases become more of a problem. In northern Thailand, while leaf rust (primitive races), *Helminthosporium sativum*, *Fusarium* spp., and *Sclerotium rolfsii* exist, they rarely cause significant yield reductions. In the Philippines, up to 60% of the established plant population has been lost due to *Sclerotium rolfsii* or a complex of foot rot organisms (27). Complete crop losses due to *Helminthosporium sativum* have been observed.

In Indonesia, in addition to these, fusarium head scab can be severe.

In discussing wheat target areas, an initial point must be established. Wheat is not a tropical crop and will require a considerable effort in breeding and crop management research to become truly competitive with traditional tropical crops. For the present, therefore, it must be viewed as an additional crop within a rotation in which, for some reason (low temperature, insufficient irrigation), there is a cropping void during the dry cool season. Under these circumstances, a number of opportunities for wheat cultivation exist.

Rainfed upland

Wheat can be sown following the harvest of upland rice or maize into a full soil profile. In northern Thailand, where most research on this system has been conducted, the optimum seeding date appears to be the first week of October, approximately 2 weeks after harvest of the preceding crop. Some rains are expected in October to partially refill the soil profile. The following months are dry until maturity. Indian experience suggests that soil moisture storage should be 200 to 300 mm/m of the soil profile for satisfactory yield levels (22). In northern Thailand, adequate yields have been obtained on soils having an available water content of 250 mm in the upper 1.5 m of soil (17).

Yields have proved variable, depending on climatic conditions and soil moisture storage capacity, but up to 2.5 t/ha have been achieved.

From surveys, two consistent problems have emerged — 1) late seeding (into a rapidly drying topsoil), usually resulting from poor organization of seed distribution, and 2) shallow seeding. The latter is not merely related to soil moisture relations. For reasons that are unclear, plant development from seeds sown 5-6 cm deep is superior to that from sowing 2-3 cm deep, with moisture as a constant factor, resulting in more fertile tillers with larger spikes.

A major potential problem is that wheat is being promoted as an additional crop in farming systems in which fertilizer is rarely, usually never, used. Given timely seeding, responses by wheat to fertilizer, principally nitrogen, are universal. The potential danger is that fertility depletion by the additional crop (wheat) will lead to a reduction of yield in the subsistence crop (rice or maize).

About 85% of the wheat area of Burma (currently about 145,000 ha) is cultivated under rainfed conditions. The same general problems exist—seeding too late (resulting from the need to carry out many cultivations to obtain a reasonable seedbed), shallow seeding, and very low fertilizer use. The average yield under rainfed conditions was reported as 1369 kg/ha in 1983/84 (24).

Upland rainfed cultivation of wheat in the Philippines has not as yet been attempted, the National Wheat Program has initially concentrated on lowland paddies. However, due to the rainfall pattern extending into December, the system would appear to have some potential.

Partially irrigated paddies
In both the upland and the lowland, there are instances where irrigation system storage is not sufficient to supply water for the complete dry season. If water is available for the first month of the wheat crop, with two irrigations, yields of up to 2.4 t/ha have been obtained (20).

Fully irrigated lowland paddies
Lowland paddies are thought to be the largest potential area for wheat cultivation. In many irrigation areas, the dry season temperatures are too low for rice production utilizing current varieties. In addition, where temperatures are satisfactory for rice, its cultivation is being discouraged due to the poor outlook in world rice trade.

Table 1. Yield estimates from a crop-cut survey in Ilocos regions, Philippines, March 1986

Crop-cut yield (t/ha)	Number of farmers	
	Ilocos Norte	Ilocos Sur
1.0 - 2.0	1	7
2.0 - 3.0	9	5
3.0 - 4.0	10	1
4.0 - 5.0	2	0

Source: Layaoen (9)

Although 4 to 5 t/ha on-farm yields have been attained in Thailand (26) and the Philippines (9), the variability among farmers with relatively restricted areas (Table 1) is indicative of the management problems that exist in rice paddy conditions.

Progress Toward Alleviating Constraints

Germplasm development
Varieties currently used in production fields are relatively old varieties. Monywa White (IP4) was introduced into Burma in 1929 and even though its rust resistance broke down in 1950 (24), it is still the most widely grown variety due to its yield stability under drought conditions. Under irrigation, V 1287 (Punjab 81), introduced from Pakistan in 1980, is consistently high yielding. Some newer lines (e.g., Veery 5) are promising.

In Thailand, INIA 66 (Samoeng 1) and Sonora 64 (Samoeng 2) are the current varieties. In the Thailand National Yield Trials for the last 2 years (14, 25), these have been outyielded by 20% by lines from crosses made at CIMMYT some 15 years ago. Some lines from more recent introductions from CIMMYT are producing similar yields.

In the Philippines, lines from local crosses between introductions made in the 1950s and 1960s have not been outyielded by more recently introduced lines. Trigo 1 (pedigree unknown) and Trigo 2 (Fiorello/Acc. 1194), while tall and rust susceptible (not a current problem in the

Philippines), possess some heat tolerance and a moderate level of helminthosporium resistance (particularly Trigo 1).

Although Indonesia does not yet have wheat varieties, lines introduced from India (HI 784) and Pakistan (V 1287) have been high yielding over a number of years on Java (6). At various altitudes in western Sumatra, lines from the University of the Philippines, Los Banos, were most promising (3).

More recently, most programs have advanced lines from selections from CIMMYT F2 populations to yield trials at differing levels. These selections under local conditions appear extremely promising, particularly in relation to spike size and fertility.

On-station yield trials, conducted at relatively favorable fertility levels and moisture availability should be treated with some caution. For example, in the northern Thailand on-station yield trials in 1985/86, UP 262 outyielded INIA 66 by 16%. However, in 10 farmer-managed experiments under suboptimal rainfed, low fertility conditions, UP 262 outyielded INIA 66 by 46% and Sonora 64 by 23% (D. Niyomthama, personal communication). More early generation testing of populations under suboptimal conditions is suggested.

Seeding date is another factor to which attention must be paid in germplasm evaluation. Farming system scientists often say that the use of earlier maturing rice varieties will allow wheat to be sown at more optimum timings. In some areas this is not possible. In Thailand, for example, there are very strong preferences for a particular rice quality and aroma that have not been transferred to photoperiod-insensitive, shorter-maturing rices. In addition, due to marketing difficulties with ordinary rice, there is now a strong promotion for the production of basmati rice, which also matures late.

In the Philippines, another problem exists — late typhoons. These are regular and devastating, occurring in mid- to late November, resulting in late rice harvesting and difficulties in seedbed preparation. Consequently, wheat can rarely be sown before mid-December, usually later.

It is therefore imperative that varieties capable of reasonable yield under late sowing are developed. Testing in the Philippines resulted in a new release (Trigo 3) that has superior yield over the older variety, Trigo 1, at late seeding dates (Figure 2). Subsequent experiments over 2 years in farmers' fields in the Cagayan Valley demonstrated the yield superiority of Trigo 3 in virtually all seeding dates (after December 17). Trigo 3 appears to consistently exhibit increased spike fertility and relative tolerance to increased post-anthesis temperatures and late drought (more stable thousand grain weight) (11).

No lines currently available have adequate helminthosporium or fusarium resistance. Recent evidence from India (18) indicates there may be variability for tolerance to *Sclerotium rolfsii*, which may be worth pursuing. Similarly, recent research in Pakistan (M.S. Sadiq, personal communication) has shown that strong tolerance to waterlogging may be available.

Crop management technologies

Seedbed preparation—With the low levels of mechanization available, seedbed preparation has proved difficult and time consuming in most localities, but particularly following lowland rice.

For this reason, some work has been carried out on zero or minimum tillage. In the Philippines this has proved successful (Table 2); there being no yield advantage with cultivation.

In Thailand where the soils tend to be heavier and less structured, zero tillage has not yet been shown to be practical. The IRRI Rotary Injection Planter becomes blocked with soil. The IRRI Incline Plate Planter glazes the furrow surfaces, restricting the wheat roots to the furrow itself. Early indications are hopeful for a small, hand tractor-mounted seeder designed at IRRI using principles developed in New Zealand. A large tractor-mounted seeder unit from New Zealand has been used in Pakistan in the rice-wheat areas and has proved an outstanding success (12).

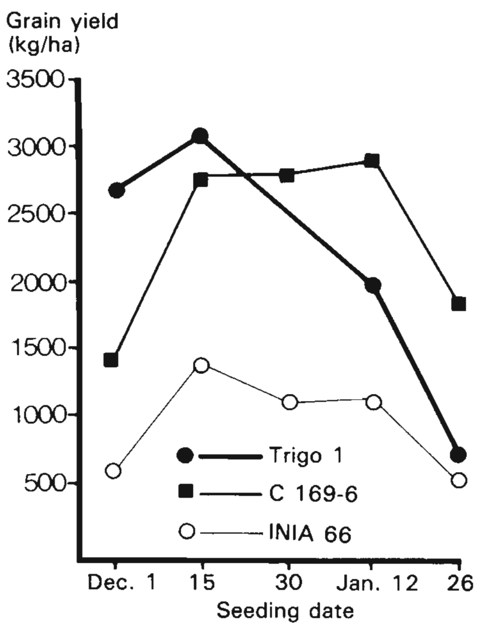

Figure 2. Effect of seeding date on yield of three wheat lines at Los Baños, Philippines, showing the superiority of C 169-6 (released as Trigo 3) over the current variety, Trigo 1.
Source: Aggarwal et al. (1)

In Bangladesh, relay seeding of wheat into standing rice approximately 2 weeks before rice harvest is proving successful and expanding rapidly. This was attempted in Thailand, but did not succeed because the wheat roots were unable to penetrate the soil. A surface root mat established which maintained the plants before rice harvest. After that time, the topsoil rapidly dried and the wheat plants desiccated.

Also in Bangladesh but in the deep-water rice area, all straw is removed immediately following rice harvest, the surface is lightly scratched, seed and fertilizer are broadcast, and the rice straw roughly returned to cover the seed. This method has given yield increases, probably because the wheat is sown some 15 days earlier than with conventional land preparation (2). However, this has not been attempted in the countries of Southeast Asia.

More development work is required on zero or minimum tillage, particularly in relation to time and quantity of fertilizer application. Chemical weed control may also prove necessary.

Fertilizer application—Research into NPK requirements for wheat has been quite extensive in Thailand and the Philippines. Responses to phosphorus have been rare (10). Banding of phosphorus with the seed has been shown to be more efficient than incorporation before planting (Figure 3). Indigenous rock phosphate applied at equivalent rates of available phosphorus produced yields not significantly different to triple superphosphate (7). In addition, residual activity was no greater than triple superphosphate in the following year (P. Jeungyusuk, personal communication).

There have been no significant responses to potassium.

With nitrogen fertilizer, a fairly consistent picture has emerged. Under irrigated conditions, a straight line response to nitrogen is obtained, usually up to 100-120 kg N/ha (Figure 4), with seeds/spike normally being affected to a greater extent than other yield components (Table 3).

However, efficiency of nitrogen response is low, rarely exceeding 10 kg additional grain yield/kg nitrogen applied, and more normally about 7 kg/kg N. The response to nitrogen is markedly affected by seeding date (Figure 4).

In no instance has the splitting of nitrogen resulted in increased yields. In fact in recent work in the Philippines (1) all fertilizer (NPK) applied at the first irrigation resulted in yields slightly higher than basal or split application, and significantly increased the number of spikes/m^2. No significant differences have yet been found between nitrogen sources.

For commercial production, median applications are recommended. In the absence of consistent responses to phosphorus and potassium, 60 kg N/ha for irrigated and 30 kg for rainfed conditions are the general recommendations.

Irrigation—Irrigation management must aim to avoid waterlogging, particularly during the establishment phase. Where possible, pre-irrigation is recommended although this is not practical in the heavier soils in

Table 2. Effect of tillage and method of planting on the yield (t/ha) of wheat (cv. UPLW1) Los Baños, Philippines

Tillage treatment	RIP (Rotary injection planter)	Dibble (Hand)	Drill (Planet jr. planter)	Mean
Zero	1.76	1.80	1.67	1.75a
2 rotovations	1.74	1.82	1.61	1.72a
Conventional	1.69	1.92	1.72	1.78a
Mean	1.73a	1.85a	1.67a	
CV (%) (a) = 8.7; (b) = 10.3				

Means followed by the same letter are not significantly different at 5% level by DMRT.

Source: Aggarwal et al. (1)

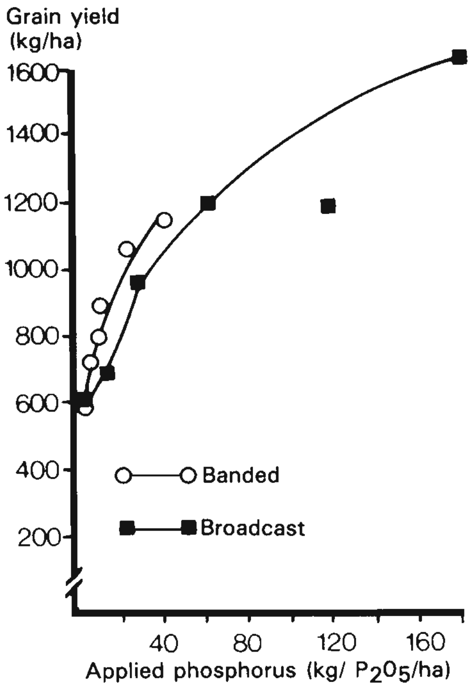

Figure 3. The response to triple superphosphate when broadcast and incorporated before seeding or banded with the seed, to a lowland paddy soil, Phrae, northern Thailand. Unpublished data of W. Uttarapong.

Thailand with present technology. Research is currently under way to investigate bed size and shape to avoid prolonged waterlogging.

Many of the soils form a crust before the wheat emerges. This can be partially overcome by increasing the seed rate to increase pressure on the crust. However, it remains a substantial problem necessitating high labor inputs to maintain a moist surface until emergence.

After establishment, the stage most sensitive to drought stress is around anthesis (15, 20).

Disease control—As the current levels of genetic resistance to tropical diseases are low, some measure of control must be attempted by crop management.

A wide range of chemicals has been tested as seed treatment against the soil-borne disease complex (*Sclerotium rolfsii, Rhizoctonia solani, Fusarium roseum*, and *Helminthosporium sativum*) in the Philippines. Thiram resulted in the highest emergence from inoculated soil and gave the most effective control post-emergence (8).

Table 3. Effect of nitrogen on wheat (cv. Sonora 64) yield and yield components, Phrae, Thailand

Nitrogen applied (kg N/ha)	Yield (kg/ha)	Spikes/m^2	Seeds/Spike	TGW (g)
0	623e	243d	9.25c	27.8c
30	963d	320bc	11.06c	28.6bc
60	1343c	339ab	14.06b	29.2ab
90	1512bc	289c	17.88a	29.6ab
120	1673b	383a	15.19b	29.9a
180	1938a	374a	17.81a	29.1ab

Means followed by the same letter are not significantly different at 5% level by DMRT.

Source: Unpublished data of W. Uttarapong

Field studies under low disease pressure indicate that both propiconazol and mancozeb partially controlled *Helminthosporium sativum* when applied at 50 days after sowing (Table 4) with the former being more effective. However, propiconazol is not currently available in the Philippines and mancozeb is recommended. Under high inoculum loads, it is totally unsatisfactory. An additional problem with helminthosporium control is that farmers must be educated to enter the crop to assess severity, instead of looking at the edges only, which are drier and hence less susceptible to the disease.

Agronomic factors may be manipulated to aid with helminthosporium control. It has been noted that wider row spacing reduced disease severity. Nitrogen application may be restricted in high disease incidence areas in order to avoid excessive vegetative growth by which high humidity is maintained within the crop. In addition, some farmers are convinced that the use of NPK fertilizers (in areas where no P or K response has been obtained under controlled conditions) reduces the severity of the disease. It is our contention that research into disease control, particularly helminthosporium and fusarium, must be intensified in the natural, high inoculum areas.

Weed control—The predominant weeds in the wheat target areas are various species of *Echinochloa*, *Eleusine*, and *Digitaria* for grassy weeds, with *Amaranthus* spp., *Portulaca oleracea*, and *Trianthema portulacastrum* the main broadleaf weeds. Volunteer rice can also be a problem.

The lower yields of wheat currently attained in rainfed conditions preclude intensive weed control measures. Where some supplementary irrigation is available, the increased yield potential should encourage

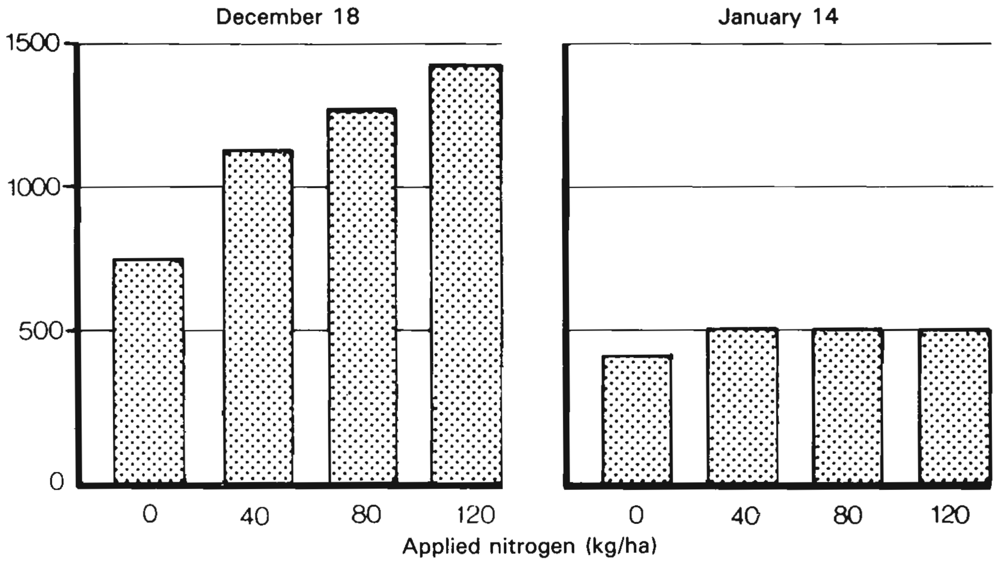

Figure 4. Response to nitrogen application in Cagayan Valley, Philippines, as affected by seeding date. Data from Liboon and Morris (11).

more thorough weed control. Experimental data show that weed control is essential in the first 4 to 5 weeks (5). If the crop is kept weed free during that period, yields are as high as those from crops kept continuously weed free. Quite low populations, particularly of grassy weeds, reduce yields (Figure 5).

Mechanical aids to weeding (rotary hand weeders, hinged hand hoes, shallow ploughs and harrow weeders) are being promoted. However, a more satisfactory long-term solution may be obtained using chemical weed control.

Beginning in 1983/84, a wide range of chemicals were tested in Thailand and the Philippines. In both countries, very few chemicals normally used on wheat in more traditional climates are freely available (only bentazon, diuron, trifluralin, 2, 4-D and MPCA). Diuron and trifluralin were shown to be quite phytotoxic to wheat under the more tropical conditions. As the major yield loss is more commonly from grass weeds, bentazon, 2,4-D, and MPCA were only marginally useful (21).

Of the most commonly available chemicals (butachlor, alachlor, and oxadiazon used extensively in rice), the first two proved the most useful in wheat. Oxadiazon gave the best broad spectrum weed control but caused mild to severe phytotoxicity that resulted in yield reduction.

In further tests the following year, the reaction of wheat to butachlor and alachlor was found sensitive to soil moisture conditions (Figure 6) and seeding depth. Heavy rains or irrigation 1 to 2 days after herbicide application caused phytotoxicity, reducing yield about 30%.

Of the traditional wheat chemicals, the combination application of diclofop-methyl and chlorsulfuron is superior in weed control and consistently results in higher yields than with other chemical treatments. The mixture adequately controls the complete weed spectrum, with the

Table 4. Chemical control of *Helminthosporium sativum* under field conditions, Los Baños, Philippines

Fungicide	Spray schedule	Percent control: Flag leaf	Percent control: Whole plant
Propicanazol (150 g ai/ha)	30 DAS[a]	51.1	45.8
	50 DAS	83.6	82.9
	30 + 50 DAS	85.1	88.4
Mancozeb (800 g ai/ha)	30 DAS	29.8	37.6
	50 DAS	48.9	60.3
	30 + 50 DAS	46.7	60.5
	WEEKLY	89.3	94.7

[a] Days after seeding

Source: Lapis (8)

possible exception of *Digitaria* spp. It also controls volunteer maize and, under certain moisture conditions, volunteer rice.

As these chemicals have not, up to now, become available in the target countries, pre-emergence application of butachlor followed by spot-weeding over the first four weeks of crop growth has been recommended where chemical control has been warranted.

Harvesting and threshing—Farmers have universally reported the difficulty of wheat threshing—much more difficult than rice.

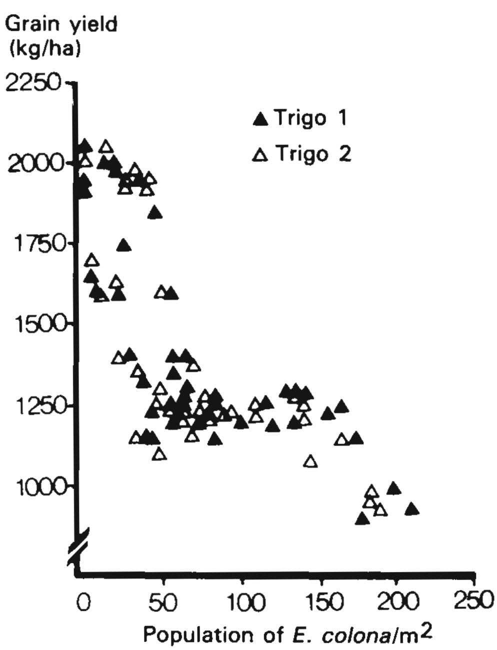

Figure 5. Effect of various populations of *Echinochloa colona* on the yields of two wheat varieties, Central Luzon State University, Philippines. Data from Meng-Umpun (16).

A study from the Philippines reported heavy losses from traditional threshing methods—recovery was only 60% from hand threshing and 53% from the pedal thresher. Using the Multicrop Rice-Wheat thresher developed under the IRRI-Pakistan machinery project resulted in a grain recovery of 93% (13). While these data undoubtedly overstate the true situation, there are obviously substantial losses from traditional hand threshing.

The difficulty for hand threshing is probably due to the harvest method having been developed from the "rice mentality." There is a general tendency to harvest prematurely and stack the material to dry. This results in the rachis and glumes being somewhat "plastic" and makes the grains difficult to extract from the head.

The on-farm recommendation is that if the grain rubs out of the head when threshed between the palms, *and* the chaff can be separated from the grains by blowing, *and* the grain cracks when bitten, then it is time to harvest.

Sustainability of yield

In the Southeast Asian region, (with the possible exception of Indonesia) and parts of South Asia (Nepal, Bhutan, Bangladesh) there is minimal use of fertilizers. With the current drop in profitability in most crops, there is even a tendency to further reduce the use of fertilizer.

Wheat is being proposed as an *additional* crop, filling a void in the cropping system and thus representing an intensification of the cropping system.

Yields in rice-wheat systems are decreasing in the Punjab of Pakistan and are related to the number of years of continuous rice-wheat cropping. While part of this decline is related to an increase in grass weed competition, other factors are operating significantly (4). This study was only involved with wheat yield, but in India (23), it has been shown that yields are declining in some areas in both crops, in others wheat, and in still others rice. Studies in these areas have shown that yields can be stabilized by high levels of NPK fertilizer.

However, in the Terai of Nepal results of various fertilizer treatments to a rice-rice-wheat

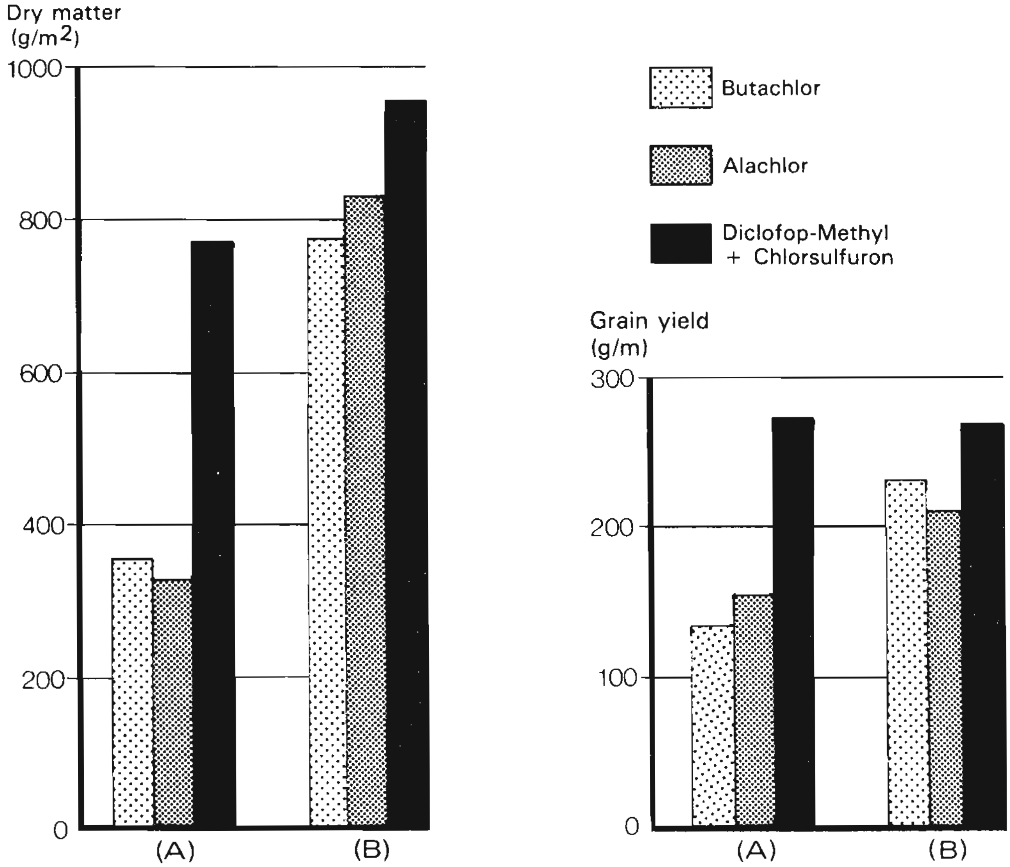

Figure 6. The effect of irrigating after (A) or before (B) the pre-emergence application of three herbicide treatments, on total dry matter and grain yield of wheat, Chiang Mai University, Thailand. Unpublished data of K. Rerkasem.

rotation show that even with substantial chemical or organic fertilizer applications, yield decline is occurring (Figure 7). This is mainly due to a rice yield decline.

Additionally, reports are now being received from parts of Bangladesh and Thailand of reduced rice yield following the introduction of wheat. This is a phenomenon to which the utmost importance must be attached. Any investigation of yield decline will require a multidisciplinary approach across crops, as the causes may be diverse—nutrient depletion, insect buildup (e.g. stem borers), soil-borne pathogens (nematodes, fungi), crossover foliar diseases and increases in weed populations.

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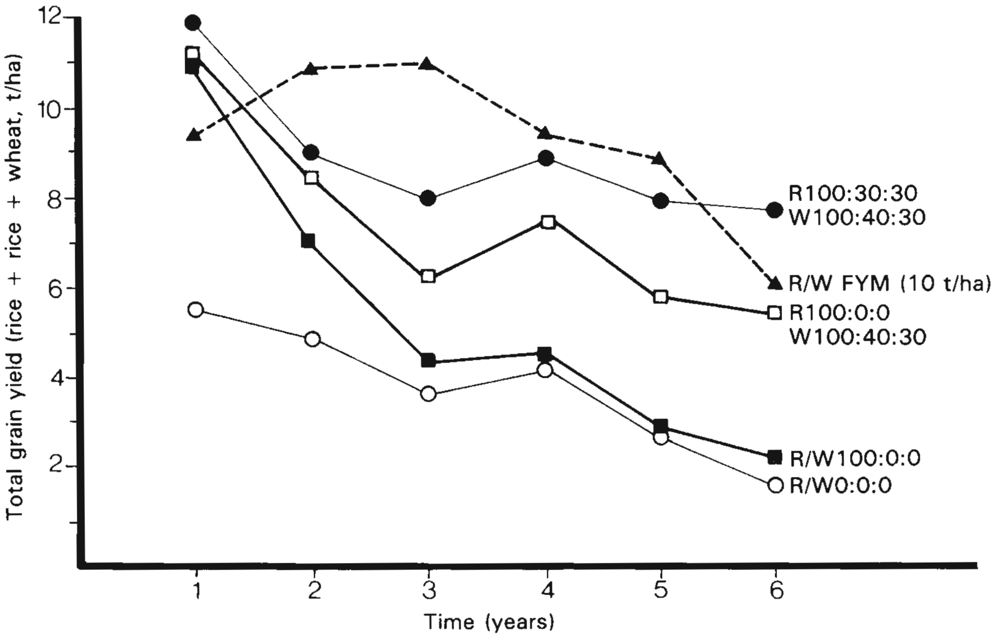

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Central and South America

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Abstract

Most of the problems associated with wheat production in the warmer areas of South and Central America are a function of three basic environmental factors: temperature, moisture, and soils. The definitions of Papadakis (5) and soil maps have been used to delineate different environments on the basis of winter temperatures, moisture, and soil type. Wheat is produced, or is under experimentation, in a diverse set of environments in the region.

High temperatures may limit yield potential, but the effects of temperature, in general, appear less serious to the crop than the effects of moisture regimes or acid soils. There is some indication that very high temperatures may cause physiological disorders. Frosts can be a problem in limited areas of the region.

Moisture regimes vary widely within the warmer areas, and in many of the environments lack of moisture is a severely limiting factor. In the wetter parts of the region, high humidity is conducive to disease development, and the combinations of temperature and moisture regimes necessary for the major diseases encountered are discussed.

Acid soils cover most of the warmer areas of South and Central America. These impose severe limitations on crop growth. Wheat varieties with some resistance to aluminum toxicity have been developed. However, it is unlikely that varieties alone will be sufficient to overcome the problems of these soils, and crop and soil management techniques will need more emphasis in the future.

In discussing the characteristics of the "tropical" wheat growing environments of South and Central America, I have not been confined by the Tropic of Capricorn. I have followed the definition of "tropical" suggested by A.R. Klatt in the Symposium, Wheats for More Tropical Environments, held in Mexico in 1984, and thus assume that we are referring here to environments that are warmer than the traditional wheat growing areas. In defining these areas I have been guided by, and used extensively, the climatic classification of Papadakis (5).

A review of the papers presented in the symposium 2½ years ago shows that the main limiting factors stressed by the various speakers were:

- High temperatures
- High humidity
- Diseases
- Aluminum toxicity
- Drought
- Frost
- Waterlogging
- Sprouting
- Insects

All of these factors, together with other actual or potential problems, can be divided into three main groups, based on whether their principal cause is the climate, especially moisture and temperature, or the soils.

Temperature-related problems
- High temperatures—direct effect
- Frost
- Insects

Moisture-related problems
- Diseases
- Rain at harvest—sprouting
- Low or erratic rainfall
- Intense rain—waterlogging

Soil-related problems
Acid soils—aluminum and manganese toxicity, low phosphorus availability.
- Calcium and sulphur deficiencies
- Micronutrient deficiencies
- Poor moisture retention
- Low infiltration rates

Obviously, in many cases there is an interrelationship between these problems and an interaction between the climate and soils. Drought, a serious problem in the winter season in many of the warmer areas, is a function not only of the rainfall, soil moisture retention, and infiltration rates, but also of the crop root exploration, often severely restricted by aluminum toxicity in the acid soil regions. However, a division of the problems into three major groups will, I hope, be useful in comparing the different wheat production and experimentation environments in Central and South America.

The various areas where wheat is being produced or researched in the warmer areas of South and Central America are shown in Figure 1. I have not attempted to define exactly the production areas, or to have marked all the experimentation areas, but rather to have identified some of the major sites for discussion purposes.

Obviously, given the number of combinations of climatic and soil factors found in the various wheat production and experimental areas, it is difficult to prioritize production constraints. However, it may be useful to enumerate the various constraints with some discussion of their importance in different areas, and to briefly outline what has been achieved in overcoming them.

Temperature-Related Constraints

Of the three environmental factors, temperature per se is probably the least limiting in the warmer, or tropical, areas. High temperatures can certainly limit potential, but probably less so than the constraints imposed by humidity and soils.

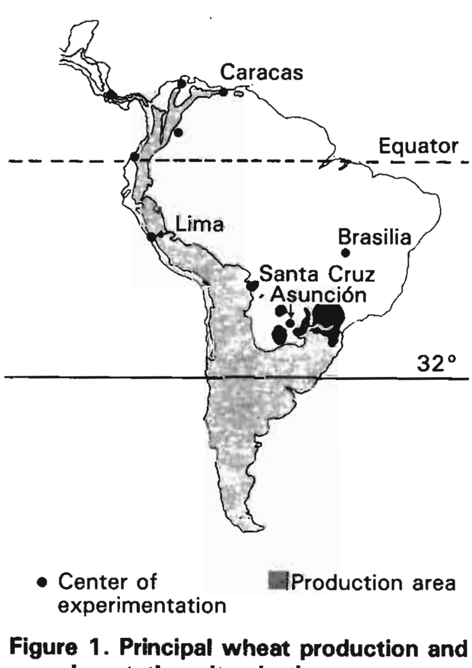

Figure 1. Principal wheat production and experimentation sites in the warmer areas of South and Central America.

The wheat crop in the warmer areas is subjected to higher temperatures than in the traditional wheat areas, especially during the early stages of development. This makes the crop develop faster, which is normally an advantage, as due to this it will fit in a rotation. However, development may be so fast that potential is greatly reduced, for instance, by bolting and the resultant lack of tillers. Thus varieties in the warmer areas need a physiological brake on their development, probably using the vernalization and/or photoperiod sensitive genes. In this regard, it is interesting to see the number of varieties in the warmer areas that are the result of spring x winter wheat crosses.

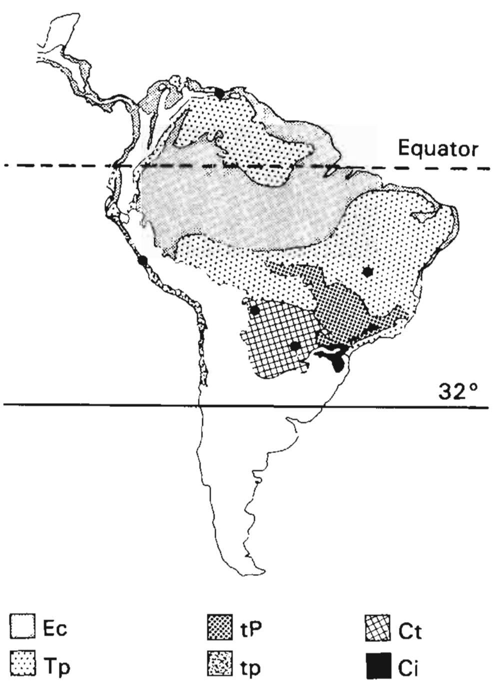

Figure 2. Winter temperature regions in the warmer areas of South and Central America (5).

The main winter temperature environments are shown in Figure 2, where these different zones are described by Papadakis as follows:

Ec—Sufficiently hot for equatorial crops (e.g. rubber, cacao)

Tp—Cooler, without frosts, too hot for temperate crops (e.g. wheat)

tP—Idem, but wheat not completely excluded

tp—Idem, but sufficiently cold for many temperate crops

Ct—Not free of frost, but sufficiently benign for citrus; marginal for temperate crops

Ci—Idem, but sufficiently cold for temperate crops

A map of this scale can, of course, only show generalities. However, it is worth noting one modification to this map and that is the presence of frosts in the Planalto of Brazil, south of the Tropic of Capricorn. These are not, evidently, confined to the area shown with a Ct classification on this map.

Also it is worth mentioning that Papadakis' description of the environments tP (wheat not completely excluded) and Ct (marginal for temperate crops) would appear now to be overly conservative. Large areas of wheat are produced in areas within a Ct winter temperature climate—the Chaco of Argentina, eastern Paraguay and Santa Cruz, Bolivia, as well as the tP climate of part of Paraná, Brazil. However, there is as yet no wheat production in areas with winter temperatures classified as either Tp (too hot for temperate crops) or Ec (sufficiently hot for equatorial crops).

In the very hot areas (Ec winter) such as the Llanos of Colombia, there has been some indication that high temperatures (22°min, 30° max) may kill the vegetative apex, leading to large numbers of aborted tillers, and, in many cases, no spikes. However, this may be a result of interactions with the other major environmental constraints. In this environment, sterility is also common and studies are under way to determine whether temperature, humidity, or soil factors are the causal agent of this phenomenon.

In the warmest areas, soil temperature may be a limiting factor, especially when associated with drier conditions. There is evidence from the Philippines (D.A. Saunders, personal communication) and from H.M. Rawson (quoted by Fischer, 1) that high soil temperatures can have very severe effects on tiller and crown root initiation.

On the other end of the scale, frost may be a problem in some of the cooler areas of the warm regions, as for instance in the higher altitudes south of the Tropic of Capricorn in Brazil (3).

Insects are more of a potential problem in the warmer areas, presumably because of their greater rate of reproduction. For the same reason, biological control with arthropod predators may be even more feasible than in the temperate climates.

Moisture-Related Constraints

Soil moisture
Figure 3 shows the principal moisture regions of South and Central America, with the following definitions:

HU—Always wet
Hu—Wet
MO—"Monsoon," wet
Mo—"Monsoon," dry
mo—Semiarid
d—Desert

It should be remembered that in monsoon-like environments, the summer is the wettest part of the year and winter the driest part.

Moisture is a limiting factor, especially in the areas that have the semi-arid (mo) or desert (d) designations, and in these either yields are severely restricted by moisture limitation (e.g., northern Santa Cruz, Bolivia; Chaco, Argentina) or crops are grown with irrigation (Brasilia, Chaco Bolivia; coastal Peru).

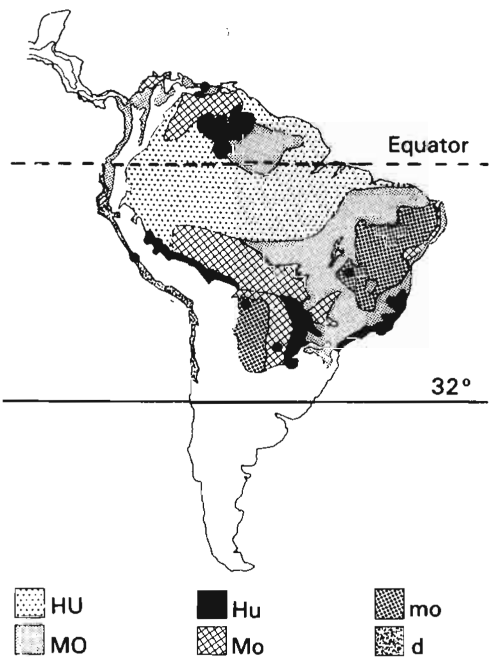

Figure 3. Principal moisture regions of South and Central America (5).

Where irrigation is used, the crop may suffer from constraints normally observed in the wetter areas (HU, Hu, MO). In these wetter areas, soil-borne diseases are a serious problem. The most important of these diseases are *Helminthosporium sativum, Sclerotium rolfsii, Gaeumannomyces graminis* and *Rhizoctonia solanii*. Of these, it appears that *H. sativum*, as a foot rot, and *G. graminis* may be confined to the cooler parts of the warmer areas. *H. sativum* is important in southern Brazil and eastern Paraguay, but not in much of the State of Paraná, Brazil. This could possibly be due to a temperature effect on the breakdown of organic matter. In areas affected by this disease, more work is needed on the effect of cultural practices on its control.

G. graminis has been reported as important in the wheat-soybean rotation of Brazil and there is evidence from Indiana, USA, that soybean may be an alternate host for this pathogen. It also becomes a problem with poorly managed liming to overcome the soil acidity problem.

In the wetter areas, waterlogging may also be a severe, albeit temporary, problem. The repercussions however, may be of longer duration. Whole nurseries have been wiped out in the Llanos of Colombia by waterlogging associated with high rainfall on level land, even though the soils are relatively free-draining. Apart from the direct effects of saturation on soil aeration and the root environment, these conditions also prove ideal for the establishment and spread of *Sclerotium rolfsii*. The disease has become the main biological limitation to wheat production in coastal Ecuador (7).

Little progress has been made in breeding for resistance to the foot rots in general. Work in many parts of the traditional areas on cultural control of these organisms is advanced, but little has been done in the warmer areas, with the exception of Brazil where a considerable research effort is under way. Farmers in Rio Grande do Sul have reduced the wheat crop intensity in the rotation to one crop in 3 or 4 years, otherwise *H. sativum* foot rot would decimate the crop.

Humidity
Humidity is a grave problem in that it provides an ideal climate for many of the foliar diseases. Even in areas where rainfall is low during the winter, relative humidity may be appreciable, leading to severe disease problems.

Rusts—The main rust problem in the warmer areas is *Puccinia recondita*, leaf rust. The humidity requirements for the spread of this disease appear lower than for the other common leaf diseases, so that it is a problem in even the driest areas, e.g., Chaco of Bolivia and coastal Peru. Temperatures in all the environments being discussed here are sufficiently warm for the establishment and spread of this disease.

Leaf spots—Leaf spots caused by *Helminthosporium* spp. are one of the major diseases in the warmer areas, and much effort, with considerable success, is being devoted to selection for resistance to the organisms. Their humidity requirement is higher than leaf rust, and they do not appear to be problems in the semi-arid or desert environments, except in northern Santa Cruz, Bolivia, which is a transition environment (MO/mo) and where the prevailing wind is a moist northwesterly. *Septoria* spp. is less common in the warmer areas, but its environmental niche appears similar to that of *Helminthosporium* spp.

Head scab—Head scab caused by *Fusarium* spp. is confined to the most humid areas and is basically neutral for temperature, so that it may be a severe problem in all the humid areas (HU, Hu, MO) of the warmer climates. Some progress is being made in identifying resistance to this disease by means of a shuttle program between Brazil, China, and CIMMYT, based mainly on partial resistance encountered in some Chinese wheats.

Powdery mildew, Erysiphi graminis—Powdery mildew is also a serious problem in the wetter (HU, Hu, mo) areas. Genetic variability is available, but more emphasis must be placed on screening for resistance in varieties for these areas.

Bacteria—Bacteria are a problem in the moist humid areas, but can also be severe in wet seasons in the drier areas, as they spread rapidly if conditions are conducive. Thus, a relatively short period of high humidity may lead to an epidemic. However, their problem status is mainly confined to the HU environments, although they may be a problem in some environments classed as MO.

Soil-Related Constraints

Figure 4, based on Sanchez and Cochrane (6), divides the warmer areas of Central and South America into two regions based on their principal soil types — high base status soils and acid infertile soils

High-base status soils
Generally high base status soils are not a major constraint except in terms of macronutrients. Locally they may, however, prove to be the main constraint, as, for instance, in the Bolivian Chaco. Here the high proportion of kaolinite clay reduces infiltration rate to such an extent that irrigation becomes relatively ineffective after the first two or three irrigations.

Acid infertile soils
Acid infertile soils cover the major part of the warmer areas of South and Central America. The main feature of these soils is the low pH coupled with high soluble aluminum levels and low phosphorus availability. Aluminum may occupy as much as 90% of the exchange sites of the clay fraction. Definite advances have been made in both the genetic and cultural avenues for overcoming this problem. Genetically, tolerance has been incorporated into wheats with high yield potential, using mainly the old Brazilian wheats as donors. However, generally even the "tolerant" wheats

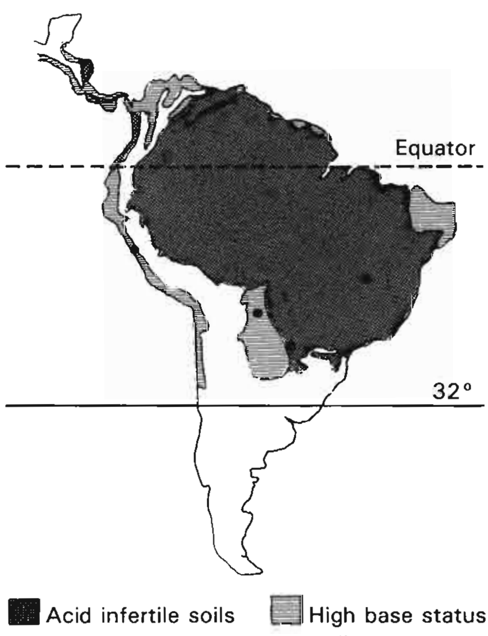

Figure 4. Soil regions of the warmer areas of South and Central America (6).

do not produce well when Al saturation is above 60%. Liming to replace some of the Al on the clay fraction has been successful, especially when combined with resistant varieties. The main problem with liming has been the lack of movement of Ca downward in the profile; thus the root zone is restricted to the top 20 to 25 cm, leading to drought and nutritional problems. Recent work in Brazil with gypsum as a source of calcium shows great promise, especially in a mixture with agricultural lime, as the gypsum is far more soluble and moves farther down the profile (4).

These soils generally have a low moisture holding capacity, a severe problem where root exploration is inhibited by soluble Al, and exacerbated where temperatures are high and organic matter breakdown is rapid.

Other nutrient limitations which have been identified on these soils are sulfur deficiency and micronutrient deficiencies (B, Zn), and further work is needed in most areas to establish nutritional limitations. One nutrient that is often overlooked is calcium, and large responses have been obtained to relatively small applications of this nutrient in parts of the Cerrados of Brazil on wheat, (2) and in other crops in the Llanos of Colombia.

The production areas and experimentation sites are shown in Figure 1 and classified in Table 1, according to the three major factors shown in the preceding maps.

It is interesting to note that no two of these areas share the same conditions, and thus problems will differ greatly among areas.

Conclusions

The potential for wheat production in the various areas of the warmer regions of South and Central America depends on the combination of three main environmental factors: temperature, moisture, and soils. Of these, the most devastating are the acid infertile soils predominant in this region and high humidity, especially in the hotter areas. Of the environments in the region, potentially the most productive are those with the coolest temperatures,

Table 1. Latitude, winter temperatures, moisture regimes, and soil "classification" of wheat production and experimentation sites in South America

	Latitude (°S)	Winter temp.[a]	Rainfall pattern[a]	Soil type[b]
Chaco Argentina (prod.)	26	Ct	Mo/mo	High base
Eastern Paraguay (prod.)	25	Ct	Hu	Acid
Rio Grande do Sul. Brazil (prod.)	28	Ci	MO	Acid
Paraná, Brazil (prod.)	23	tP/Ct	MO/Hu	Acid
Santa Crus, Bolivia (prod.)	17	Ct	mo	High base
Brasilia (exp.)	16	Tp	mo	Acid
Coast of Peru (some prod.)	7-18	tp	d	High base
Valledupar, Colombia (exp.)	11	Ec	MO	High base
Villavicenciio, Colombia (exp.)	4	Tp/Ec	HU	Acid
Portoviejo, Ecuador (exp.)	2	Ec/Tp	mo	High base

[a] Classifications of Papadakis (5)
[b] Based on Sanchez and Cochrane (6)

and high base status soils, e.g., coastal Peru. The most difficult will be those with equatorial climates, humid or wet moisture regimes and acid soils, as for instance, the Llanos of Colombia.

Wheats that produce in areas with winter temperature classifications tP, tp, Ct, and Ci (5) are available. Diseases are serious problems in all the warmer environments, but are potentially worse in the wetter (HU, Hu and MO) climates, especially where associated with higher temperatures. The prevalent diseases depend on the moisture and temperature environment. Acid soils impose a severe limitation on crop production, and this limitation must be overcome by both genetic and cultural means.

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Africa

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Abstract

While the majority of the wheat produced in Africa comes either from the East African highlands or from the irrigated winter season crops of southern Africa, several countries are producing and/or conducting research on wheat under more tropical environments. The environments encountered in these countries are characterized according to their thermal and humidity regimes. For the specific countries selected, major production constraints are described and potential solutions are presented.

Given that more than 40 African countries fall within the latitudinal boundaries set by the Tropics of Cancer (23° N) and Capricorn (23° S), it is exceedingly difficult and perhaps foolhardy to attempt to generalize about wheat production in Africa. Just as a diversity of human cultures exists on the African continent, virtually every conceivable mode or system of wheat production is currently in practice somewhere in Africa. Wheat is grown under rainfed conditions (in areas receiving unimodal or bimodal distribution of precipitation), on residual moisture in river basins or seepage depressions, and under irrigation (flood and sprinkler). Some countries, such as Ethiopia, have a cultural association with wheat extending back through their recorded history, while for others wheat was a crop introduced by the Arab traders, the missionaries, or the colonialists. Wheat seed is sown and covered by hand, by ox plow, or by grain drill and harvested by sickle or by combine harvester. Wheat is grown on state farms or on private plots managed by large- or small-scale operators.

Notwithstanding this amazing degree of diversity, allow me to engage in a few, hopefully indisputable, generalizations:

(1) Despite the fact that most African countries produce some wheat (Table 1), none is self-sufficient and few even approach that target, which the majority have adopted as national policy. In fact, due to high rates of population growth and urbanization, the shrinking landholding unit, political disruptions, and policy constraints, sub-Saharan wheat importation has grown at a faster rate than domestic production in the past decade (2). Additional constraints to wheat output have been imposed by nature: in 1984, wheat yields in many regions were halved due to severe drought, and even under irrigated production systems, such as in Zimbabwe, wheat area was drastically reduced because of shrinking reservoir and ground water levels.

(2) The bulk of the wheat crop produced in Africa comes from rainfed production systems in the East African highland areas at altitudes above 1500 masl (i.e., Ethiopia, Kenya, Tanzania), or from the irrigated "winter" season crops of Southern Africa (i.e., Zimbabwe, Zambia, Malawi). In the East African highlands, yields of up to 3.5 t/ha have been realized, especially at the higher altitudes ranging up to 3000 masl; in this ecosystem, fluctuations in annual rainfall can result in a drought-stressed crop in dry

seasons, whereas, in years with higher than average rainfall, problem diseases such as stripe rust (*Puccinia striiformis*), leaf and glume blotch (*Septoria tritici* and *S. nodorum*) and spot blotch (*Helminthosporium sativum*) are exacerbated. In southern Africa, commercial farms south of 10° S an altitude of between 1000 and 1500 masl produce very high yielding irrigated wheat crops, often in excess of 6 t/ha, as the wheat is subjected to minimal moisture, temperature, and disease stresses.

(3) FAO agroclimatic suitability assessments of Africa classify extensive land areas (424 million ha) as being suitable for maize, but a much smaller area (38 million ha), mostly in the Eastern African highlands, as suitable for wheat production (4). Since approximately 1 million ha of wheat are currently grown in sub-Saharan Africa, there is some potential for increasing wheat production in "traditional" wheat growing agroclimatic zones. However, in these high potential areas many

Table 1. Wheat production and importation in sub-Saharan Africa, 1981-1984

		Area ('000 ha)	Imports ('000 t)
I.	**West Africa**		
	Mali	2	17
	Niger	1	18
	Chad	2	15
	Nigeria	16	1498
	Cameroon	1	120
II.	**East Africa**		
	Sudan	140	425+
	Ethiopia	600	300+
	Kenya	110	135
	Tanzania	40	49
	Rwanda	4	11
	Burundi	14	11
	Somalia	4	180
	Uganda	5	N/A
III.	**Central and Southern Africa**		
	Angola	16	158
	Zaire	9	189
	Malawi	1	12
	Zambia	4	100
	Zimbabwe	17-41	40
	Mozambique	4	117
	Madagascar	1	56

Sources: 1985 CIMMYT World Wheat Facts and Trends (2); CIMMYT report to CIDA on aid requirements for maize and wheat research in six East African countries, July 1986; Proceedings of Regional Wheat Workshop for Eastern, Central, and Southern Africa and Indian Ocean, September 1985.

other food staples compete with wheat for land (e.g., barley, teff, grain legumes, oil crops, potatoes, banana/plantain, cassava, etc.).

Thus, as a result of high wheat importation bills and despite questions of comparative advantage, domestic political pressure in much of sub-Saharan Africa is applied in favor of increased domestic wheat production. As illustrated by the selected cases we shall review, sometimes this has resulted in attempts to produce wheat under extremely challenging and perhaps inappropriate conditions (i.e., Zambian rainfed wheat); in other cases, wheat has filled or could fill an otherwise underutilized niche in the national production system (i.e. irrigated lowland wheat in Sudan, Ethiopia, Somalia, and Malawi).

Principal Thermal and Humidity Regimes

As a point of reference, I have chosen to characterize and discuss the tropical wheat environments in Africa using the thermal and humidity regimes proposed by Fischer (3). Specifically, four principal regimes are encountered in Africa (Table 2), and case studies will be discussed under each category.

Very hot, humid regime (Somalia) The Ministry of Agriculture of Somalia is interested in increasing domestic wheat production in order to reduce the annual importation of approximately 180,000 tons of bread wheat and durum wheat. Wheat products such as spaghetti, injera, bread, and cakes are the preferred food in Somalia. Thus, as incomes rise, consumption of wheat is

Table 2. Characterization of tropical wheat environments in sub-Saharan Africa

Thermal and humidity regime	Location	Latitude	Altitude (m)	Mean min. temperature (°C)	R.H. %	Precipitation (mm) Total	Precipitation (mm) Crop cycle
Very hot, humid	Jenale, Somalia	2°N	50	16-20	75-92	580	<100
Very hot, dry	Wad Medani, Sudan	14°N	410	14-18			
	Melka Werer, Ethiopia	9°N	740	14-24	45-65	470	<100
	Shira Valley, Malawi	15°S	450	14-17			
Hot, dry	Kano, Nigeria	12°N	470	14		873	1
Warm, humid	Chilanga, Zambia	16°S	1210	17	85	1110	

Source: Fischer (3)

expected to rise disproportionately as per capita maize and sorghum consumption decreases (currently, maize and sorghum consumption totals 180,000 and 400,000 tons per year, respectively).

At present, only 4000 ha of rainfed wheat are produced by smallholders in the remote highlands of the northwestern region of Somalia, with yields in the order of 350 kg/ha. The state farm that used to produce wheat in the northwestern region was abandoned due to the departure of the Soviets, the increase in tensions, and the refugee influx along the border with Ethiopia.

In the last 2 years, the Agricultural Research Institute (ARI) has initiated limited trials on irrigated wheat in the highly productive Jenale area, south of Mogadishu. While Somalia has a total potentially irrigable land area of 310,000 ha, ARI scientists estimate that 20,000 to 30,000 ha would be allocated for wheat production. In Jenale, wheat is envisioned to have potential value as a short season crop (i.e., less than 90 days to maturity), growing between the maize (harvested in mid-July) and the sesame crops (planted in late October during the second rainy season). Obviously, more research will be required to determine the optimum economic cropping pattern and practices.

In 1985, the ARI received seeds of six bread wheat cultivars (Haramoun, Belbec, Mexipak, Super X, Sannine, and Florence Aurora) and one durum wheat cultivar (Produra) from FAO. Trials were planted on two different dates in the Jenale area (using a 30-cm row spacing, diammonium phosphate with the seed, a topdressing of 50 kg urea/ha, handweeding, five irrigations and Furadan insecticide to control stem borers). Yields varied considerably, but in one seeding, Belbec yielded over 3 t/ha. A subsequent trial of five of the cultivars in 1986 produced grain yields from 700 to 1550 kg/ha over a maturity range of 71 to 90 days (Table 3).

That these "nontropical" wheat cultivars survive, let alone produce seed at this location, is quite surprising in itself. Jenale has an altitude close to sea level, a latitude of approximately 2°N and a mean minimum temperature that ranges between 16 and 20°C (the mean ranges between 24 and 28°C and the maximum between 30 to 34°C). In addition to the temperatures, one would expect that the high relative humidity (70 to 90% year-round) would have encouraged the growth of foliar pathogens; to the contrary, the plots that I have seen had good stands of well-tillered (but short) plants with clean leaves. In the 1986 planting, a trace infection of spot blotch (*H. sativum*) was present on the leaves, and a 10% level of infection of the seeds (i.e., blackpoint) was observed after harvest, probably due to the rains during grain filling. One possible explanation for such an unexpected performance of "nontropical" wheats under tropical conditions is that the high and constant winds coming off the Indian Ocean cool the plants and minimize leaf wetness periods.

Since irrigated wheat research in Somalia is in the fledgling stage, there are many agronomic and economic issues yet to be tackled. We consider that the introduction of new germplasm is an important first step—germplasm selected for heat tolerance and resistance to the diseases such as spot blotch and scab (*Fusarium* spp.) which could logically be expected to increase in severity as wheat area expands. Additionally, more detailed work on irrigation schedules, fertilizer rates, weed control, and cropping systems will have to be undertaken to facilitate the development of an optimum production package.

Very hot, dry regime (Sudan, Ethiopia, Malawi)

Sudan—With 140,000 ha of wheat annually, Sudan represents the major tropical production regime currently utilized in Africa. In the early 1960s, government policy was directed toward the expansion of wheat production on the irrigated clay soils in a double cropping system with the main season crop, cotton (1). In the Sudan, wheat is grown during the short winter period (October to March) during which the relatively high temperatures are probably the major constraint on yield (i.e. monthly mean minimum temperatures descend to 14°C while mean maximums reach 34°C during the same period). In the major wheat growing region of Gezira, commercial-scale yields have fluctuated between 550 and 1400 kg/ha over the past decade. Additional factors reported to have significantly affected wheat yield levels in Sudan are high aphid infestations, necessitating one or two insecticide applications, and serious rust problems, controlled by the use of resistant varieties (1).

Ethiopia—In the vicinity of Melka Werer (300 km east of Addis Ababa, 700 masl), the potential exists for the double cropping of up to 175,000 ha of irrigated wheat with cotton. The constraints to expansion of the wheat area include: 1) the supply of water from the Awash river, which is only sufficient to irrigate 175,000 ha; and, 2) the availability of sufficient labor for timely hand harvest of the cotton crop.

The Institute of Agricultural Research (IAR) of Ethiopia has conducted agronomic trials for several years at this location and now has a package of wheat varieties and recommended agronomic practices to provide to the state farms, which are currently growing only cotton in the summer season. The wheat varieties are early maturing to allow a 60-day vegetation-free fallow period preceding the cotton crop; by eliminating all vegetation, the most serious pests of the cotton crop, the American bollworm and the white

Table 3. Yield trial results from Jenale, Somalia (1986)

	Yield (kg/ha)	Maturity (days)	Height (cm)	1000 KW (g)
Super X	726	71	52	32
Sannine	1105	76	60	30
Haramoun	847	78	66	31
Belbec	1536	90	69	36
F. Aurora	1470	85	75	46

Source: Dr. Mohammed Tahir, ARI, 1986

fly, are at least partially controlled. Seed of three wheat varieties has been multiplied to supply a pilot production area of approximately 500 ha for 1986-87 (Ethiopia currently produces about 600,000 ha of rainfed wheat, yielding 1.2 t/ha). The three early-maturing (90 to 110 days to maturity) wheat cultivars (Bluejay, Pavon 76, and Chenab 70) have yielded 5.5 to 6 t/ha under experimental conditions. All but Bluejay are resistant to leaf rust (*Puccinia recondita*). The variety selection program at Melka Werer is completely divergent from the highland, rainfed wheat breeding program. IAR currently has 17 outstanding bulked F_6 lines under yield test, all of which originated in CIMMYT's F_2 nurseries.

Agronomic research continues to be conducted on sowing dates, seed rates, row spacing, irrigation frequencies, herbicides, and fertilizer rates. Currently recommended agronomic practices include the use of 125 kg of seed and 100 kg of urea broadcast/ha and manual weeding for weed control. When planted in dry soil in mid to late October, the wheat crop flowers and enters grain filling during December and January under the lowest possible ambient temperatures (14°C minimum night temperatures). Irrigation water is applied seven times or approximately every 2 weeks during the crop cycle.

An additional bonus is inherent in this projected production system: equipment lying idle on the rainfed-wheat-producing state farms during the February to April period can be used to harvest wheat in the lowland cotton areas.

There are two potentially serious threats to the future of wheat production in this area. First, grass weeds in particular may be an extremely serious problem (*Echinochloa colona* and *Sorghum verticilliflorum* especially) and there has been little relevant weed control research before this season. Second, and perhaps the most ominous, is the high rate of salinization of crop land in the lowland cotton growing areas. The Ministry of State Farms has not installed adequate drainage systems in this area; as a result, water tables and soil salinity levels have risen dramatically and land is frequently abandoned after several years of cropping. Intensified crop production (i.e. two crops per year—wheat and cotton) will surely exacerbate this problem.

Malawi—The Government of Malawi has conducted research into the feasibility of producing wheat as a winter season crop in rotation with rice on the state-managed land lease schemes near the southern tip of Lake Malawi (e.g., Shira valley, 450 masl). With minimum temperatures only as low as 13°C, temperature is again perceived as being the most limiting factor to wheat production. While winter season wheat grown commercially under sprinkler irrigation on the tobacco estates in western Malawi (altitude about 1200 masl) attains yields of 6 t/ha, the flood irrigated wheat in the Shira valley only reached 3 t/ha, experimentally.

Deep tillage of the heavy clay soils in the rice schemes has been deemed necessary to ensure aerobic conditions suitable for wheat growth. As the small land units are tilled primarily by manual labor, this recommendation has imposed an additional constraint to wheat production. No work has been done to date on sowing wheat into rice stubble using minimum tillage practices.

The following agronomic practices are recommended as the optimum for irrigated wheat in this specific environment: wheat is to be sown at 100 kg/ha in mid-May in a 30-cm row spacing (to facilitate hand weeding) with 100 kg N/ha as a topdressing. Irrigation furrows are situated at 1.5-m intervals across the field.

Unless a solution can be found to the land preparation constraint mentioned previously and higher yielding cultivars can be developed, wheat is unlikely to gain acceptance by the rice farmers, who currently obtain higher economic yields with horticultural crops in the winter season.

Hot, dry regime (West Africa)
In common with the other countries of sub-Saharan Africa, those of West Africa are interested in increasing the domestic production of wheat as a means of reducing high levels of grain importation. By far, Nigeria is both the largest wheat importer and producer in West Africa (Table 1).

Wheat production in Nigeria, estimated at 16,000 ha, is restricted to the river basin irrigation schemes in its northern states, lying between the latitudes of 10 and 13° N (5). The potential wheat production area is estimated to total 345,000 ha in the Sudan savanna areas.

Planting date is one of the most critical management factors. Wheat is sown in mid-November at the start of the cool season, during which temperatures range between 5 and 30°C, and harvested at the end of February or in early March. Early maturing cultivars are used in order to escape high temperatures at both ends of the season (i.e., during stand establishment and grain-filling). Currently, national wheat yields average between 2.5 and 3 t/ha.

Since the rivers which provide the irrigation water are replenished by variable and often low rainfall, water can be a limiting factor, especially in dry years. Thus, wheat germplasm for this region of Nigeria must possess a degree of drought tolerance in combination with heat tolerance, in order to stabilize yields under poor growing conditions.

Additional problems constraining wheat production in Nigeria include: shortages of fertilizer at the time of wheat planting; competition for labor during the harvest of rainfed crops, which limits the labor available for wheat planting; and insufficient machinery for land preparation and the threshing of the harvested crop. Currently, research is aimed at developing optimal water management practices and fertilizer recommendations.

Several other countries in West Africa currently have small areas of commercial wheat production or at least have a potential for growing wheat, including Mali, Niger, Chad, Cameroon, Senegal, and Burkina Faso (6). The agroclimatic patterns and varietal needs for these other countries in West Africa are similar to the situation just described for Nigeria. Siete Cerros and its derivatives have gained prominence in several of these countries where disease is not a major constraint to wheat production.

Warm, humid regime (Zambia, Zimbabwe, Malawi)
In an attempt to increase domestic wheat production without incurring the heavy capital expenditures associated with irrigated wheat, Zambia, in the mid-1970s, and, more recently, Zimbabwe embarked upon research in rainfed wheat. Although the altitudes of the proposed production sites are on the high side of the range defined for tropical environments (e.g., Mbala, Zambia, has an altitude of 1650 masl), the rainy season climate provides the optimal conditions of temperature, humidity, and free water for many "tropical" foliar pathogens. For example, at the Mount Makulu Research Station (Chilanga, Zambia) the mean maximum and minimum temperatures in the rainy season are 26 and 17°C, respectively; the heavy dews and frequent rains (i.e., seasonal totals exceed 1000 mm) maintain long periods of leaf wetness, while the relative humidity averages 85%.

Pathogens causing leaf spots, head blights, and seed infections run rampant in this environment. *Helminthosporium sativum*, which infects all plant parts, is the major obstacle to successful rainfed wheat production, but scab (*Fusarium* spp.) and bacterial infections (*Xanthomonas campestris*) are often components of the rainy season disease complex.

Delayed planting of wheat is one means of reducing disease pressure on the crop, but this mechanism has two major drawbacks: 1) the intense rainfall in the early rainy season stimulates lush weed growth, which if controlled by tillage incurs high costs and renders the soil vulnerable to erosion; and 2) in vast areas of Zambia, high levels of aluminum in the acid soils restrict rooting, contributing to drought stress in the late-planted wheat crop in seasons characterized by early cessation of the rains. One possible means of circumventing this constraint is that utilized by small farmers in the intermediate altitudes of Malawi; there, wheat is planted as a relay intercrop after tasseling of the main crop, maize. Thus, the wheat crop avoids the high disease pressure associated with late planting, and by utilizing residual fertility and moisture, contributes additional income to the peasant farmer.

A major research effort in Zambia has been directed toward developing cultivars with high levels of disease resistance in combination with tolerance to high aluminum levels in the soil. In order to substitute for imports, Zambia would require in excess of 50,000 ha of rainfed wheat. In many of the Zambian soils, however, relatively high input costs are incurred, both for fertilizer and lime amendments, resulting in poor economic returns for rainfed wheat. Yields are often low despite the high levels of inputs, frequently falling below 1 t/ha.

One additional aspect of rainfed wheat production has been a subject of debate among wheat scientists, particularly in Zimbabwe. There is a perceived potential risk that rainfed wheat crops will endanger irrigated wheat growing in the same country by providing high levels of disease inoculum early in the season, particularly for leaf and stem rusts.

Conclusions

Wheat production and research are taking place in diverse tropical wheat environments in sub-Saharan Africa. However, each environment imposes serious constraints on the wheat crop, constraints which may only be solved by more extensive breeding efforts and agronomic research. In most countries, however, there is a notable shortage of trained personnel and funds to conduct the necessary research.

Tropical wheat has been most successful in Africa where it has been included in intensified cropping patterns (i.e., double, triple, or relay cropping systems).

In general, apart from increased heat tolerance, germplasm for tropical wheat environments in sub-Saharan Africa requires early maturity (to escape high temperatures or to fit into an intensive cropping system), drought tolerance (where the supply of irrigation water is erratic), and greater resistance to or tolerance of spot blotch (*H. sativum*), scab, bacterial blight, and leaf rust.

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5

Constraints Associated with Rice-Wheat Rotations

Effects of High Temperatures on the Development and Yield of Wheat and Practices to Reduce Deleterious Effects

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Abstract

Yield potential for wheat at hot locations is dependent on the photothermal quotient (PTQ: radiation receipt per unit temperature). Annual PTQ at sea level reduces linearly with decreasing latitude though it increases with elevation. Thus at sea level, in a marine environment, mean annual yield potential at 10° latitude is only about 3 t/ha. However, PTQ changes monthly, reaching its highest level as photoperiod is increasing most rapidly. Matching the floret formation stage between terminal spikelet appearance and heading to this time optimizes yield.

High temperature has minimal effects on plant time (the number of day degrees to complete any phenological or ontogenetic stage). It therefore has minimal effects on the potential number of organs produced by the plant, such as leaves, tillers, ears, spikelets, and florets. These are determined by genotype and photoperiod. Its major effect is on the calendar time required to complete each stage and therefore on the rate at which the growth resources of radiation, water, and nutrients are required to satisfy potential growth. If growth resources are not supplied at the increased rate demanded by increased temperature, the size of the organs is reduced. Because potential yield is accumulated progressively through tillers, spikelets, florets, and the grain, with overlap between stages, growth resources can be manipulated at any stage of plant time to affect the appropriate yield component.

Though the recipe for producing a 10-t/ha crop under high temperatures is included here, together with the requirements for water at different vapor pressure deficits and for nitrogen and radiation, the effects on crop growth of restrictive environments is also considered. Emphasis is placed on optimizing agronomy in the early stages of growth prior to double ridges, and on the selection of a genotype to match the expected growth conditions. Genotypic characters to vary include seed size, area of the first leaf, phyllochron interval, and vernalization response.

Growth and Yield Potential under High Temperatures

In the field environment it is difficult to separate the effects of high temperature on growth and yield from the effects of radiation, vapor pressure deficit (VPD), and soil water availability. Even in studies (18) that enclosed and heated sections of field crops and demonstrated yield reductions, particularly when the treatment was applied during the pre-anthesis period, it could not be concluded that the effects were solely due to temperature, as VPD was also changed. VPD has major effects on water-use efficiency (WUE) (58).

Perhaps the only way to examine the effects of temperature alone is to use fully controlled environments. Traditionally, these have had severe limitations, particularly in their inability to achieve radiation levels comparable with sunlight and their inability to mimic the daily cosine changes in temperature, radiation, and VPD that occur in nature. With the advent of inexpensive microcomputer controls and high output discharge lamps, these objections have been overcome (52). Several of the unpublished studies referred to in this paper were done in such cabinets (Thermoline Scientific P.L., Sydney, Australia). The programmed daily cosine cycles were from 16 to 34°C, 4 to 34 mb VPD, and 0 to 1.5 mmol PAR providing 24-hr means of temperature of 23°C, VPD of 11 mb and total short wave radiation equivalent to 24 MJ/m^2/d.

In order to examine yield potential under such high-temperature conditions, mini-crops, 3.32 m^2, of genotype Tobari (*Triticum aestivum* L.) were grown in gravel beds at 100 plants/m^2 and drip-fed a nutrient solution so that water and nutrients were nonlimiting. Carbon dioxide ranged between 10 and 380 ppm. matching normal field patterns. Though the double ridge stage was reached as early as 2 weeks after planting, first anthesis by 6 weeks, and maturity by 11 weeks, grain yield was remarkably high at 1005 g/m^2. Figure 1 details the growth of these mini-crops. Salient features were that crop growth rates reached 60 g/m^2/d, rather higher values than have been recorded for crops in temperate climates (61). Furthermore, very high leaf area indices (LAIs) of over 9 were generated and maintained, and shoot/root ratios were comparable with those in high latitudes (24). Indeed, if the x-axis of Figure 1 showing day degrees (thermal time) is used instead of that showing days (calendar time), it is very difficult to distinguish the performance of these mini-crops from those grown under much lower temperatures.

The question then arises as to whether the fortuitous choice of Tobari was one of an outstandingly heat-tolerant genotype; these seemingly are available (56). However, data produced in high-temperature glasshouses (30 to 25°C) suggest that Tobari is quite ordinary, as it ranked 8th for grain yield among 24 genotypes selected at random (47). Although yields in that soil-based study (with lower nutrition) were not as high as in the cabinet crops, 70% of the genotypes exceeded 500 g/m^2. The indication, therefore, is that potential yields under conditions of high temperature are very high, and especially so when considered in terms of yield per unit of calendar time.

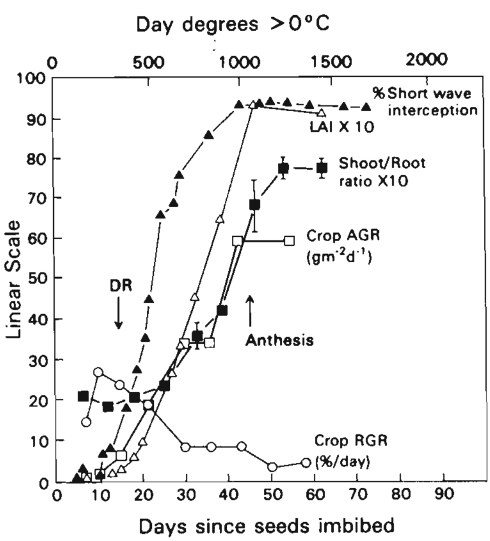

Figure 1. Growth and radiation interception for mini-crops of Tobari wheat grown under a high temperature and radiation regime in a growth cabinet (see text).

Effects of Temperature on Radiation Accumulation

If such high yields can be achieved in controlled environments, why are they not achieved in the field? Furthermore, why do controlled-environment studies with spaced plants invariably show a decline in growth with increasing temperature (2, 21, 59), even when it can be demonstrated that the effects are not due to VPD (69)?

I propose that the effects of temperature on growth are, in fact, not due to temperature per se, but due to the increased requirement for growth resources per unit of calendar time as temperature increases. If the three main growth resources of radiation, nutrients, and water are not supplied at the increased rate per day demanded by increased temperature, growth suffers. Temperature, therefore, has no effect except to change the relationship between plant time and calendar time.

The usual way to express plant time is in day degrees (DD), which in the simplest form is calculated by summing mean daily temperatures. Thus, a plant growing over a day with a mean temperature of 20°C will accumulate 20 DD on that day (5, 39). In the example in Figure 1, the double ridge stage was reached in 345 DD (15 days x 23°C), anthesis by 1100 DD, and maturity by 1880 DD. Though increased temperature accelerates such phenological development in calendar time, it has no effect in plant time. Consequently, each developmental stage requires a fixed number of DD for completion for a specific genotype, regardless of temperature (with some modification by photoperiod). Figure 2 demonstrates this for Kalyansona grown under three different temperature regimes (see 44 for the responses of other genotypes to temperature). In spite of an effect of temperature on calendar time to anthesis of 40 days, approximately 950 DD were accumulated to this stage in all treatments. Similarly, the double ridge stage, which signals the end of leaf primordia production and the start of spikelet appearance (cf. pictures by 35 and 72), occurred after about 300 DD, and the terminal spikelet was laid down after 500 DD in all treatments: the appearance of the terminal spikelet is a rough measure of the start of floret initiation, and flag leaf emergence marks the approximate end (3).

Just as each phenological stage accumulates a particular number of DD before completion, so too does each organ. Each leaf needs approximately 80 DD, each spikelet 10 DD, and the first tiller on each shoot 240 DD. These numbers change with genotype and various environmental factors, as will be

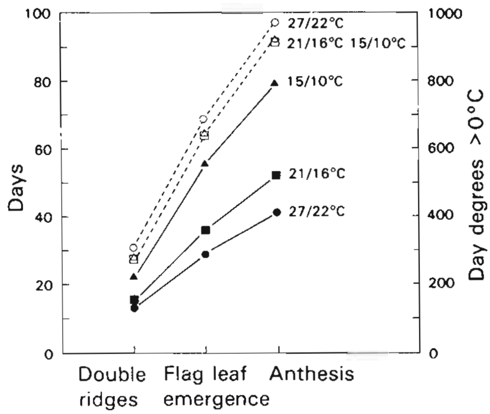

Figure 2. Calendar time (days: continuous lines) and thermal time (day degrees: dashed lines) elapsed before Kalyansona wheat reached double ridge, flag leaf emergence, and anthesis stages, when plants were grown under three temperature regimes.
Source: Rawson and Bagga (49)

discussed later. Now, each organ, to reach a particular size, requires a particular amount of substrate. Taking an hypothetical case, if the plant clock allows 30 DD for a specific organ to be produced, the plant will have 3 days to accumulate the substrate for that organ at 10°C, but only one day at 30°C. At 10°C, that is 3 days of photosynthesis and nutrient and water uptake, but at 30°C, it is only 1 day.

As temperature has minimal effects on rate of photosynthesis per unit leaf area, providing water is not a limitation (2, 13, 63), carbohydrate accumulation is directly proportional to hours and intensity of sunlight and area of leaf per unit ground area. Thus in our hypothetical case, the organ at 10°C will grow three times as big as at 30°C. However, we could make that organ grow as big at 30°C as at 10°C if we increased radiation threefold and kept nutrients and water nonlimiting. Taking this argument of matching inputs to requirements, and knowing the stage in the plant's life when each organ is developing and its potential contribution to yield (26, 50), it should be possible to manipulate inputs at each stage to control the size of each organ and thus the final yield up to a genetic ceiling.

Returning now to controlled environment studies, which have demonstrated a reduction in growth with increased temperature; these all changed temperature in a common radiation environment. Thus the effect of increased temperature was to reduce the radiation received for each developmental stage, thereby reducing growth proportionately. This was recognized by Rawson and Bagga (49), who were assessing the relative sensitivity of different developmental stages of wheat to high temperature by transferring plants among three temperature regimes every 4 days after double ridge appearance. They expected to see steep changes in sensitivity, much as has been found after water stress (40). However, they showed that no 4-day stage between double ridge stage and ear emergence was any more sensitive than any other, because this whole period is an overlapping progression of development for different florets; thus, it is a period when potential grain number is being progressively accumulated. They demonstrated this by expressing all their temperature treatments in terms of the amount of radiation received by the plant per unit temperature (equivalent to an expression of the amount of radiation received in each developmental stage, Figure 3).

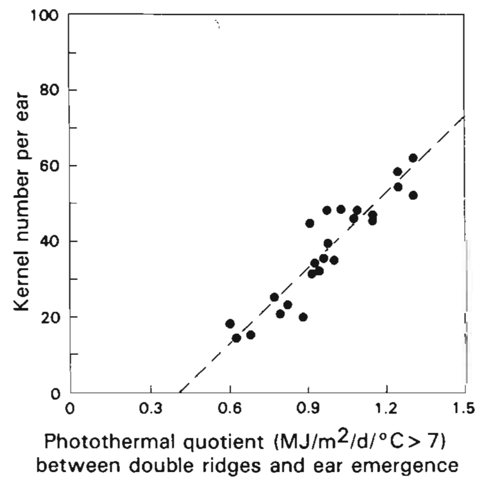

Figure 3. Kernel number per ear in two genotypes of wheat moved among various temperature regimes prior to heading, expressed against the photothermal quotient (MJ/m^2/d/°C > 7) accumulated between double ridge and ear emergence stages.
Source: Rawson and Bagga (49)

The concept of such a photothermal quotient (PTQ) was popularized by Nix (37); also see 39 for an early PTQ. Fischer (17) has recently argued convincingly, by using data from a wide range of field crops, that kernel number increases in proportion to PTQ in this pre-anthesis period, and therefore that PTQ is an important determinant of grain yield.

The Balance Between Temperature and Radiation as Changed by Latitude

It has been shown that PTQ varied with month of the year. This can be seen in Figure 4 for two locations at high and low latitude (37) in Australia: PTQs at each location are lowest in autumn and highest in spring, with the amplitude being greater at high latitude. Details of temperatures and radiation from which PTQ was calculated (Figure 5) indicate that the monthly differences are largely due to the difference in soil heat storage after summer and winter, respectively. Autumn was 4°C hotter than spring for the same radiation receipt in this example at low latitude, but can increase to 6 to 8°C hotter at high latitudes.

The monthly change in radiation and temperature with latitude is better demonstrated in Figure 6 where it can be seen that with reduction in latitude, in a marine environment, temperature increases, but radiation does not. Mean annual PTQ for marine locations at sea level can be estimated from the relationship shown in Figure 7. Elevation increases PTQ at any latitude.

Using the relationship in Figure 7 (though remembering that it is an annual mean for a marine environment) together with the knowledge that kernel number per m^2 is determined by the PTQ in the 30 days before anthesis (17), or more precisely by PTQ during the floret development, it follows that yield potential for wheat can be roughly estimated for any global location.

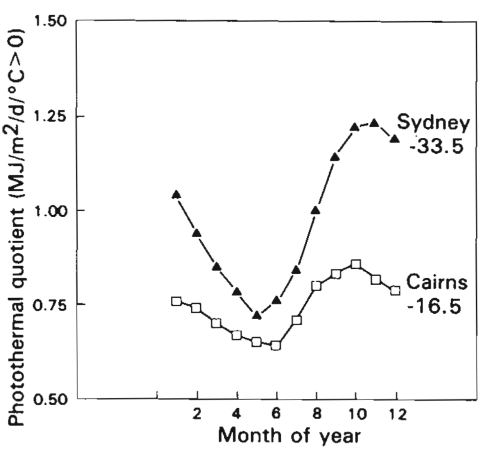

Figure 4. Change in photothermal quotient throughout the year at high and low latitude maritime locations.
Data source cited in Nix (38)

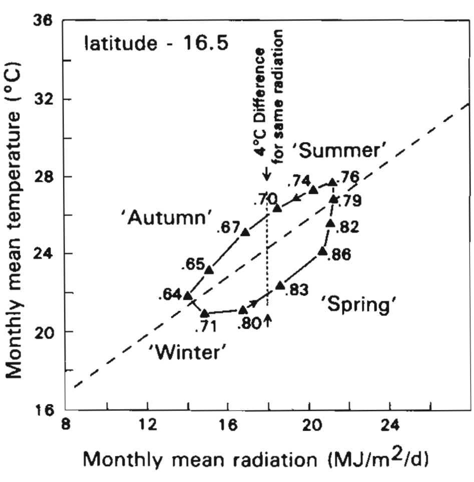

Figure 5. Temperature and radiation relationships used in Figure 4 for the low latitude location. The values of photothermal quotient are shown adjacent to each data point.
Data source cited in Nix (38)

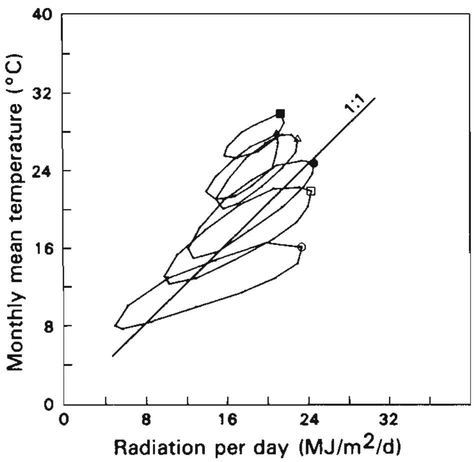

Figure 6. Relationship between monthly mean temperature and mean radiation for six marine locations at the southern latitudes of 11.6 (■), 16.6 (▲), 19.1 (△), 27.3 (●), 33.5 (□) and 42.9 (O). Each symbol marks January for each location.
Data source cited in Nix (38)

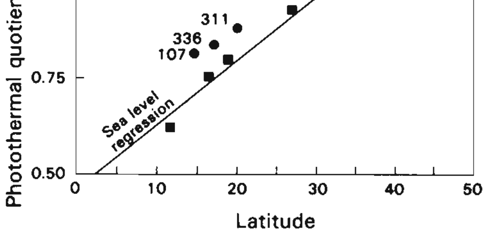

Figure 7. Relationship between photothermal quotient and latitude for the six marine locations in Figure 6 where Y = 0.454 + 0.017X; r^2 = 0.99. Data are also shown for inland locations at various elevations (●).
Data source cited in Nix (38)

Yield Potential at Different Locations

Mean annual PTQ at sea level changes from around 0.45 MJ/m²/d/°C at the equator to around 0.85 at the edge of the tropics. The simplest way to test whether changed PTQ in this range does change yield is to grow glasshouse mini-crops at controlled temperatures and vary radiation input by sequential plantings throughout the year. This was done using a moderate temperature regime of 21 to 16°C day/night and three genotypes (11), and using hot conditions of 30 to 25°C and six genotypes.

The studies are compared in Figure 8. The regression shown in Figure 8 is plotted through the high-temperature studies. There, PTQ between terminal spikelet and heading accounted for 92% of the variation in yield. A regression through Evans' (11) data, excluding his shading treatments and using a PTQ from 35 to 15 days before anthesis, accounted for 84% of the variation. The slopes of the two regressions were not significantly different. Thus, in controlled environment studies, temperature per se during this pre-anthesis period does not alter kernel number. Rather, it is the effect of temperature on shortening the period that reduces the amount of radiation received, which in turn, reduces kernel number.

Figure 8 also includes field data from several hot sites (34) where PTQ only explains 69% of the variation, but more importantly, the slope of the regression is much lower than in the glasshouse data. Though the conclusion from this observation could be that controlled environments bear little relationship to the field, the positioning of one of the Midmore et al. (34) values on the line at a PTQ of 0.9 $MJ/m^2/°C$ may indicate that the line does indeed predict the potential of crops, and that the generally lower slope of the field data is because of limitations other than radiation. Because the relationships between kernel number (K) and yield (Y, g/m^2) in the field and glasshouse data were not different ($Y = 59.2 + 3.33K$; $r^2 = 0.88$), it must be concluded that the limitations in these field studies were effective prior to anthesis and affected kernel number rather than the ability of the crop to fill its grains.

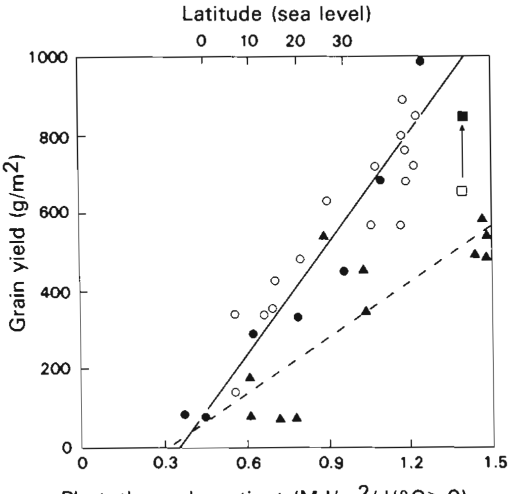

Figure 8. Grain yield as related to photothermal quotient for four data sets: Evans (11) mini-crops grown at 21/16°C (O); Midmore et al. (34) crops grown at various hot sites (▲); Rawson (unpublished data) mini-crops grown at 30/25°C (●); and Spiertz and Ellen (61) crops grown with two nitrogen treatments (□, ■). PTQ was accumulated for the 30 days prior to anthesis for the first two data sets and from terminal spikelet to anthesis for the third. The regression was fitted through the Rawson data where $Y = -345 + 959X$; $r^2 = 0.92$.

The field data of Spiertz and Ellen (61), also included on Figure 8, demonstrate the importance of nitrogen in reaching potential yield. Raising their early application from 50 to 100 kg/ha, and adding 50 kg/ha at the boot stage increased yield from 65 to 87% of the estimated potential yield at the appropriate PTQ. This change resulted largely from a 15% increase in kernels/m^2, which paralleled an increase in LAI and radiation interception. In order that potential yields at particular PTQs be achieved, radiation interception by the crop must be complete. Plants are exposed to the temperature part of PTQ regardless of canopy cover, but the effective PTQ is reduced as radiation interception is reduced (17).

Ways to Increase Radiation Interception

Delaying phenology

Midmore et al. (33, 34) highlighted the correlation between phenology and leaf area production under high temperatures. Their conclusions are substantiated by Figure 9 which shows LAI data for six genotypes of wheat grown at 30 to 25°C in a glasshouse and subjected to two vernalization treatments and various radiation levels. The figure shows that treatments resulting in earlier floral initiation (double ridge) resulted also in less leaf area at 5.5 weeks after planting; this was the anthesis stage in the early genotypes, and a little beyond double ridge in the latest lines. According to the regression, each day's delay in floral initiation increased LAI by 0.34. Though phenology explained 70% of the variation in LAI for the earlier genotypes, there was a poor relationship once LAI exceeded about 6.0.

The effect of phenology on leaf area production is often via tillering, which can cease at the double ridge stage (3, 70), though this relationship can be modified by plant spacing (9) and nitrogen availability (43). Indeed, nitrogen applied continuously to Tobari grown at high temperature resulted in new tillers emerging up to heading of the main shoot and final tiller numbers of $1350/m^2$: this yielded 1110 $ears/m^2$.

Changes in the rate of phenological development arise through photoperiodic or vernalization sensitivity (10, 64). Unfortunately, little work has been done on the phenology of plants under high temperatures as affected by these factors and so the performance of genotypes in the tropics cannot be predicted from their phenology in temperate regions (31). Recently, it has been demonstrated that the vernalization response of plants, normally thought to be satisfied by cold, can be more rapidly satisfied by shorter photoperiods than by low temperatures (12), and can also be accelerated by high radiation. This implies that genotypes with a vernalization response are not precluded from the tropics where photoperiod is around 12 hours, and the degree of vernalization response can be used to manipulate phenology and optimize leaf area for the particular location (67).

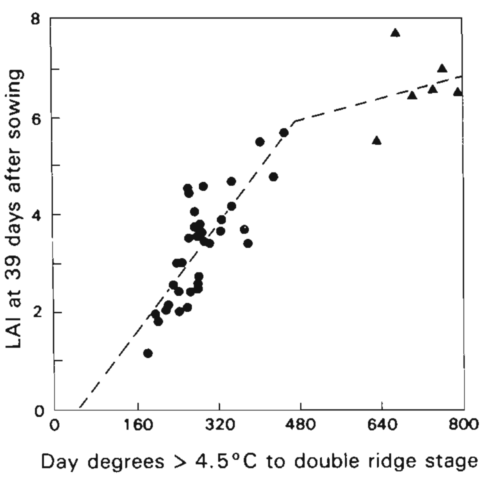

Figure 9. Leaf area index as affected by changed phenology at 39 days after sowing for six genotypes of wheat grown at 30/25°C (Rawson, unpublished data). Imbibed seeds were exposed to different periods of vernalization to change time taken for plants to reach double ridges. The drawn regressions were fitted through the data points for plants that reached double ridge prior to (●) or after 22 days from sowing (▲).

Unfortunately, phenological delay does not necessarily result in more yield (33, 34), particularly if the delay results in water or nutrition becoming limiting. Indeed, R.A. Richards (personal communication) has shown that as environments progressively deteriorate with respect to available water, the ranking of genotypes for yield also changes progressively from the latest to the earliest; there must always be enough water left in the profile at anthesis to fill the grain (41, 42, 54).

Expanding leaf area faster

Via reduced phyllochron interval (PI)— Since Friend (20) demonstrated the close association between leaf emergence and tiller emergence, several authors have shown that leaves appear at strict intervals measured primarily in day degree terms. This phyllochron interval (PI) can be modified by photoperiod (22) and apparently by rate of change of photoperiod (4), though I suspect that the latter response would be more appropriately described by PTQ, which affects leaf expression (51) and is correlated with rate of change of photoperiod ($r^2 = 0.80$) (54). PI also marks time for tiller appearance (27, 28, 32).

The range in PI for winter wheats in temperate zones is from 70 to 100 DD (5). In the high-temperature study of Figure 1 with Tobari, PI was 70 DD (3 days) for all tillers that appeared prior to the double ridge stage. It reduced slightly, though progressively, for tillers that emerged after this stage by 0.078°C/DD>300 DD (Figure 10 and cf. 68 for a similar response). Consequently, the PI for a spring wheat fitted at the margins of response for winter wheat in temperate zones, and conclusions can be interchanged between the groups with caution. As there is variation among genotypes in PI in temperate regions (5, 65), there will also be variation that can be utilized at high temperature (47).

Unfortunately, there is a general positive correlation between area per leaf and PI, so that fast leaves equates with small leaves (52), and so selection for shorter or longer PI is unlikely to influence leaf area production, though it will influence potential tiller and ear number.

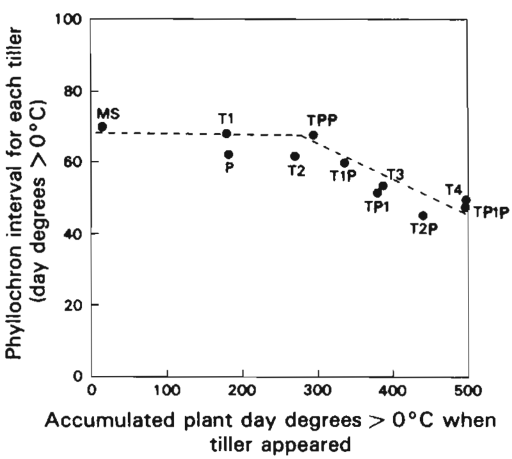

Figure 10. Phyllochron interval for each tiller as affected by plant phenology in Tobari wheat plants grown as in Figure 1 (Rawson, unpublished data). Tiller nomenclature as in (60).

Via reduced sowing depth—Sowing depth is often determined by depth of available water. It has been suggested that deeper sowing should increase the plant's proportion of roots to emerged shoot at emergence and thus enable the plant to meet more readily the higher evaporative demand usually associated with increased temperatures (47). The argument was based on the premise that shoot/root ratio would not change significantly until the shoot emerged. In fact, under conditions of high temperature and evaporative demand, shoot/root ratio increased linearly over the first few days after planting regardless of whether the shoot was emerged or not. Thus, deeper planting, by delaying emergence, resulted in an increased total shoot/root ratio at emergence. In spite of this, seedlings sown at 50 mm had 30% more root upon emergence than those sown at 25 mm (Figure 11), while those sown at

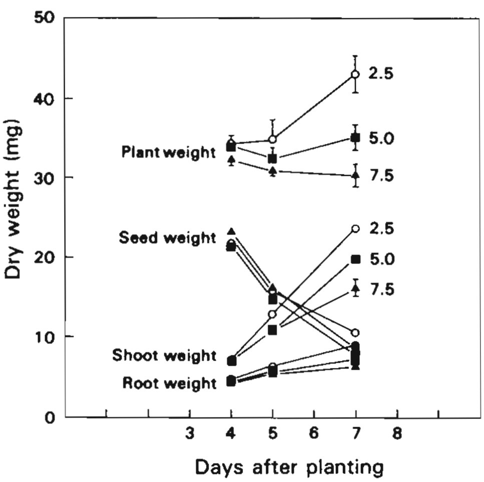

Figure 11. Effects of depth of planting at 2.5, 5.0, and 7.5 cm under high temperatures on the early dry weight changes of root, shoot and seed in C306 wheat. Plants grown as in Figure 1 (Rawson, unpublished data).

75 mm had the greatest proportion of root of all, though establishment was reduced.

Although root to emerged shoot ratio was increased by deeper planting as predicted, there was a negative aspect; emergence was delayed. Figure 11 shows that the seedling increases in weight very rapidly once it emerges and photosyntesis begins. For example, at one week after planting, seedlings sown at 25 mm were 23% heavier and had proportionately more leaf area than those sown at 75 mm, because of a difference of 3 day's photosynthesis. This difference would gradually disappear in the long growing seasons of temperate regions, but in the shorter seasons of hot regions with the likelihood of low LAIs the proportional differences could remain until harvest (and see 16 and 25 for effects in field plantings).

A further important and negative aspect of progressively deeper planting is that an increasing proportion of the early order tillers fail to emerge, and these are potentially the best yielders (e.g., 45 and see 62 for comparative developmental rates of main shoot and tillers) because they accumulate more time and leaf area before the double ridge stage. As plant time accumulation commences at seed imbibition, deeper planting also reduces the amount of photosynthesis that can be accomplished before double ridge and also curtails the accumulation of tillers at higher positions. In the example of Figure 9, more than 50% of the time to double ridge stage had elapsed by the time that the earliest seedlings in the deepest planting emerged and started to photosynthesize and accumulate leaf area. The conclusion, therefore, must be that the shallowest planting consistent with water depth is to be encouraged for rapid early leaf area production and early growth.

Via increased seed size—The importance of large seeds for good establishment and rapid early growth has been stressed from as early as 1899 (8, 25). This is demonstrated again for high-temperature conditions in Figure 12 where seedlings were grown from half or full seeds and at two radiation levels. Because seeds were planted at 25 mm, only half the full seed was exhausted by seedling emergence (Figure 11) and there were no effects on establishment. However, at low radiation (PTQ = 0.3), plants from half seeds were 25% smaller than plants with all their seed after 4 weeks growth; the proportional difference due to seed amount at high radiation (PTQ = 1.15) was less but absolute differences were similar. Removing half the seed significantly reduced the areas of leaves 1 and 2 by 15% (and by 27% after total endosperm removal following emergence). Tiller numbers were also reduced. This study therefore suggests that seed reserves continue to influence growth after seedling emergence and even under radiation levels that should be sufficient to optimize photosynthesis.

Conclusions from the above study may be dubious because of damage to the seed. However, the results were substantiated by using genotypic variation in seed size in a further high-temperature study. Plants of six genotypes were established at 30 to 25°C and under various PTQs and coefficients of determination calculated between initial seed weight and leaf area at 14 days after planting. Seed size accounted for 70% of the variation in leaf area under dull, hot conditions, but for only 15% under bright conditions (Figure 13). Thus, although large seeds may germinate slightly more slowly than small seeds (30, and see 7 for variation in this), they are essential for vigorous early growth, particularly under conditions of deep planting and low radiation.

Via increased area of the first leaf and changes in biomass allocation— Just as a large seed leads to rapid leaf area establishment, so too can a large first leaf have a major effect. The contrast between two barleys and Hira wheat is seen in Figure 14. The barleys have first leaves that are twice the area of Hira's. In spite of a higher rate of photosynthesis per unit leaf area, a higher shoot/root ratio, and a marginally higher relative growth rate after leaf 1 emerged, Hira had achieved only half the plant leaf area of the barleys at 30 days after planting and only 55% of the biomass. Similarly a wheat, Cleopatra, with a 50% larger first leaf than Hira, had produced 25% more biomass by this stage. There is of course a correlation between seed size and area of the first leaf, but it is by no means fixed.

The pattern of allocation of biomass by the seedling can also have major effects on the rate of production of leaf area. Thus, a high specific leaf area, which generally equates with a large area of thin leaves, and a high shoot/root ratio are allocation strategies that increase leaf area, and both are common characteristics of barley. There is significant genotypic variation in these characteristics in wheat grown at high temperatures, however (47, 52). It should be pointed out that large leaves frequently have lower rates of photosynthesis (6, 48), and so the small-leaved genotypes eventually catch up, and may overhaul the large-leaved genotypes if given

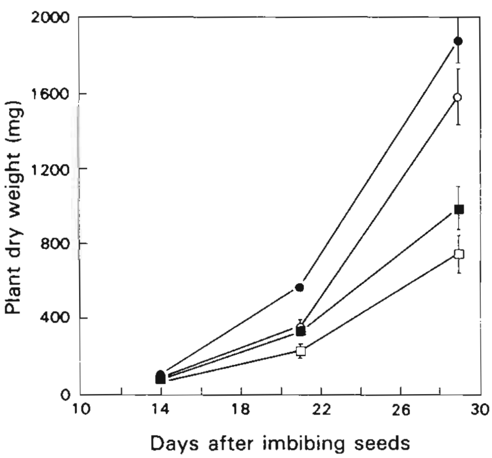

Figure 12. Effect of removal of half the seed endosperm on growth of Tobari wheat at high temperature and high (○, ●) and low (□, ■) radiation. Whole seeds depicted by closed symbols, half seeds by open symbols (Rawson, unpublished data).

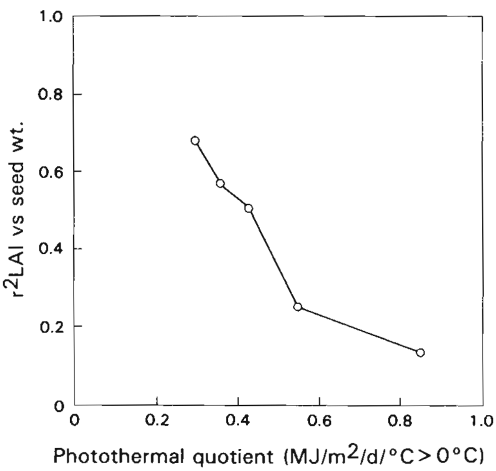

Figure 13. The dependence of leaf area index on seed weight at various photothermal quotients in 6 genotypes of wheat grown at 30/25°C (Rawson, unpublished data). The y-axis is the coefficient of determination for leaf area on seed weight at 2 weeks after planting.

enough time. The other complication is that small-leaved genotypes often have a shorter PI (53), which means that leaves and tillers are produced faster. So, given enough time and good enough conditions, they can also produce more ears.

Requirements Additional to High Radiation Interception for a 10-t/ha Crop

Increased leaf area inevitably means increased water use, though part of this can be offset by improved water efficiency (14), and if the water requirements cannot be met then the components of the plant being generated during the stress period will suffer. In Figure 15 the water-use pattern of a crop with the equivalent progression of biomass accumulation to that in Figure 1 is calculated, though grown under a range of VPDs. The calculations assume that WUE = 50/mbVPD (58), and so would overestimate water use after canopy closure; measurements in the growth cabinet showed that water use increased only slightly 40 days after planting. These data demonstrate that a high-yielding crop needs a lot of water, particularly under conditions of high evaporative demand.

In addition to needing copious amounts of water, a high-yielding crop also uses a large amount of nutrients. If it is conservatively estimated that all new tissue produced by the plant has 3% nitrogen (see 23 for the likely range in N%), and that no nitrogen is retranslocated during the period up to heading (this is unlikely but will reduce the error in the previous assumption, 29, 71), then with an average growth rate of 30 g dwt/m^2/d (Figure 1), the preheading period requires 36 g N/m^2 (360 kg/ha). The peak requirement during the floret development phase between terminal spikelet production and anthesis would be 1.8 g N/m^2/d. If the plant could not find this from direct

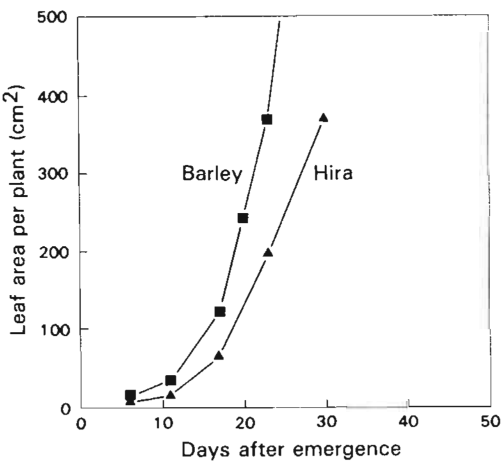

Figure 14. Leaf area per plant in two barleys (meaned) and Hira wheat grown as in Figure 1, showing how plant leaf area can correlate with the area of the first leaf (Rawson, unpublished data).

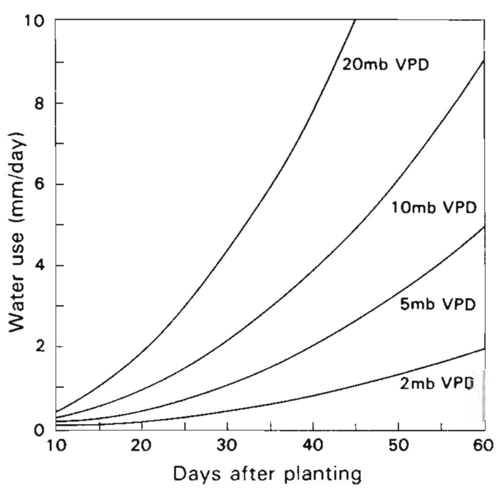

Figure 15. Calculation of water use per day at different mean daily vapor pressure deficits (mb) to produce a crop with the growth pattern of Figure 1.

uptake or retranslocation, kernel number would be reduced (57), because all the floret primordia initiated would not grow large enough to become competent to set grains (49).

Recommendations

The first requirement before introducing a crop into a new environment is that the environment should be adequately described (31). The timing and degree of severity of the climatic constraints can then be gauged and the development of the crop matched to them.

If water is not a constraint
If water is not a constraint because of deep soil storage, a high likelihood of rainfall, or the availability of irrigation water, the following practices should be adopted:

1) Planting time calculated by day degree summations, so that the floret development stage from terminal spikelet to anthesis, when LAI is high, coincides with peak PTQ.

2) Utilization of a large-seeded genotype if the PTQ at emergence is low.

3) Shallow planting into a uniform seed bed to ensure good establishment.

4) Selection of a genotype with the characteristics of a short PI to provide high tillering potential, and a high specific leaf area and a high shoot/root ratio to ensure vigorous early above-ground growth. This results in early shading of the soil to minimize soil evaporation (66, 67) and decreases soil temperature.

5) Nitrogen applications split between sowing, to optimize early growth, and post-terminal spikelet production, when requirements reach a peak and the numbers of competent florets are determined. Applications to be determined by plant time rather than calendar time.

6) If nitrogen and water availability are sufficient to match leaf area and VPD demands, use of genotypes with a vernalization response to increase yield by extending anthesis beyond full canopy light interception. The effects of this delay interposed before floral initiation (double ridge), will be to increase main-shoot leaf number, spikelet number per ear, and potential ear number.

If water is a constraint
If water is likely to be a limitation the following should be considered:

1) Plant into available moisture (minimum of 10% moisture, -3 Mpa) (19), using a large-seeded genotype particularly if the available water is deep. Always aim for the shallowest planting consistent with good germination, so as not to waste plant time in the pre-double ridge stage.

2) Use a genotype with a large first leaf to maximize early photosynthesis, although a high proportion of that growth will be utilized in deep root production (a low shoot/root ratio).

3) Select a genotype with a long PI; large leaves (2) and long PI are correlated, so this is probably inevitable. This will result in sparse tillering because of the reduced number of tiller sites

available prior to double ridge, and particularly if low-order tiller buds have failed to become competent tillers through deep planting (1). Long PI will lead to low tiller mortality.

4) Provide fertilizer only at planting; late fertilizer may stimulate late tillering, which will waste water.

5) As water becomes progressively more limiting, proportionately reduce the period from planting to the double ridge stage (by using genotypes which approach day neutrality and have zero vernalization response) (44, 46). This will further curtail tillering and save water for the floret phase and grain filling. Alternatively, use genotypes which "stool sparingly" (15) or with a uni-or oligo-culm habit.

6) Use genotypes with heavy glaucousness to increase water-use efficiency (55 and see 14 and 36 for other proposals on WUE).

7) Use taller genotypes as there is some evidence that they can root deeper (R.A. Richards, unpublished data), and produce greater root biomass, at least prior to stem elongation (7).

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Problems Associated with Soil Management Issues in Rice-Wheat Rotation Areas

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Abstract

Under irrigated conditions, wheat after rice seems to have great potential and could be extended to the areas of good soil and favorable climate in northern and northeastern Thailand. One of the major yield constraints is poor plant establishment, which is widely observed when wheat is sown in paddy fields. Problems associated with soil and irrigation management are discussed. Alternative tillage management practices are suggested for research.

In upper northern Thailand, three potential areas of wheat production have been reported (2). Wheat for local markets is currently grown only on uplands that are rainfed or partially irrigated. However, yields and production are limited or unstable and are dependent on climatic constraints. In order to meet the demands of national consumption and partially substitute for the amount imported, more wheat has to be produced. Wheat cultivation after irrigated rice seems to have great potential in the vast rice lands of the northern and northeastern regions of Thailand. Rice-wheat rotation research is another challenge for agricultural research scientists in the development of appropriate cropping practices to increase and stabilize wheat production.

This paper discusses the problems associated with soil management in areas with rice-wheat rotation, particularly from the standpoint of studies of agronomic practices and soil fertility improvement in Phrae Rice Research Centre experimental fields during the last 2 years.

Phrae Rice Research Centre

The Phrae Rice Research Centre is located at 18°13'N, 103°14'E, at about 170 masl. Soil samples from wheat experimental plots indicate an average organic matter of only 0.63% with 5.6 and 29.7 ppm of available P_2O_5 and K_2O, respectively. Soil pH ranges from 5.9 to 8.0 or about an average of 7.0. Soil structure is generally a sandy clay loam belonging to the Lampang series. The monthly average temperatures during the period of study (1984/85 and 1985/86) from October to March were 27.8, 25.7, 23.1, 23.4, 24.5, and 27.4°C, respectively. The average minimum was around 15 to 16°C from December to February (Table 1).

Soil and water management

At the Phrae Research Centre conventional wetland tillage is used for rice cultivation. Plowing and harrowing are done by tractors The main disadvantages of puddling are that it results in poor soil structure and the formation of a hard plow pan that restricts water percolation. After rice harvesting, the land is left to dry before preparation for wheat growing. Heavy four-disc harrows are used to turn over the soil surface and break the plow pan. The big clods are broken down by lighter disc harrowing after 3 to 4 days. A rotovator is used 2 to 3 times to reduce the soil clods. In our experimental fields, the beds are raised along the length of the field. Generally, the beds are 1 to 2 m wide and 20 to 25 cm high.

To irrigate wheat fields after rice, two to three irrigation methods are used at the Center. The first time (after sowing), furrow irrigation is used. Sometimes the water is left between the furrows overnight to allow the moisture to move by capillary force across the beds. Supplemental water is splashed by hand over the bed. Bed flooding followed by immediate drain-out is used when the plants are well established. The field is usually irrigated 3 to 4 times at approximately 20-day intervals after the young seedlings have emerged.

Problems Associated with Soil and Irrigation Management

In our studies, we have observed that poor plant establishment is mainly associated with soil and water management problems.

Soil compaction
When dried after the puddled rice crop is harvested, the soils shrink and crack and become extremely compact. Plowing is difficult and results in a largely cloddy condition. When wheat is sown into these conditions, emergence is extremely low. Rotary cultivators have been used to reduce the clods to a more manageable size.

In 1986 tests, seeds were placed on a cloddy soil surface and irrigated. The irrigation washed a minimal amount of soil over the seed. This resulted in excellent emergence and appears to be an attractive alternative to repeated cultivation to produce a good seedbed.

We recognize that, in general, farmers do not possess the equipment we use, so we are planning to do research on zero or minimum tillage.

Waterlogging
Even when heavy disc harrows are used, the hard compact layer (at about 20-cm depth) cannot always be broken. This causes waterlogging problems which are most severe in the seedling stage, due to lack of aeration and seedling blights, particularly *Sclerotium rolfsii*.

Table 1. Average temperatures at Phrae Rice Research Centre during the wheat growing seasons (1984-85 and 1985-86)

		Average temperature (°C)					
		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
Maximum	1984-85	34.9	31.9	31.6	32.4	34.3	36.1
	1985-86	32.5	30.5	28.9	29.8	31.8	35.0
Minimum	1984-85	22.2	19.1	14.8	15.0	16.5	21.0
	1985-86	22.2	21.5	17.1	16.4	15.5	17.6
Average (1984-85 + 1985-86)	Max. + Min.	27.8	25.7	23.1	23.4	24.5	27.4

Waterlogging causes fewer problems at later growth stages.

Some form of bed system appears appropriate to provide drainage for wheat. However, bed preparation consumes time and labor, which delays the seeding date. In addition, furrow irrigation requires narrow beds to obtain uniform moisture distribution and very uniform land leveling.

Surface crusting
A system of splashing or throwing water from the furrow over the beds has been developed in some other upland crops such as tobacco or garlic grown after rice. This is now used for early irrigation of the wheat crop.

However, because the topsoils are structureless, a substantial surface crust forms after the water is splashed. The effect of this crust on plant establishment is minimized if the topsoil is kept moist. This necessitates labor-intensive irrigation by hand every day (if not more frequently) for the first 5 to 6 days after seeding.

We have increased the seeding rate at Phrae to 150 kg/ha in an attempt to overcome the establishment problem caused by crusting. In addition, the use of straw mulch to reduce crusting and to slow the drying of the topsoil is being investigated.

Turn-around time
Irrigation management has been a prime constraint to high and stable wheat yields at the Phrae Rice Research Centre. However, the turn-around time is also very important. Late seeding can markedly reduce yields as has been reported from India (6) and other parts of South Asia. As it is unlikely that changes in rice varieties will result in substantial changes in the rice harvesting date, more attention must be placed on reducing the time between rice harvest and wheat seeding. Given that in Thailand the paddy soils are generally heavy and difficult to cultivate into a traditional wheat seedbed, and given that very little mechanization exists on the small farms of northern Thailand, it seems most appropriate to develop zero or minimum tillage options. Zero tillage has been suggested as an alternative to reduce soil disturbance and minimize soil compaction (7). It also has been found that directly sowing wheat into standing rice stubbles and applying nitrogen fertilizer at the tillering stage could maximize the yield of wheat after rice (1).

Only limited work on zero tillage for wheat has been attempted in Thailand, with little success. The techniques developed must be simple and cost effective. They must be appropriate to small farmers and utilize hand labor, animal draft-power or at their most sophisticated, small hand tractor-powered tractors.

A wheat-rice rotation in northern Thailand will require considerable fertilizer for wheat, as the nutrient status is low. However, farmers' purchasing power is generally very low and will be a major constraint to high yields.

A study on wheat response to nitrogen fertilizer in paddy fields (8) was conducted during 1984/85 using four wheat varieties (INIA 66, Sonora 64, SW 9, and SW 23) and six levels of nitrogen (0, 30, 60, 90, 120, and 180 kg N/ha). The highest average wheat yield was obtained with 90 kg N/ha. Sonora 64 (Samoeng 2), SW9, and SW 23 showed response at 30 to 90 kg N/ha. INIA 66 (Samoeng 1) responded at high levels of nitrogen and was generally lower yielding. These data indicate that Sonora 64, SW9, and SW23 are probably suitable varieties for paddy soils with a low fertility status (Table 2).

Further investigation on rates and timings of nitrogen application (9) was done in 1985/86 using Sonora 64 and six levels of nitrogen from two sources (calcium ammonium nitrate and urea) in basal and split application (at sowing and 20 days after emergence) methods. Wheat yields obtained indicated no differences due to nitrogen source.

Our studies on soil fertility improvement have indicated the yield improvements possible at the moment. The aim now is to increase the response efficiency.

Varietal evaluations for the rice-wheat rotation (5, 10) were made to find both rice and wheat varieties for a suitable pattern. In the rainy season, four improved rice varieties (RD 10, Niaw Ubon (NUBN) 1, Muey Nawng 62M, and RD 6) were grown. Each rice variety was followed by five wheat varieties (Sonora 64, SW 9, SW 21, SW 49, and Anza in 1984/85; and INIA 66, Sonora 64, Anza, 1510, and UP 262 in 1985/86) in four replications after harvesting rice (Figure 1). The 1984/85 results shown in Figure 2 indicate systems with Anza and SW 9 after NUBN 1 gave the highest combined yields (3044 kg/ha for NUBN 1, 1175 kg/ha for Anza and SW 9). In 1985/86 Anza and UP 262 gave the highest combined yields when grown after NUBN 1—2500, 2750, and 4631 kg/ha for Anza, UP 262, and NUBN 1, respectively (Figure 3).

Marked increases in wheat yields were observed in the experiment conducted in the 1985/86 crop season. This is probably due to better management. CIMMYT (4) has also reported that the progressive yield increase from 1.5 to 4.1 t/ha in the production plots of the Multiple Cropping Project of Chiang Mai University during 1972/73 to 1975/76 was probably related to improved technology over time.

Table 2. Yield (kg/ha) and plant establishment of four wheat varieties under different levels of nitrogen fertilizer, 1984-85

N-levels	INIA 66		Sonora 64		SW 9		SW 23	
(kg N/ha, basal)	Yield (kg/ha)	Estimated plants/m^2	Yield (kg/ha)	Estimated plants/m^2	Yield (kg/ha)	Estimated plants/m^2	Yield (kg/ha)	Estimated plants/m^2
0	1000	312	1050	252	1094	260	1081	268
30	938	316	1294	272	1500	276	1356	272
60	1219	260	1069	244	1681	244	1594	284
90	1362	296	1562	268	1556	268	1625	236
120	1369	284	1538	224	1394	276	1475	248
180	1394	284	1469	280	1525	300	1575	240
Average	1212	292	1331	256	1456	272	1450	256

5% LSD = 23.28, 10% LSD = 34.19
ANOV A* B** A x B NS
CV (%) A 16.7 B 18.2

Adapted from Uttarapong, et al. (8)

Although the Phrae Rice Research Centre is representative of a large area, there are many paddy fields that are more easily managed. Profitable yield levels have been obtained (Table 3) under more favorable soil conditions (better internal drainage) with proper irrigation and fertilizer management in farmers' fields under the Mae Chaem Watershed Development Project area. This area is characterized by sandy loam soils that are relatively easy to manage.

Until soil and water management studies at Phrae develop a viable package of technology for the less favorable conditions, the extension of wheat in northern Thailand should concentrate on the superior draining soil types.

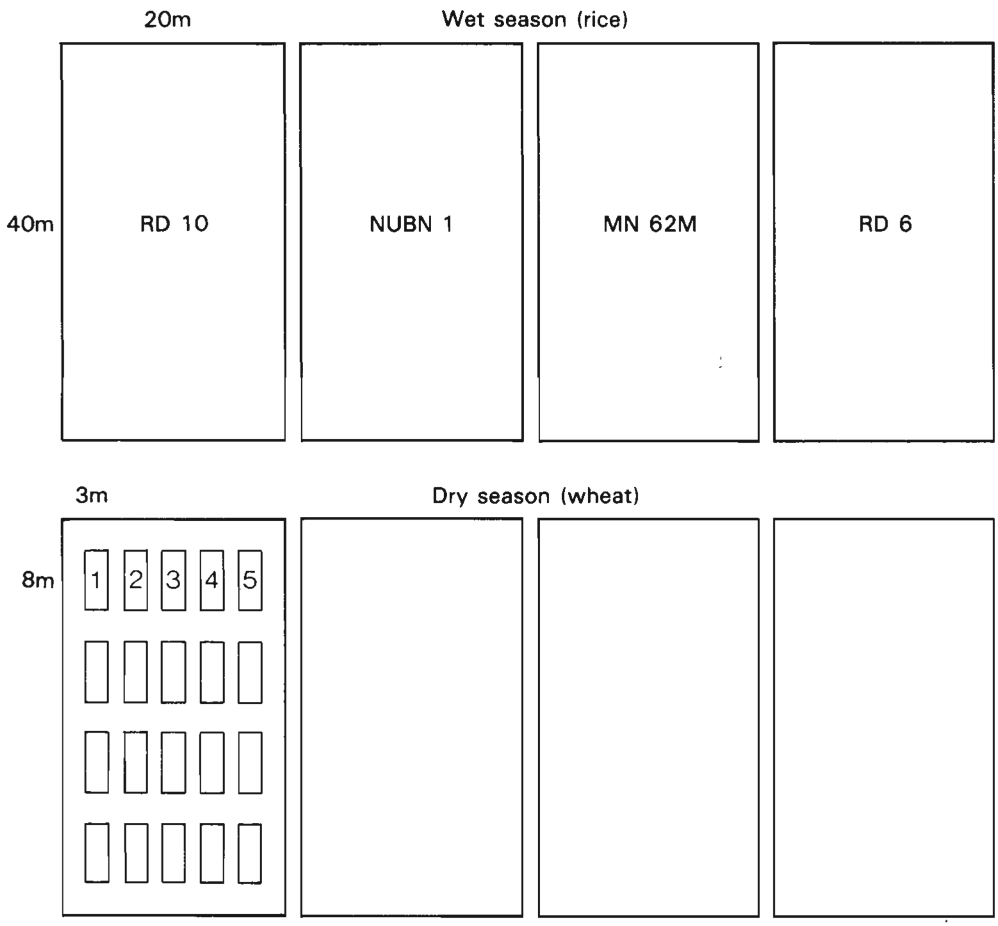

Figure 1. Plot lay-out for rice-wheat rotation trial, Phrae Rice Research Centre. 1984/85.

Source: Homdawk et al. (5)

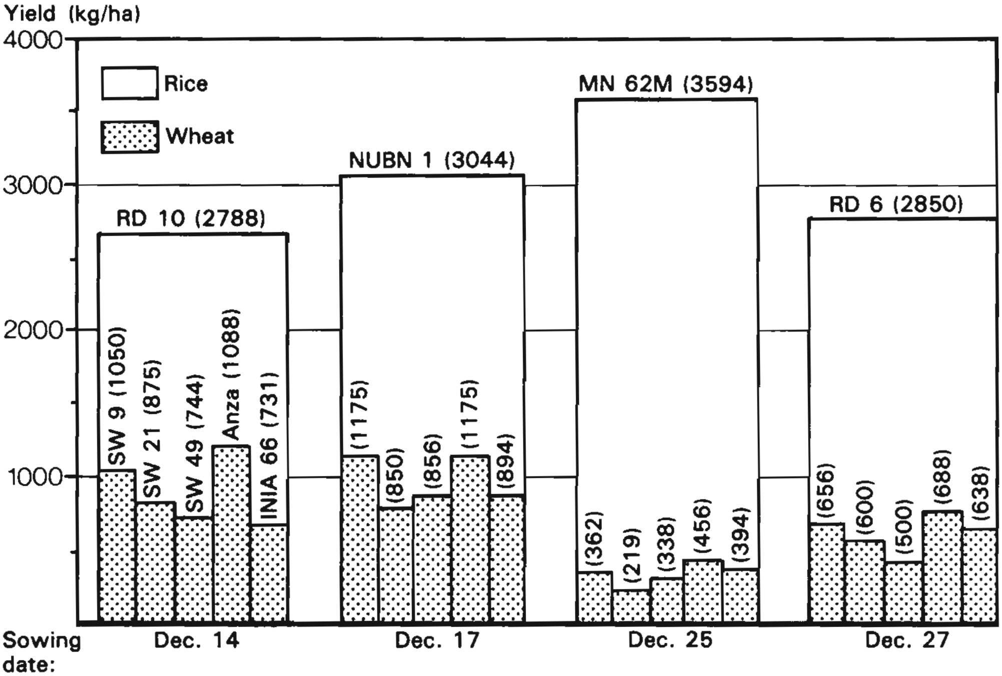

Figure 2. Yields of four rice varieties and five wheat selections in rice-wheat rotation trial, Phrae Rice Research Centre, 1984-85

Source: Homdawk et al. (5)

Table 3. Average yields and plant establishment of four wheat varieties from five testing sites in Mae Chaem Watershed Development Project area, Chiang Mai, 1985-86

Wheat	Yield (kg/ha)		Number of plants
	Average	Range	(per m^2)
INIA 66	3156	1512-3719	328
Sonora 64	3069	1750-3888	357
1015	3550	2281-4138	335
1510	3112	2126-3350	228
CV (%)	7.60		10.5
F-test	*		NS

Adapted from Chungyoosuk et al. (3)

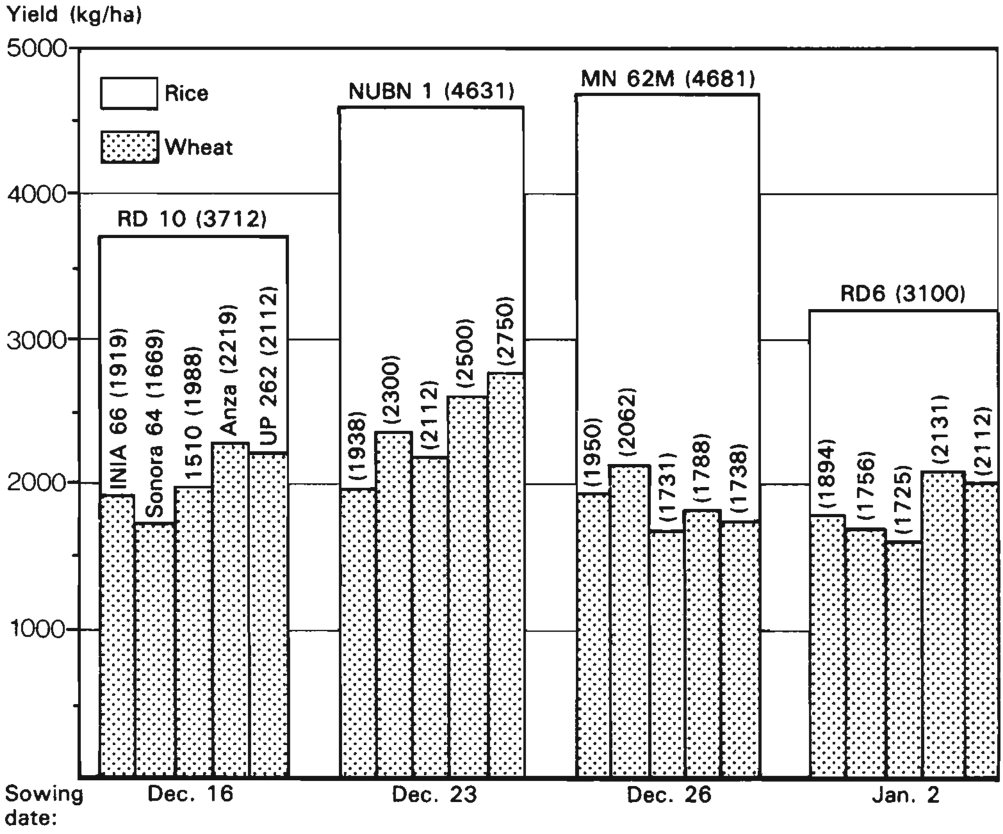

Figure 3. Yields of four rice varieties and five wheat selections in rice-wheat rotation trial, Phrae Rice Research Centre, 1985-86

Source: Youngsuk, et al. (10)

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Potential Use of Minimum Tillage in Wheat After Rice

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Abstract

Wheat planted after rice is a major cropping pattern in an estimated 17.5 million ha of the Indian Subcontinent and China. Delayed planting and poor crop establishment are major factors in the low wheat yields generally associated with this pattern.

This paper reviews the potential for zero tillage as a crop management practice. Results presented show that zero tillage is equivalent to traditional tillage techniques in regard to wheat yield when the crop is planted at the same time, and superior economically in terms of power use. Research is needed on development of a suitable drill, effects of the rice stem borer populations in the next rice crop, and fertilizer management.

Wheat is planted after rice on more than 17.5 million ha on the Indian Subcontinent and the Chinese mainland (7). It is one of the major cropping patterns for the region. Wheat yields in this cropping pattern are also some of the poorest in the region.

Late planting of wheat is the major reason for low wheat yields in this cropping pattern. Using 4 years of planting-date data from Pakistan, Hobbs (6) calculated wheat yield losses of 35 to 40 kg/ha per day when wheat was planted after November 20. Similar data were presented from India (10). Long-duration varieties gave the highest yields when sown in late October and short duration varieties when planted during the first 2 weeks of November. All varieties lost yield linearly with time planted after mid-November.

Late planting of wheat after rice is the result of several factors in the subcontinent. In the Punjab province of Pakistan, Basmati rice, a photoperiod sensitive, fine quality, desi-type variety, is grown on 80% of the land. This variety does not mature until after mid-November and many farmers do not harvest it until December. Many farmers also put priority on drying and threshing the rice crop, one of the major cash crops, before starting land preparation for wheat. The 20% of land grown to rice of the International Rice Research Institute (IRRI) varieties is harvested from late October to early November, depending on the date of transplanting, and wheat planting is not delayed. In the Indian Punjab and the Sind province of Pakistan, IRRI varieties are the major varieties grown and they are not a factor as to when the wheat is sown.

Basmati is a tall rice variety, and its stubble residues are a major problem in preparing a good wheat seedbed. In Pakistan, farmers average 6 to 8 plowings with the spring-tined cultivator or animal-drawn plow to tackle this problem. Even after this input of time and power, residues persist. The farmers are forced to broadcast-plant wheat because rice stubble prevents the use of a seed drill.

Most farmers stop irrigating their rice after flowering to hasten maturity of the crop. If no rains occur in this period and farmers plow their fields, soil moisture for a good wheat crop can be insufficient. In this instance, farmers must irrigate their fields and wait for the correct moisture condition before preparing their land for wheat. With cool temperatures and low evaporation rates in late November and December, delays can be 10 days to 2 weeks or more.

For heavy textured soils, preparation of a suitable seedbed for wheat after rice is almost impossible and very costly (5). The resulting poor stands are a factor in poor wheat yields after rice. Another factor is the low N availability resulting from extensive removal of mineralized nitrogen by rice and microbial immobilization of N applied to the following wheat crop (4, 9). Increased soil bulk density and reduced soil stability after flooding and puddling may also be important.

This paper will concentrate on the potential of reduced tillage for wheat after rice to help reduce the turnaround time between rice and wheat for more timely wheat sowing.

Zero Tillage vs. Traditional Land Preparation

In Pakistan, traditional land preparation for wheat after rice consists of 6 to 8 cultivations with the spring-tined cultivator followed by leveling with a heavy wooden plank. Usually, after every two plowings, the land is left for a few days to allow residue decomposition before the next plowing. The land is planted when the farmer is satisfied with the tilth obtained, although in the majority of cases the resultant seedbed is not perfect for wheat emergence. Some farmers use rotovators to get a better seedbed but with resultant higher costs.

A comparison was made between the above traditional method and a system of planting directly into the rice stubble. All other management factors were kept constant. These trials were done over 2 years and 23 locations in farmers' fields with each field divided into half for two equal treatments. The results are shown in Table 1. Both plots were planted on the same date. Grain yield and biomass production were similar. Spikes/m^2 were equal or even better for direct drilling, whereas other yield components showed a compensatory effect. Direct drilling did improve plant emergence (Table 2), possibly because of more uniform placement of seeds in the soil.

In Australia (1) it has been demonstrated that direct drilling techniques with the rice stubble retained on the surface or burned gave up to double the growth of plants where the stubble was incorporated or burned and then cultivated (Table 3). The experiment was conducted over 4 years. The plots with the stubble retained had either the highest yield or were not significantly different from the best treatment in each season. Burning the stubble did create a problem in some years because it exposed the soil and heavy rain caused crusting, which inhibited water penetration and subjected the plants to severe drought stress later.

Dhinam and Sharma (5) compared zero tillage with traditional methods of tillage for wheat after rice (Table 4). Part of the benefit of zero tillage was due to being able to plant 5 days earlier.

We can conclude that direct drilling with zero tillage is a feasible technology for establishing wheat after rice. It has the added benefit of allowing earlier planting which should result in higher yield and better use of the residual moisture following rice harvest.

Economically, direct drilling saves the farmer substantial production costs and makes wheat cultivation after rice more profitable. In Pakistan, plowing and planking costs for wheat after rice are estimated at between US$50 to $60/ha or almost 20% of the cost of production (2). Similarly, in India zero tillage gave significant savings in expenditures and energy required for sowing wheat compared to traditional methods (5).

Weeds were a major problem in wheat following rice in Pakistan (11) (Table 2). The most common weed encountered was *Phalaris minor*. Populations of this grassy weed were lower in the direct drilled plots than in those traditionally cultivated. Traditional cultivation exposes more seed to air and results in a higher population of weeds than in the zero tillage plots. The conditions for weed germination are also better in cultivated plots. Very few weeds are observed following rice harvest and those that are present are warm-season weeds that do not compete well in the cool season. Problem weeds for wheat have not germinated at this stage of the wheat cycle. Therefore, good stands of wheat in zero tillage plots have a competitive edge over winter-season weeds.

Table 1. A comparison of zero and traditional tillage on the yield of wheat at 23 locations in farmers' fields of the Punjab, Pakistan

Method	Grain yield t/ha	Total biomass t/ha	Spikes per m^2	Grains[a] per spike	Individual grain wt (mg)
Direct drilling	3.52	10.6	255	38	39
Conventional planting	3.41	10.3	242	43	38
Significance	ns	ns	ns	*	ns

[a] Mean of 1985-86 only

Table 2. Effect of tillage operations on number of plants emerged per m^2, number of weeds per m^2, and percentage of tillers infested by stem borer (1985-86)

	Emerged plants/m^2	Number of weeds/m^2	Tillers infested with stem borer (%)
Direct drilling	114	43	12.0
Conventional planting	96	66	3.1
Significance	*	*	*

Other Tillage Methods

The traditional bullock plow and tractor-drawn, spring-tined cultivator used in much of India and Pakistan are not ideal implements for preparing land for wheat after rice. In Pakistan, in 1984, the use of a moldboard plow followed by the spring-tined cultivator was compared with conventional tillage and direct drilling. There were no significant differences between these tillage treatments. However, in the area where the experiment was done, subsoil sodium and salinity were brought to the surface by the moldboard plow and affected wheat growth. The moldboard plow did reduce the problem of rice stubble residues.

Dhinam and Sharma (5) compared five different tillage operations on the yield of wheat after rice in heavy-textured soils in Haryana, India (Table 5). The best results occurred with six tillage treatments and irrigation before field preparation, but these results were not significantly different from other treatments with less tillage. Energy requirements and expenditures on sowing operations were maximum for treatment 3 (19.6 kilowatt hours/ha and 222 Indian rupees/ha) and the lowest in zero tillage (18.2 kilowatt hours/ha and 80 rupees/ha). Dhinam and Sharma concluded that zero tillage was promising, keeping in mind the reduced time and power invested.

Deeper plowing with moldboard and disc plow does reduce the problem of rice stubbles and will break the plowpan resulting from soil puddling for rice. The better rooting and drainage should have positive effects on wheat yield. The use of a rotovator or rotary hoe in combination with deep plowing should produce a good seedbed in reduced time. However, unless the

Table 3. Effect of stubble management on the grain yield (t/ha) of a subsequent wheat crop

	Stubble management				
Year	Early incorp	Late incorp	Stubble retained	Burned	Burned and incorporated
1978	1.61	1.63	2.32	0.51	na
1981	1.73	1.37	1.87	1.79	1.50

Source: Bacon and Cooper (1)

Table 4. Effect of zero tillage on the yield of the wheat variety Sonalika, 1982-83

	Grain yield	Grains/ spike	1000-grain wt wt	Spikes/m^2
Zero tillage	4.17	32.7	54.2	314
Conventional	3.68	30.4	50.8	254

Source: Dhinam and Sharma (5)

plowpan is reformed, water use in the next rice crop will be significantly increased.

Future Researchable Issues

Development of a suitable drill
The success of zero tillage will depend on the development and availability of a suitable drill. In Pakistan, a drill imported from New Zealand gave excellent results. A simpler, single-row drill is shown in Figure 1. This seeder with inverted-T openers was developed at the Agricultural Engineering Department at IRRI based on design features and components evolved from data by M.A. Chaudhary and others at Massey University, New Zealand (3). The coulter uses an inverted-T groove opener. This opener creates in-groove micro-environments that facilitate proliferation of plant shoot and roots. It allows the surface soil and residue to remain intact.

The other important feature of the drill is a seed metering assembly that uses a horizontally mounted circular foam pad. Seeds are delivered vertically downward through a throat-type opening molded as an integral part of the hopper base. This allows a range of seed species and fertilizers to be metered without damage. This is important for farmers who grow several crops on their land.

The drill can be adapted for use with bullocks or small or larger tractors and can plant seeds in prepared or non-prepared land. The tractor-mounted seed drill used in Pakistan has a three-point hitch to enable use in small fields.

The rabi drills presently being manufactured locally in the subcontinent could be modified in strength and the openers and a seed metering device added. A drill would then be available within farmers' budgets that would ensure uniform and proper placement of seed and fertilizer in any soil condition.

Rice stem borer studies
Yellow and white stem borers cause 20 to 25% damage to rice every year in Pakistan (8). Larvae of both species overwinter in rice stubbles and the adults emerge in March-April. Destruction of the rice stubble and late sowing of nurseries after May 20 are recommended to avoid stem borer damage. Studies done in

Table 5. Effect of different tillage operations on wheat crop after rice harvest, averaged over 2 years

Treatment	Spikes/m^2	Straw yield t/ha	Grain yield t/ha
Zero tillage	317	7.37	2.81
Lister plow + 3 tillage operations	323	7.96	3.23
6 tillage operations	350	8.61	3.37
Moldboard + 4 tillage operations	350	7.72	3.19
5 tillage operations + seed soaked	344	9.14	3.20

Source: Dhinam and Sharma (5)

avoid stem borer damage. Studies done in collaboration with the rice scientists on larvae populations in zero and traditional tilled plots in early February showed 12 and 3% infested tillers, respectively, for these two treatments (Table 2). More research is needed to study how this pest can be controlled to both allow the use of zero tillage and maintain the total productivity of the system.

Fertilizer studies

It is not possible to incorporate broadcast fertilizer with zero tillage methods of wheat sowing. Studies are needed on other methods of application. Data from Pakistan and Australia (1) show that fertilizer can conveniently be broadcast after emergence at the first irrigation without loss in efficiency. In Pakistan, even phosphorus can be broadcast at the first irrigation with no loss in yield.

Studies are also needed on the long-term effects of zero tillage on soil physical and chemical properties, weeds, pests, and other factors associated with the restricted soil rooting volume resulting from the plow pan caused by puddling soils for rice cultivation. Sustainability of wheat and rice yields in a zero tillage system is very important.

Broadcasting seed into rice

Another practical way to plant wheat is to broadcast seed in the standing rice crop. In Bangladesh (D. Saunders, personal communication), there is a rapid expansion of relaying wheat into rice. The area planted was about 810 ha during 1985. The mean overlap was about 2 weeks. Although the highest yield in the surveyed area was 2.8 t/ha, the mean yield, 1.5 t/ha, was only 500 kg less than the national

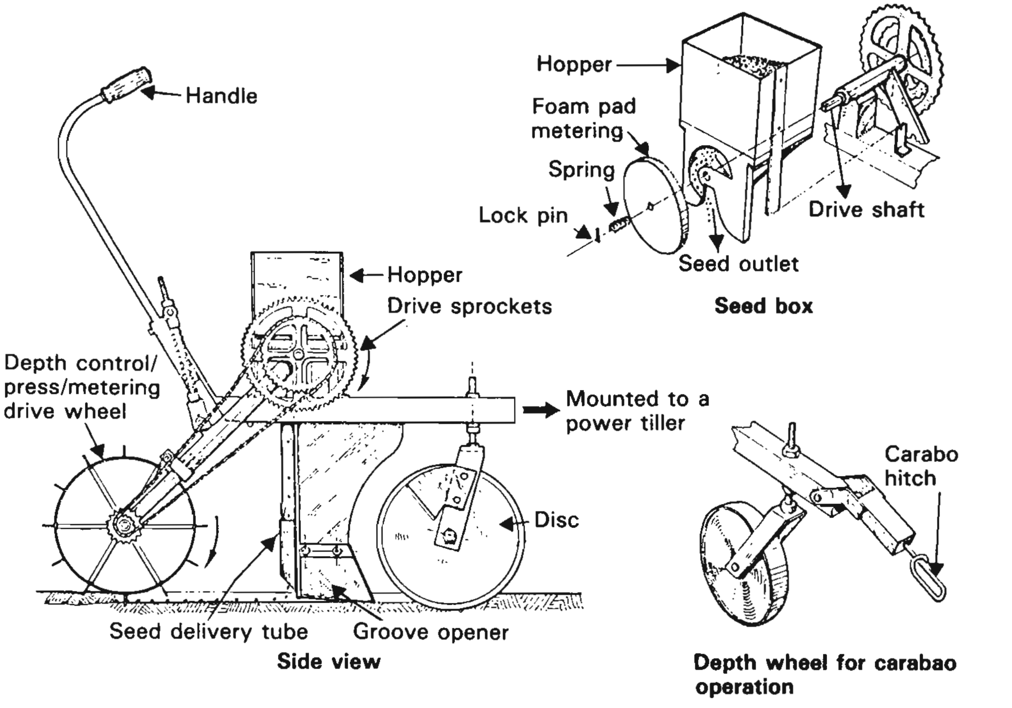

Figure 1. Side view, seed box, and depth wheel of inverted-T Multicrop seeder.

average. The hot climate in Bangladesh was a major factor in reducing yield of broadcast wheat since surface-planted wheat did not develop a good root system when temperatures were high. The technique should be evaluated in other areas.

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Macro-Element Requirements and Fertility Management Issues in Rice-Wheat Rotation Areas

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This paper is dedicated to the late Dr. Robert Glenn Anderson.

Abstract

Fertilizer (N-P-K) studies from 11 sites in northern, northeastern, and northwestern India indicate that it is essential to apply 120 kg N with 40 to 80 kg P_2O_5/ha to both rice and wheat in a rice-wheat rotation system in order to sustain or improve productivity. Preferably, P should be applied to wheat for better response and K at 40 kg K_2O/ha to rice.

In other countries of South and Southeast Asia, the rice-wheat rotation is practiced to some extent and is being intensified. There are now preliminary investigations under way on N-P-K use in the wheat crop of the rotation. In Pakistan, wheat after rice responded with up to 75 kg N/ha and with marginal response at 50 kg P_2O_5/ha. In Nepal and Bangladesh, it has been observed that planting wheat after rice depletes the soil. In Sri Lanka, wheat is competing with vegetables, and is yet to be well fitted into the rice-based system. In the Philippines and Thailand, wheat after rice responded to 80 to 120 kg N/ha with no response to applied phosphorus.

The possibility of topdressing of P within 45 days after sowing in wheat is certain in almost all categories of soils. This dispels the old belief that P could only be applied at or before sowing. The efficiency of all P together with the N topdressed just before the first irrigation or half of the total fertilizer at the first irrigation and the remaining half at the second irrigation has been found to improve yields.

This practice will help to adjust the economic balance due to the shortage of fertilizers during peak sowing times.

N-P-K Management in Rice-Wheat Rotations in India

Until the early 1960s wheat was the main crop in the northern plains of India, while rice dominated in the eastern and southern parts of the country. With the introduction of high-yielding, semidwarf varieties of wheat and rice, very significant changes in the cropping pattern of northern India have taken place. Rice has moved to the nontraditional areas of the Punjab, Haryana, Rajasthan, Delhi, and western Uttar Pradesh (Table 1), replacing maize, sorghum, and pearl millets; while wheat has moved into areas of northeastern India, such as West Bengal, Assam, Orissa, and the northeastern hill region (Table 2). In all the above areas, most of the rice acreage is rotated with wheat, except under waterlogged conditions. On well-drained upland irrigated areas of the north, northwest, and northeast parts of India, rice-wheat is now the dominant cropping system.

Wheat yields after rice are reported to be lower than after maize, ranging from a high of 7.2 t/ha after maize in Kathuliafarm, in 1970-71 to a low of 1.1 t/ha after rice in Kajat (Maharastra) in 1969-70, although wheat showed good yields (5.5 t/ha) after rice in Chaltan, 1968-69. The maize-wheat-cheena rotation gave high combined yields (15.3 and 14.7 t/ha in 1969-70 and 1970-71, respectively) at Kathulia farm (Madhya Pradesh). In Rudrur (Andhra Pradesh) the total grain yield for the rice-maize-moong rotation was 9.1 t/ha in 1969-70 and the rice-wheat-moong rotation totaled 10t/ha in 1970-71. The high yields of rice over other *kharif* (monsoon season) crops have led to the rapid expansion of rice area in the northern wheat belt and the case of wheat in the northeastern rice belt of India has been similar.

The rice-wheat sequence has been tested under continuous cropping and various combinations of fertilizer (N-P-K), under the All India Coordinated Agronomic Research Project (ICARP) for the past 15 years and in other experiments at universities and state research institutions.

Submontane areas

The results indicate that, in the submontane parts of Palampur (Uttar Pradesh) rice yields and wheat yields over the years, have been fairly static. In this area, the *kharif* crop of rice has responded up to 120 kg N/ha and 40 kg K_2O/ha, without any response to phosphorus, while the following (*rabi*, dry winter season) wheat crop has given a response up to 120 kg N, 40 kg P_2O_5, and 40 kg K_2O/ha. Yields were increased 900 kg/ha with 40 kg P_2O_5/ha and about 600 kg/ha with 40 kg K_2O/ha. At

Table 1. Area, production, and yield of rice in the traditional wheat growing states of India

Region	Area 000 ha	Production 000 t	Yield kg/ha
Punjab			
71-72	450.0	920.0	2044
84-85	1645.0	5057.0	3074
Haryana			
71-72	291.0	536.0	1842
84-85	557.0	1363.0	2447
Rajasthan			
71-72	133.4	159.4	1195
84-85	169.9	212.8	1253
Delhi			
71-72	2.6	2.4	923
84-85	3.4	6.2	1824
Uttar Pradesh			
71-72	4722.2	3776.5	800
84-85	5535.5	7178.3	1297

Bagatisheroo in the Kashmir valley, both rice and wheat responded significantly up to 120 kg N/ha and up to 80 kg P_2O_5/ha. Application of K improved yields marginally. In the Tarai soils of Pantnagar, both crops responded up to 80 kg N/ha, with marginal response to phosphorus. There was no response to applied potash.

Laterite soils
In the laterite soils of Kharagpur (Orissa), both crops responded up to 120 kg N, 80 kg P_2O_5, and 40 kg K_2O_5/ha. General yield increases of both crops were observed with fertilizer application in subsequent years, due to the previous practice of continuous cropping and manuring.

Alluvial soils
In the alluvial soils of Varanasi (Uttar Pradesh), wheat yields have improved in general over the years, while rice yields have shown a declining trend. Both crops responded up to 120 kg N and 80 kg P_2O_5/ha. There was a low response to applied K in wheat, and the rice response was not significant. In the alluvial soils of Sabour (Bihar), rice yields have been maintained without appreciable decline, although the wheat yields are low. Rice responded up to 120 kg N/ha in the presence of 40 kg P_2O_5/ha, while potash application had no positive influence on yield. The wheat crop had poor yields and the response to N-P-K fertilizers could not be properly evaluated because of poor management.

In the alluvial soils of Pura farm at Kanpur (Uttar Pradesh), there has been a decline in the grain yield of both rice and wheat in the rice-wheat rotation. Fertilizer responses in both crops were obtained up to 120 kg N and 80 kg P_2O_5/ha, with no response to K. In the alluvial soils of Masoda at Faizabad (Uttar Pradesh), wheat yields have declined slightly over the years, but the rice yields have been increasing. There was a fertilizer response up to 120 kg N and 80 kg P_2O_5/ha in both crops, but no response to K application.

Medium black soils
In the medium black soils of Rudrur (Andhra Pradesh), yields of rice and wheat have declined. Fertilizer responses up to 120 kg N and 40 kg

Table 2. Area, production, and yield of wheat in traditional rice growing states of India

Region	Area 000 ha	Production 000 t	Yield kg/ha
West Bengal			
64-65	40.8	27.8	681
78-79	521.0	998.0	1094
Assam			
71-72	40.0	48.0	1200
84-85	99.2	127.9	1290
Orissa			
71-72	20.9	38.7	1852
84-85	77.0	150.0	1950

Source: Area and production of principal crops in India, Directorate of Eco. and State, Dept. of Agriculture and Cooperation, Ministry of Agriculture, Government of India.

P_2O_5/ha for rice and up to 120 kg N and 80 kg P_2O_5/ha for wheat have been obtained. Neither crop responded to K application. In the mixed red and black soils of Kathulia farm (Madhya Pradesh), yield levels of wheat and rice have been maintained. Both crops responded up to 120 kg N and 40 P_2O_5/ha, without any significant response to K. In the medium black soils of Jabalpur (Madhya Pradesh), there has been a significant reduction in the yield of both rice and wheat. Both crops responded up to 120 kg N and 40 kg P_2O_5/ha.

Deep black soils

In the deep black soils of Navsari (Gujarat), a general reduction in the rice yield has to some extent been compensated by an improved wheat yield in the *rabi* crop. Fertilizer responses up to 120 kg N/ha and 40 kg P_2O_5 for both crops have been obtained, without any response to K (13).

Indications for fertilizer management

A general trend emerging from these studies on rice-wheat rotations in India indicates that for obtaining best results, it is essential to apply 120 kg N and 40 to 80 kg P_2O_5/ha to both crops in order to sustain or improve productivity. Potassium at 40 kg K_2O/ha should be applied to maintain the fertility balance, particularly in the rice crop. The irrigation water in the northwest alluvial plains generally contains enough potassium to recharge the potassium reserve of the soil. Data also show that to maintain wheat and rice yields there is little scope for skipping or reducing the amount of N or P applied to either the rice or wheat crops in the sequence.

Data from on-farm trials of rice-wheat rotations from seven districts (Table 3) indicate that at the recommended level of fertilizer application (120-60-60 applied to both crops), the productivity of the system ranged from 8 to 10 t/ha. With total fertilizer application at rates of 240, 300, and 360 kg/ha between the *kharif* and *rabi* seasons results indicate that at the 240 kg/ha rate (50% of the recommended amount), it would be beneficial to distribute the fertilizer equally in the two seasons. With the 360 kg/ha rate, it was found that a potassium application of 90 kg K_2O/ha to rice, a phosphorus application of 90 kg P_2O_5/ha to wheat, and 90 kg N/ha to each of the two crops increased total productivity to 7 to 8 t/ha. The productivity was almost the same if the phosphorus was applied to the rice and the potassium to the wheat (15).

Preferential application of P in the *rabi* season in the wheat belt is an established practice. At Ludhiana (Punjab), an application of 60 kg/ha P_2O_5 in the *rabi* season increased yields 1.96 t/ha more than the same amount applied in the *kharif* season (5). The same fertilizer applications during both seasons at Masoda (Uttar Pradesh) gave the *rabi* season a 0.54 t/ha yield advantage over the *kharif* season (6). Further data in Tables 5-8 clearly indicate that in the rice-wheat cropping system, it is more beneficial to apply phosphorus to wheat in the rabi season than to the *kharif* crop of rice (5, 6).

Nutrient uptake

Information on nutrient removal from rice-wheat rotations, together with information on fertilizer dose and yield from Ludhiana and New Delhi, clearly indicate that there has been depletion of soil fertility with this cropping sequence, particularly for potassium and to some extent for nitrogen (2).

Table 3. Total grain yield (t/ha) for the rice-wheat cropping system on farmers' fields, with different levels of fertilization

		Nutrient level (kg/ha)								
	N-P-K Kharif	60-0-0	60-30-30	60-0-60	60-60-0	60-30-30	90-0-90	90-90-0	90-45-45	120-60-60
	N-P-K Rabi	60-30-30	60-30-30	60-60-0	90-45-45	90-90-0	90-90-0	90-0-90	120-60-60	120-60-60
State/ district	Total N-P-K	180	240	240	300	300	360	360	420	480
						t/ha				
Uttar Pradesh/ Gorakhpur (1974-77)		6.5	6.9	6.7	7.5	7.5	7.6	7.4	8.3	8.6
Fetehpur (1974-77)		5.6	6.2	6.1	6.8	7.0	7.3	7.2	8.0	8.5
Banda (1974-77)		6.0	6.9	6.6	7.0	7.4	7.2	7.4	7.9	8.6
Faizabad (1977-79)		6.3	7.3	6.8	8.1	7.8	7.6	7.4	9.0	9.5
Jaunpur (1977-79)		5.5	6.0	5.8	6.6	6.5	6.9	7.0	7.6	8.3
Bihar/ Muzaffarpur (1977-79)		6.3	7.4	6.6	7.5	8.0	7.6	7.5	8.7	9.6
Punjab/ Gurudaspur (1977-79)		7.3	7.6	7.2	8.0	7.9	8.4	8.6	9.3	9.8

Source: Narain et al. (15)

Table 4. Response to phosphorus in rice-wheat rotations in India

Center/Soil type	Mean yield at P_0 (t/ha)		Response to P at 40 kg P_2O_5/ha (t/ha)	
	Kharif	Rabi	Kharif	Rabi
Palampur (Grey brown podsolic)	4.17	1.86	0.22	1.33
Purafarm (Alluvial)	3.20	2.12	0.37	0.57
Raipur (fine loamy)	3.73	1.35	0.43	0.33
Rewa (fine loamy)	3.71	2.16	0.21	0.82

Source: Project Bulletin No. 2 AICARP 1985

Table 5. Effect of missing an application of phosphorus on crop yields (t/ha) in rice-wheat rotations

Treatment		Wheat 1976-77	Rice 1977	Total of cropping system
Wheat	Rice			
N100 P50	N100 P50	4.57	8.11	12.68
N100	N100 P50	4.56	8.06	12.62
N100 P50	N100	4.88 (+.32)	7.98	12.86

Source: Meelu and Rekhi (14)

Table 6. Effect of phosphorus application to rice in different cropping systems at Punjab Agricultural University farm, Ludhiana

Cropping system	Rice grain yield (t/ha)		
	P0	P30	P60
Wheat-rice	7.24	6.91	7.31
Wheat-maize fodder-rice	7.05	7.35	7.28
Berseam-rice	5.75	5.32	5.37
Wheat-moong-rice	6.68	6.69	5.37

Application: 60 kg P_2O_5/ha to wheat and 75 kg P_2O_5/ha to Berseam.

Source: Meelu and Rekhi (14)

Fertilizer economy through manuring

Green manuring significantly increased rice yields and also had a significant carry-over effect on the succeeding wheat crop (Table 7) (24). The soils of Punjab Agricultural University, Ludhiana, are low in available N, P, and organic matter. Green manuring alone during the past 3 years increased rice yields more than the application of 60 kg N/ha. Furthermore, the combined use of green manuring and 60 kg N/ha produced rice yields equal to those obtained with 100 kg N/ha (14). The combined use of 80 kg N/ha and 12 t farmyard manure/ha gave rice comparable to those obtained with 120 kg N/ha (Table 8). Farmyard manure also gave a residual effect equivalent to 30 kg N and 30 kg P_2O_5/ha in terms of chemical fertilizer in the yield of the succeeding wheat crop (Figure 1).

Fertility Management in Other Countries

Rice is grown in Asia in temperate, subtropical, and tropical countries with the major share in India and China. It is grown under rainfed as well as irrigated conditions. Wheat is mainly cultivated in the subtropical and temperate countries with irrigation, and in lowland rainfed areas with soils of good moisture-holding capacity.

Table 7. Nitrogen economy in rice-wheat cropping system with green manuring

Applied N (kg/ha)	Rice (t/ha)		Residual effect on wheat (t/ha)	
	Fallow	Green manure	Fallow	Green manure
0	2.37	3.85	1.67	2.37
40	4.04	4.91	1.71	2.78
80	4.63	5.27	1.88	3.18
120	4.98	5.37	2.27	3.35
Mean	4.01	4.85	1.88	2.90

Source: Meelu and Rekhi (14)

Table 8. Effect on farmyard manure on N economy in rice at Punjab Agricultural University farm, Ludhiana

Manure (t//ha)	Nitrogen (kg/ha)	1977	1978	1979	Average
			Yields (t/ha)		
0	0	2.96	3.06	3.43	3.15
12	0	3.38	3.96	4.23	3.85
12	40	5.08	5.32	5.08	5.16
12	80	6.39	7.43	6.41	6.74
0	120	6.70	7.03	6.13	6.62

Source: Meelu and Rekhi (14)

Rice-wheat rotations became common even in nontraditional temperate and subtropical areas with the advent of high-yielding rice and wheat varieties relatively well adapted to the local conditions and responsive to higher inputs. The spread was also partly due to the development of an agronomic package for the individual rice and wheat crops and the expansion of irrigation systems over the last 15 years.

Rice-wheat rotations are mainly practiced in India (as described earlier) and Pakistan, and recently in Nepal, Bhutan, and Bangladesh.

In tropical countries where wheat is not a commercial crop, attention is now being given to producing wheat because of the heavy costs of importing it for local consumption (Table 9). Research to develop wheat production technology is now in progress in Indonesia, Thailand, the Philippines, Burma, Vietnam, Malaysia, and Sri Lanka, countries that have become surplus producers of rice. The objective is to diversify with wheat because it is relatively drought tolerant and a potential alternative crop for cultivation in the cool and dry season after rice.

However, some very critical problems have started to appear in the areas where this continuous cropping system is being adopted. The foremost among them is soil fertility management, which affects production to a great extent.

Information on the use of N-P-K in rice-wheat rotations is meager, as research is only in the preliminary stages in these South and Southeast Asian countries. A brief review in this direction is presented here.

Table 9. Size and value of wheat imports by Southeast Asian countries

Country	Wheat Imports in 1983 (1000 t)	Value[a] (000's $US)
Hong Kong	189	34,020
Indonesia	1,757	316,260
Malaysia	538	96,840
Philippines	811	145,980
Singapore	149	26,820
Thailand	203	36,540
Vietnam	228	41,040
Burma	7	1,260
Sri Lanka	598	107,640
Regional total	4,480	806,400

[a] at US$180/t

Pakistan

The main rice-wheat area of Pakistan lies in Punjab and Sind provinces, and covers approximately 1.5 million ha.

The most commonly practiced fertilizer application to wheat after rice has been 1 bag/acre of diammonium phosphate (DAP) at planting time followed by 1 bag/acre of urea at the first irrigation (i.e., 80-57-0 kg/ha N-P-K). About half of the farmers follow this practice, which is close to the recommendation of 1.25 bags/acre each of DAP and urea, although significantly less than that applied by the extension service in its demonstrations, i.e., 2 bags of urea and one bag of DAP. Evidence suggests that N application at 75 kg/ha gives highest returns. Phosphorus at 50 kg P_2O_5/ha gave a positive, but substantially lower return (Figure 2). Some farmers applied ammonium sulfate instead of urea and reported positive results. This is possible as most of the soils are alkaline and the use of ammonium sulfate would help lower the pH. A few farmers also applied potash, but without definite results.

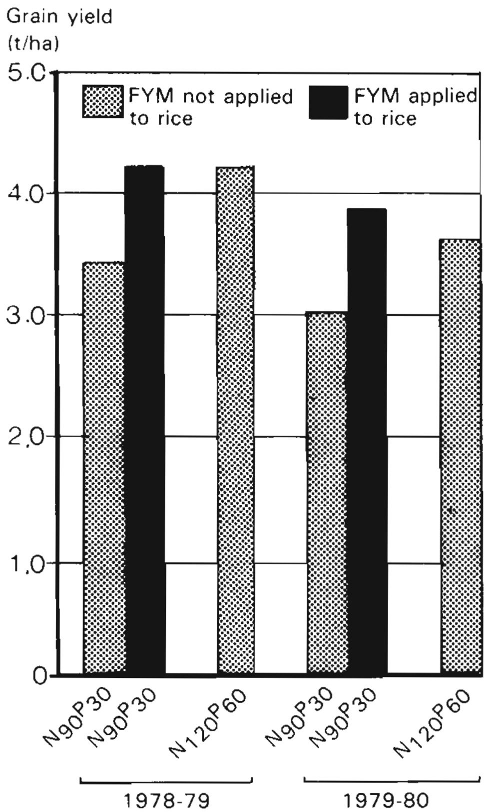

Figure 1. Residual effect of farmyard manure (FYM) on suceeding wheat yield.

Source: Meelu and Rekhi (14)

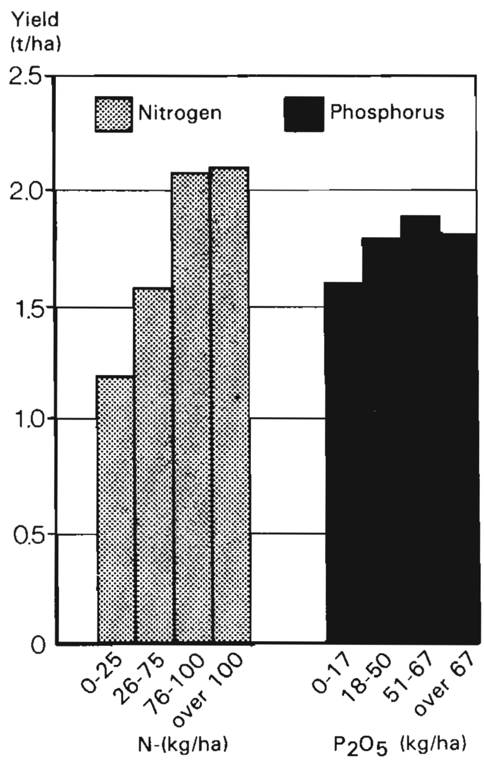

Figure 2. Average wheat yields at different levels of fertilizer in Pakistan.

Source: Byerlee et al. (3)

Comparatively more N is applied to wheat after rice than after other crops or after fallow. This is probably to compensate for late sowing of wheat after rice and poor seedbed preparation, as well as lower available nitrogen following rice. Farmyard manure was applied to wheat at only 4 t/ha. It is a traditionally known source of nutrients, but the high cost of application has reduced its use (3).

Nepal

Rice-wheat rotations are practiced on approximately 480,000 ha in Nepal. There is potential for doubling the area in the Tarai region. Wheat is rotated with rice in both the irrigated and rainfed areas. The yield and economic returns of different cropping patterns tested in Ratna Nagar and in Bahuwari with tubewell clearly indicated that wheat has good potential in Nepal (Table

Table 10. Yield and economic returns of different cropping patterns tested in Nepal, 1982-83

Cropping Pattern	Yield (t/ha) Crop 1	Crop 2	Crop 3	Net return $
Ratna Nagar				
Irrigated, lowland				
(F) Rice (Masuli) - Wheat (RR 21) - Fallow	3.18	2.10	-	232
(FA) Rice (Laxmi) - Wheat (Lumbini) - Mungbean (Pusa Baisakhi)	5.19	4.01	0.54	860
Rice (Bindeshwari) - Wheat (Lumbini) - Maize (Arun)	4.27	3.80	2.48	951
Rice (Malika) - Mustard (Local) - Maize (Rampur Comp)	3.78	0.53	3.64	580
Rice (Janaki) - Wheat (UP 262) - Dhaincha (Local)	4.25	3.48	-	562
Rice (Janaki) - Wheat (UP 262) - Fallow	3.19	3.48	-	523
Rainfed, lowland				
Rice (Janaki) - Wheat (UP 262) - Fallow	4.25	2.28	-	400
Bahuwari with tubewell				
(F) Rice (Masuli) - Wheat (Improved) - Rice (Local and Improved)	1.79	3.04	4.20	1079
Rice (Malika) - Wheat (UP 262) - Mungbean (PS-7)	3.55	3.15	0.89	879
Rice (Janaki) - Wheat (Lumbini) - Dhaincha (Local)	4.93	3.22	-	971
Rice (Janaki) - Wheat (Lumbini) - Fallow	4.08	3.22	-	894
Rice (Masuli) - Wheat (Lumbini) - Rice (Malika)	1.76	2.94	4.86	1096

F - farmers' practice
FA - alternative cropping pattern

Source: Cropping Systems Staff, 1984

10). While some attempts are being made to work out the N-P-K requirement in rice-wheat rotations and their effects on soil fertility, precise information is yet to be gathered.

Bangladesh
Wheat is a new crop in Bangladesh. However, in the 1970s a tenfold increase in wheat production was achieved. Approximately 500,000 ha are now under a rice-wheat cropping system. Wheat is generally grown after transplanted Aman rice in rainfed and irrigated areas. The most common cropping patterns involving wheat are rice-wheat and rice-rice-wheat. A belief shared by many farmers is that wheat reduces the yield of the following rice crop. This problem is being studied in a series of fertility experiments (N-P-K applications to both wheat and rice), conducted in 10 locations on farmers' fields. It is assumed that the nutrient uptake of the wheat crop resulted in lower yields of the succeeding rice crop because of insufficient application of nutrients to wheat.

Sri Lanka
Wheat is a new introduction and still has not been commercially grown in Sri Lanka. However, there is potential to grow wheat after rice, especially in the high-elevation areas. The wheat has to compete with other cash crops and present yields are quite low at 1.07 t/ha (21). The dominant cropping patterns are rice-potato and rice-vegetables. With the new varieties, a three-crop system has been established. The first crop is rice seeded in February; the second crop is potato or any other vegetable seeded in June, and the third crop seeded in November can be wheat or soybean or any vegetable of the season. However, little work has been done on fertility management with this cropping system.

Philippines
The Philippines imported 811,000 tons of wheat valued at US$145,980,000 in 1983. This expenditure is a heavy drain on foreign reserves and a big burden to a developing economy. Many believe that local wheat production has a potential role in Philippine agriculture. Specific areas of production, as well as their cultural management requirements, are being investigated.

Agronomic adaptation studies conducted at the International Rice Research Institute (IRRI) from 1981-1984 demonstrated that wheat could be grown after rice, yielding moderate levels of 1.5 to 2.0 t/ha. The use of 80 kg N/ha appeared to be optimum (Table 11). All N could be applied at planting (11) when the crop is grown either under rainfed or irrigated conditions (Table 12). For some reason, the wheat did not respond to phosphorus application. In another study at Cagayan, the grain yield and total matter production increased linearly up to 120 kg N/ha (12), with maximum values of 2.6 and 7.1 t/ha, respectively.

Table 11. Grain yield of wheat as influenced by fertilizer application, IRRI, 1982 dry season

N-P_2O_5 (kg/ha) Treatments	Grain yield (t/ha)
0-0	0.981
40-0	1.264
80-0	2.090
120-0	2.024
40-30	1.711
40-60	1.747
80-30	2.026
80-60	2.014
120-30	2.080
120-60	1.963

Thailand
Rice-wheat cropping systems are possible in northern Thailand, where wheat appears to have some potential. There are about 500,000 ha of irrigated rice land where rains end quite suddenly in October, so that any dry season cropping after rice must rely on irrigation or utilization of stored soil moisture. The period from November to February has sufficiently low temperatures for a temperate crop such as wheat to be grown. Experimental yields of 3.6 t/ha have been achieved, while highest yields, on the order of 5 t/ha, have been reported recently. The rice-wheat rotation offers an improvement in land- and water-use efficiency with the shorter growing season and better adaptation of wheat to cool weather. However, there are general agronomic considerations that may have implications with the large-scale adoption of the rice-wheat system in northern Thailand. Soil fertility and nutrient management may become one of the serious limitations.

Table 12. Grain yield of wheat as affected by rate and time of nitrogen application, Dec. 1982-Apr. 1983

N (kg/ha)	Time of application	Yield (t/ha) Irrigated	Yield (t/ha) Rainfed
0	Control	0.952	0.690
40	FO	2.065	1.987
	SP	1.910	1.877
80	FO	1.670	1.677
	SP	1.690	2.042
	PI	1.905	1.572
120	FO	1.615	1.985
	SP	1.525	1.977
	CV%	11.1	13.5

FO = all at planting (basal), PI = all at panicle initiation, and SP = split (½ as basal, ½ at PI).

Yield response to N has been obtained up to 40 kg N/ha in rainfed upland (16) and lowland conditions and up to 80 to 120 kg N/ha with irrigation. Split application of N has not demonstrated any clear yield advantage over a single basal application. Although P levels measured in these soils are low, virtually no response to applied phosphorus has been obtained, even at rates up to 300 kg P_2O_5/ha. Applications of K have also given no response. However, even with the generally low yields of wheat that have been achieved, this region of northern Thailand is a potentially productive area and deserves further experimentation (23).

Prospects of N and P Topdressing in Wheat

The author first conducted field studies on the prospects of topdressing fertilizer in wheat for 4 years (1973-77) with N only. Later, in a second study, emphasis was given to both N and P for 3 consecutive years (1977-80), and to further investigations in a third study (1980-1983). This research was conducted on a sandy loam soil of low N and P content at IARI, New Delhi, to assess the efficiency of late application of N in general and P in particular, for which placement at sowing had been the only recommended practice.

Nitrogen: time and method of application
Results of the first 4 years of the study indicate a linear increase of wheat yields and corresponding N uptake (Table 13) as applied N increases to 120 kg N/ha. This was

due to the increased plant vigor (height) and more tillers and final earheads per m^2, coupled with more grains per head.

In general, the results suggest that the N applied at sowing (basal) was somewhat less efficient for grain production and for N recovery through grain yield. The efficiency was higher when all N was applied by topdressing at first irrigation (21 DAS), or in two splits, half at first irrigation plus half at tillering (or second irrigation, 45 DAS), or in three splits, i.e., half at first irrigation, one quarter at tillering, and one quarter at jointing (65 DAS). The N efficiency was slightly reduced (but was still better than all applied at sowing), when all N was topdressed at the second irrigation (tillering). When all N was applied at the boot stage an acute reduction in efficiency was obtained, resulting in 2/3 the grain yield and one-half the N uptake of the best treatments.

Similar results occurred in another study when the highest yield was obtained when N was applied half at sowing and half at first irrigation or all at first irrigation. Hamid (7) reported the highest grain yield when 20 kg N/ha was applied at sowing, 50 kg/ha at tillering, and 50 kg/ha at boot stage. Ayoub (1) reported highly increased uptake when the N was applied at tillering or at the jointing stage. Soper (22) reported that split N application is better and that all N applied at tillering showed greater efficiency for increasing grain yield and N uptake, based on results of experiments from 15 countries in Africa, Asia, Europe, and South America.

Nitrogen and phosphorus: time and method of application

In the second study, the application of N significantly increased dry matter accumulation in all plant parts. The increase in dry matter was greatest in grain, followed by chaff, stem, and leaves. In general, total dry matter accumulation was slightly more when the fertilizer was applied at first irrigation compared to all fertilizer applied at sowing or at second irrigation (Table 14). The placement of fertilizer at sowing proved slightly superior to broadcast in respect to grain yield and dry matter in the leaf.

The increase in N uptake due to 30 kg P_2O_5/ha was significant in grain, leaf, and chaff and with 60 kg P_2O_5/ha the increase was significant in the grain only. Phosphorus uptake was also found significantly increased in all plant parts with addition of 30 kg P_2O_5, while with 60 kg P_2O_5/ha, P uptake increased significantly in the grain and leaf only. Topdressing of N and P fertilizer at first irrigation increased the N and P uptake significantly in almost all plant parts over that of basal or later applications (20). This treatment was very similar to the results obtained from half basal and half topdressed at first irrigation. The above results have been confirmed by the N (Figure 3) and phosphorus (Figure 4) uptake patterns obtained at critical physiological stages of the wheat plant. Findings also indicate that a major portion of the P was assimilated after tillering and this benefited grain and straw yield (9).

Table 13. Grain yield of wheat and N uptake as affected by application of N at different times and methods

N Levels (kg/ha)	Grain yield (t/ha)					Nitrogen uptake (kg/ha)				
	1973-74	74-75	75-76	76-77	Mean	1973-74	74-75	75-76	76-77	Mean
0	3.3	1.7	2.0	1.6	2.2	37.4	15.2	32.7	19.0	26.1
80	5.3	4.8	5.1	4.7	5.0	73.4	72.8	85.3	72.7	176.1
120	5.8	5.8	5.7	5.3	5.6	102.8	108.8	108.8	94.9	103.6
LSD for treatments (5%)	0.2	0.1	0.1	0.1	-	5.88	5.38	5.75	17.23	-
LSD for content vs treatments (5%)	0.4	0.3	0.3	0.1	-	16.10	15.69	17.74	36.09	-
Time and method of N application										
1. All placed at sowing	-	5.0	5.0	5.0	5.0	-	76.3	87.0	78.1	80.5
2. ½ placed at sowing ½ topdress 1st irrigation	5.5	5.2	5.4	5.2	5.3	96.9	88.3	91.5	84.5	90.3
3. All topdress 1st irrigation	5.7	5.4	5.8	5.5	5.6	101.5	93.1	102.9	89.4	96.7
4. ½ topdress 1st irrigation ½ topdress at tillering	5.8	5.4	5.8	5.5	5.6	104.2	88.1	105.9	87.4	96.4
5. All topdress at tillering	5.4	5.3	5.6	5.2	5.4	88.3	85.7	97.9	83.7	98.9
6. ½ topdress 1st irrigation + ¼ topdress at tillering + ¼ topdress at jointing	5.6	5.0	5.7	5.5	5.5	102.6	100.2	112.8	102.4	104.5
7. ½ topdress at 1st irrigation + ½ at late tillering	5.2	5.0	5.6	5.3	5.3	103.1	92.9	92.8	87.9	94.2
8. ½ topdress 1st irrigation + ½ topdress in soil at spray time	5.6	5.2	5.9	5.3	5.5	108.6	101.4	113.7	102.1	106.5
9. All topdress at Boot stage	-	-	3.9	2.4	3.1	-	-	83.2	38.0	50.6
LSD (5%)	NS	0.3	0.2	0.2	-	10.9	10.8	12.2	28.5	-

Source: Singh et al. (20)

Table 14. Dry matter accumulation and nitrogen and phosphorus uptake in different plant parts of wheat (at harvest) as affected by time and method of N and P application (average for 1977-78, 1978-79, and 1979-80 seasons)

	Dry matter accumulation (t/ha)					Nitrogen uptake (kg/ha)					Phosphorus uptake (kg/ha)				
Treatment	leaf	stem	chaff	grain	total	leaf	stem	chaff	grain	total	leaf	stem	chaff	grain	total
Fertilizer (kg/ha)															
N P_2O_5															
0 0	0.8	1.3	1.0	2.0	5.0	5.7	4.9	7.3	31.8	49.6	0.4	0.7	0.7	5.7	7.3
120 0	1.6	2.6	2.3	5.3	11.8	14.3	12.1	25.5	94.7	146.6	1.2	1.5	1.7	20.0	24.3
120 30	1.8	2.8	2.8	5.8	13.3	16.1	14.2	28.4	107.3	166.1	1.4	2.3	2.9	22.9	28.3
120 60	1.8	3.0	2.8	6.1	13.8	16.8	15.4	28.2	113.4	173.7	1.6	2.2	2.9	25.0	30.8
(LSD) at 5% for															
(i) treatments	0.6	0.2	0.2	0.3	-	0.8	1.2	3.7	7.6	13.3	0.1	0.1	0.7	1.7	-
(ii) Content vs treatments	2.5	0.2	0.2	0.6	-	1.5	1.7	3.7	11.3	18.3	0.2	0.2	0.2	2.9	-
Time and method of application															
1. Placed at sowing	1.8	2.8	2.7	5.7	13.0	15.0	14.0	26.1	97.9	153.0	1.4	1.7	1.8	20.9	25.8
2. Broadcast at sowing	0.6	2.8	2.8	5.6	12.8	15.1	13.0	26.8	94.3	149.3	1.2	1.7	1.7	19.5	24.1
3. Topdressed at 1st irrigation	1.8	2.9	3.0	6.2	13.9	16.8	14.9	29.4	113.3	174.4	1.5	2.2	2.0	25.2	30.9
4. Placed at 1st irrigation	1.8	2.8	2.7	6.0	13.4	16.1	13.9	26.6	100.9	165.5	1.4	1.8	2.0	23.8	29.1
5. Topdressed at 2nd irrigation	1.7	2.7	2.7	5.3	12.4	16.0	13.9	27.5	105.6	163.0	1.4	1.9	1.8	23.6	28.8
6. Placed at sowing (½ N & ½ P) and (½ N & ½ P) topdressed at 1st irrigation	1.7	2.9	2.8	6.0	13.4	15.5	13.8	28.1	110.6	168.1	1.4	1.9	2.0	22.5	27.7

Source: Singh et al. (20)

Nitrogen and phosphorus uptake and grain yield
Nitrogen application significantly increased wheat grain yield and N and P uptake during all the three years of the second study (Table 15). There were further increases in yield due to the application of P. As P dosage increased to 60 kg P_2O_5/ha, the grain yield increased significantly during first the 2 years and P uptake during the third year. When N and P were topdressed at the first irrigation compared with all fertilizer applied at sowing, grain yield increased about 10%, N uptake 15%, and P uptake about 23% . However, the values obtained with the fertilizer topdressed at first irrigation were almost equal to those when the fertilizer was applied half at sowing and half topdressed at the first irrigation. Topdressing fertilizer at tillering (45 DAS) produced the same yields as that of the basal application at sowing, but resulted in increased N and P uptake (20). Broadcasting fertilizer at sowing proved inferior in all respects. Hamid

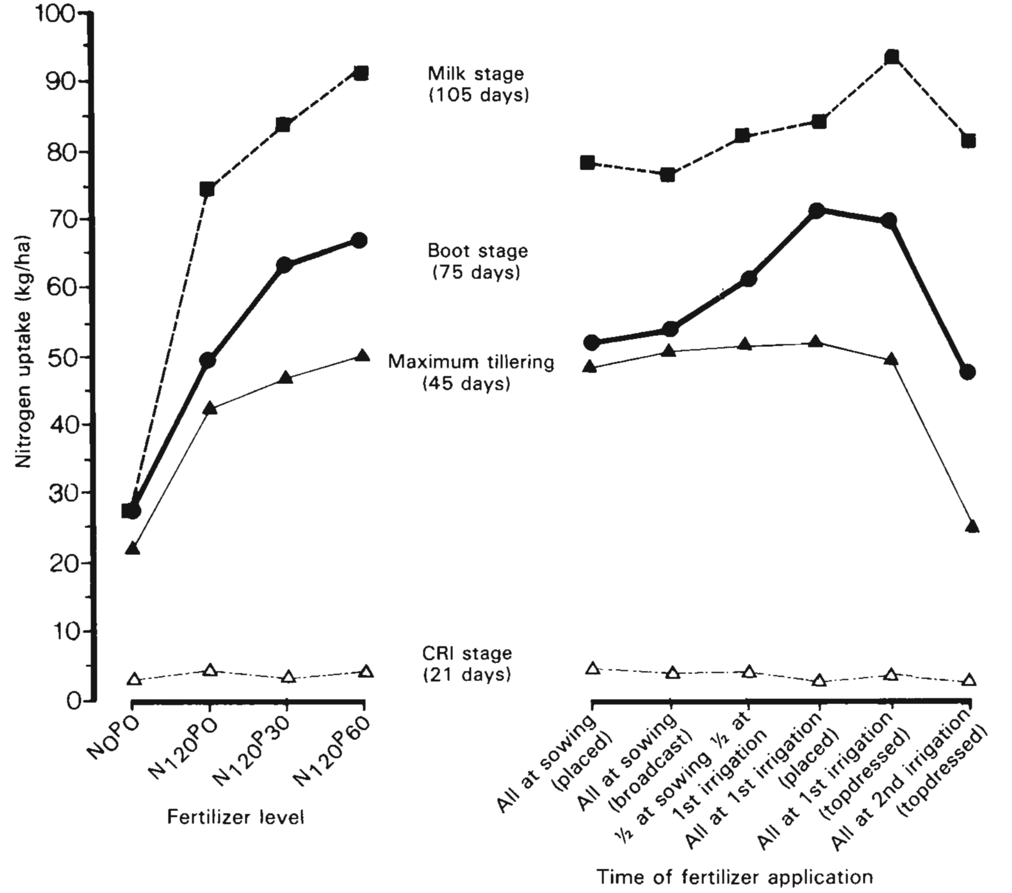

Figure 3. Nitrogen uptake (kg/ha) in the wheat plant at different stages of plant growth as influenced by levels and time of fertilizer application (Average of 3 years data 1977-80).

and Sarwar (8), using 32p labelled superphosphate, reported that P applied at tillering was most efficient for grain and straw yields and its utilization was significantly higher than the P applied at sowing.

Nitrogen and phosphorus in single and split application

Results from the third study indicated that applied N (120 kg/ha) contributes about 52% of yield, P (60 kg P_2O_5/ha) 15-23%, and soil nutrients about 25%. With single N-P (120:60) applications, the highest yield was obtained with topdressing at first irrigation followed by topdressing at second irrigation (45 DAS). With split applications, best results were obtained when half the N-P was topdressed at first irrigation and half at second irrigation.

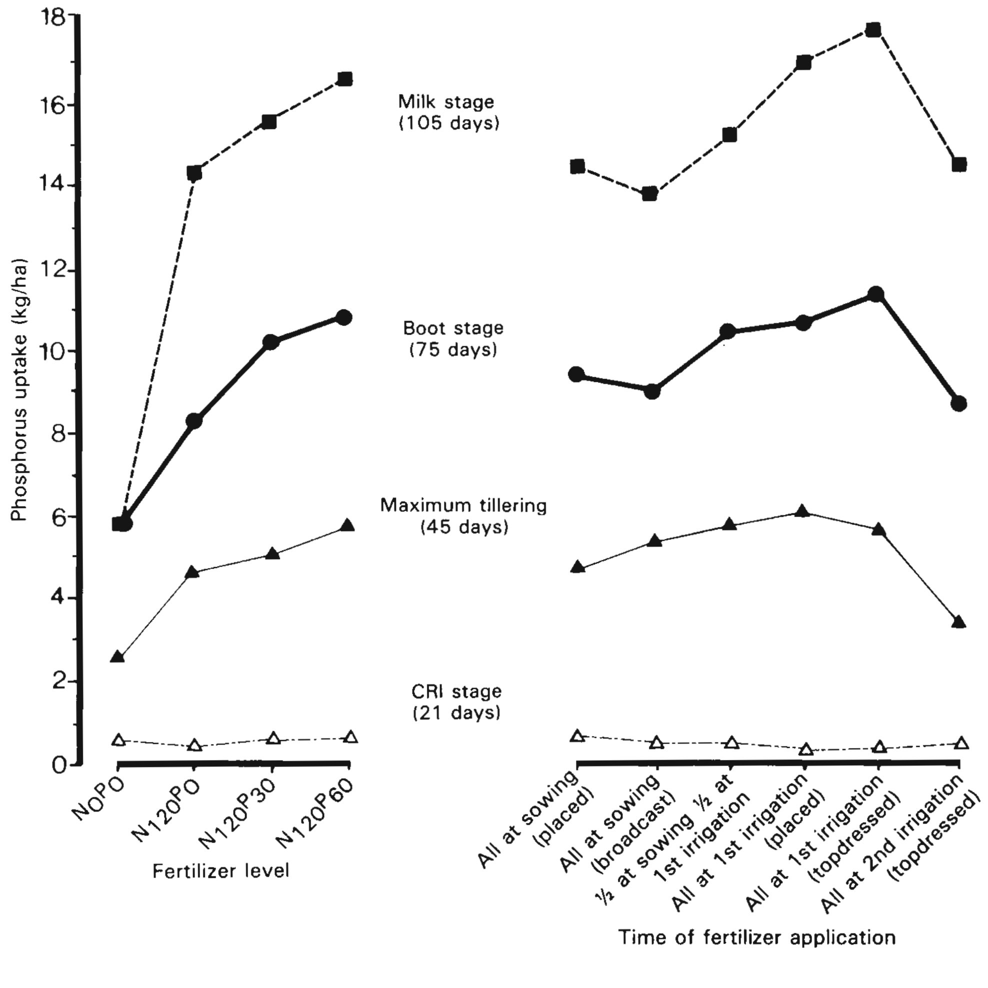

Figure 4. Phosphorus uptake by the wheat plant at different fertilizer levels and times of application (Average of 3 years data (1977-80).

Table 15. Nitrogen and phosphorus uptake and grain yield of wheat as influenced by time and method of N and P application

Treatment	Grain yield (t/ha)				Nitrogen uptake (kg/ha)				Phosphorus uptake (kg/ha)			
	1977-78	78-79	79-80	Mean	77-78	78-79	79-80	Mean	77-78	78-79	79-80	Mean
Fertilizer (kg/ha)												
N P_2O_5												
0 0	2.9	1.7	1.8	2.2	43.3	25.1	26.9	31.8	9.6	3.9	3.8	5.8
120 0	5.7	4.6	4.5	4.9	105.0	84.7	94.8	94.7	23.5	19.6	17.0	20.0
120 30	6.3	5.0	5.1	5.4	116.3	95.7	106.0	106.0	26.0	22.6	19.9	22.8
120 60	6.8	5.4	5.5	5.9	125.5	106.4	109.3	113.4	27.8	24.4	23.0	25.1
LSD treatment for 5%	0.2	0.2	0.1	-	8.9	3.8	10.1	-	1.7	2.4	1.1	-
LSD at content vs treatments 5%	0.4	0.4	0.2	-	15.9	4.9	13.0	-	4.3	3.6	1.4	-
Time and method of application												
Placed at sowing	6.0	4.9	5.0	5.3	99.8	93.5	101.3	99.2	23.0	21.1	18.7	20.9
Broadcast at sowing	6.1	4.4	4.7	5.0	105.3	81.9	96.3	94.3	23.7	18.7	16.2	19.5
Topdressed at 1st irrigation	6.5	5.2	5.5	5.8	126.1	106.1	107.7	113.3	27.6	23.7	34.3	28.5
Placed at 1st irrigation	6.5	5.3	5.2	5.6	122.2	103.2	101.3	108.9	28.1	21.3	22.0	23.8
Topdressed at 2nd irrigation	6.1	4.9	4.5	5.1	115.8	90.0	111.4	105.7	24.9	25.9	20.0	23.6
Placed at sowing (½ N + ½ P) + topdressed at 1st irrigation (½ N + ½ P)	6.4	5.2	5.2	5.6	122.2	99.5	109.6	110.4	27.3	21.7	18.5	?
LSD at 5%	0.3	0.2	0.2	-	12.6	5.4	-	-	2.4	3.3	1.5	?

Source: Singh et al. (20)

Based on 4 years of on-farm trials (1981-85) under the All India Coordinated Wheat Improvement Project (Wheat Project Directorate), a recommendation was identified in 1985 that clearly advocated topdressing all P together with half or all N just prior to the first irrigation or topdressing of all fertilizer, half at first irrigation plus half at the second irrigation. This recommendation has merit under conditions of delayed availability of fertilizers (19), which is frequently the case in India.

Movement of phosphorus in the soil

With water soluble P, there seems to be no problem with P movement, particularly in sandy loam soils. The data in Table 16 demonstrate that at 65 DAS the P was quite evenly distributed in three different soil layers, 0-15, 15-30, and 30-45 cm. There seems to be little difference in distribution of applied P in the soil up to a 45 cm depth. The distribution was better when the P was topdressed just before the first or second irrigation rather than at sowing. A possible explanation is that with irrigation water, the superphosphates and urea N go into solution and form ammonium phosphate, which is reported to be more soluble and mobile than P alone. Since water serves as the carrier, it facilitates the downward movement of both N and P. Recently, movement of applied P has been observed to a depth of 48 cm in a sandy loam soil and to a depth of 24 cm in a clay loam soil within 15 days of its application with an irrigation of 10 cm of water.

Future Research

Rice stubble creates a problem of high C:N ratio, but the more serious fertility problems in a rice-wheat system are nutrient immobilization, exhaustion, and leaching. The utilization of green manuring, farmyard manure, and bio-fertilizers in the rice crop, the balanced use of N-P-K in both the crops with split applications, including a small dose of N at the time of seedbed preparation after rice, will improve soil fertility and fertilizer use efficiency. These practices may help to minimize the chances of fixation and leaching of nutrients, particularly in rice crops. Further investigations in soil and fertility management in rice-wheat systems are urgently needed.

Table 16. Phosphorus availability (movement) in soil at 65 days after sowing (flowering stage), average of 3 years data, 1980-83

	Treatments		Phosphorus (ppm) in soil (cm) layers		
Placed at sowing	Topdressed at 1st irrigation	Topdressed at 2nd irrigation	0-15	16-30	31-45
1. P60 + N60	N60	–	33	15	22
2. P30 + N60	P30 + N60	–	24	41	24
3. N60	P60 + N60	–	31	34	42
4. –	P60 + N120	–	34	34	23
5. –	P30 + N60	P30 + N60	32	36	32
6. –	P30 + N60	P60 + N120	32	24	33
7. N0P0 (Control)	–	–	8	8	4

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Deficiencies of Micronutrients and Sulfur in Wheat

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Abstract

The paper summarizes the role of micronutrients and sulfur in plant growth, and their contents in soils and plants. A brief account of sensitivity of wheat and its genotypes to micronutrient stresses has been presented. The effects of sulfur deficiency on wheat quality are discussed. On the basis of soil tests, plant analysis, and response of wheat to micro- and secondary nutrients, probable areas of their deficiencies and toxicities are identified. Options for overcoming the deficiencies are outlined.

The essential elements for plant growth are usually grouped into macronutrients or micronutrients on the basis of the relative amounts of each required for normal plant growth. Crop nutrition has generally focused on the "primary" macronutrients, nitrogen (N), phosphorus (P), and potassium (K). Historically, much less attention has been given to the "secondary" macronutrients, calcium (Ca), magnesium (Mg), and sulfur (S), principally because soils were generally well supplied with these nutrients, or they were applied incidentally as accessory elementals in N, P, and K fertilizers so that deficiencies were masked. However, with the widespread use of high-analysis fertilizers, this situation is changing, particularly in the case of sulfur, which has been called "the fourth major nutrient"; its requirement by crops is comparable to that of P.

In comparison to macronutrients, the micronutrients-boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn) — are present in and needed by plants in relatively small amounts. For example, a 10-t crop of wheat (5 t of grain plus 5 t of straw) may contain around 125 kg of macronutrient N and only about 250 g of micronutrient Zn. This represents a difference of 500 times. Although the quantity of micronutrients found in crop plants is small, all these nutrients have to be present in sufficient quantities for optimum plant growth and maximum yield. A deficiency of any one of these will obstruct normal yields and a severe deficiency could result in complete crop failure. Chlorine as a micronutrient is rarely deficient and is largely of academic interest, while its toxic effects are considered a salt effect.

Interest in micronutrient and secondary nutrient research in developing countries of the tropics increased in the mid-1960s. During that time, modern varieties of wheat were developed and introduced, and researchers realized that treatment with these nutrients was necessary for the new varieties to achieve their potential yields. Although deficiencies must have existed earlier than that, the adverse effects on yields were not felt because of the inherently low yields of the indigenous cultivars.

At the same time that higher yielding varieties put increased demands on the soil for the supply of nutrients, fertilizer production shifted from the use of low-analysis materials such as single superphosphate and ammonium sulfate to high-analysis products such as urea, triple superphosphate, and ammonium phosphates. Since sulfur was no longer being applied incidentally in the low-analysis materials, S deficiencies in numerous crops, including wheat, have become increasingly widespread.

Throughout this paper we provide information on the general role of micronutrients and sulfur in crop plants, the sensitivity of wheat to nutrient stresses, and diagnostic techniques to identify the deficiencies. On the basis of diagnostic criteria of soil and plant analysis and actual field response data, we have attempted to delineate tropical wheat-growing regions with probable micronutrient deficiencies. We have highlighted soil, crop management, and environmental variables that lead to a deficiency. We have also discussed the options for amelioration if a micronutrient or sulfur deficiency is encountered. Because micronutrient toxicities are rare, we have discussed them briefly.

Micronutrients

Role of micronutrients

Micronutrients are indispensable for innumerable enzymatic reactions because 1) they form stable complexes with naturally occurring ligands and 2) biological activity occurs only with the complexed ligands (58). Examples of these micronutrient-enzymatic associations in plants include: Zn in carbonic anhydrases and dehydrogenases, Fe in catalases, peroxidases and several cytochromes, Mn in pyruvate carboxylase, Cu in cytochrome oxidase and ascorbic acid oxidase, and Mo in nitrate reductase and nitrogenase. Severe alterations in specific enzyme activity are noticeable when micronutrient deficiencies occur. This leads to qualitative changes in plant constituents produced during biochemical processes. With this the cell integrity is affected, and certain plant parts even die. Enzymatic activity has been used as a tool for early diagnosis of micronutrient imbalances and sublethal effects (16, 80). Similarly, the fall or rise in absorption of other nutrients due to a micronutrient deficiency has led to the use of certain nutrient ratios to diagnose a deficiency (36). Wide-scale use of Fe:Mn ratio to asses an Fe deficiency is a notable example.

Sensitivity of wheat to micronutrient stresses

Crop plants are known to differ in their ability to absorb nutrients from the soil. As a result, crops show differential response to varying levels of micronutrient availability in soils (Table 1). According to Brown and Jones (10), plant response to a micronutrient stress is a genetically controlled adaptive mechanism. Possible mechanisms (30) are 1) the ability of a species to absorb micronutrients at suboptimum concentrations, 2) the ability of roots to exude certain substances that enhance availability and favor absorption, 3) the ability to retranslocate absorbed nutrients within the plant, and 4) the low nutrient requirements of a species, i.e., ability of a species to grow well at low tissue concentrations.

Response of wheat, maize, and rice to a micronutrient stress is given in Table 1. High response of a crop to a micronutrient deficiency means it has high sensitivity to a deficiency and vice versa. Compared with rice and maize, wheat appears relatively less responsive to a deficiency of Zn and Fe and more responsive to Mn and Cu. All three crops seem to exhibit low sensitivity to deficiencies of Mo and B.

In simple fertilizer experiments involving N-P-K with and without Zn, conducted on farmers' fields in India and judged by the proportion of those in a high-response category, it was evident that wheat (53%) was affected by a Zn deficiency less frequently than were maize (73%) and rice (65%) (Table 2). This lower vulnerability of wheat to a Zn deficiency has been established in several other independent studies. Tiwari and Pathak (79) found that, contrary to lowland rice, wheat did not benefit from Zn application on an alluvial soil testing 0.8 ppm DTPA-Zn (DTPA-Zn refers to plant-available Zn, as discussed in a subsequent section). Once the soil was depleted to less than 0.6 ppm DTPA-Zn, wheat began to respond to Zn application. Relatively higher critical limits of plant-available Zn for rice growth than wheat growth (30) (see Table 5 for wheat) proved

Table 1. Response of wheat, maize, and rice to micronutrients under conditions of deficiency

Crop	B	Cu	Fe	Mn	Mo	Zn
Wheat	L	H	L	H	L	L
Maize	L	M	M	L	L	H
Rice	L	L	H[a]	M	L	H[b]

L = low, M = medium, and H = high
[a] Mainly upland rice
[b] Mainly lowland rice
Source: Lucas and Knezek (44)

Table 2. Distribution of response of maize, rice, and wheat to Zn application in India (farmers' fields experiments)

Crop	No. of experiments	Zn application <200 kg/ha	Zn application >200 kg/ha
		(% experiments with response)	
Maize	77	27	73
Rice	994	35	65
Wheat	1416	47	53

Source: Katyal (32)

that on soils where normal yields of rice will be obstructed by a Zn deficiency, wheat yields may remain unaffected.

In another study (65, 66), none of the wheat tissue samples showed inadequacy of B, whereas 95% of the groundnut tissue samples from the same area (light-textured Entisols and Inceptisols) were found to be B-deficient. A remarkable improvement in the yield of groundnut in comparison to a nil response of wheat to B fertilization confirmed tolerance of wheat to conditions of B deficiency for groundnut.

Wheat has also shown differential sensitivity to Fe and Mo stresses. Monocots in general are less efficient in Fe uptake than are dicots (15). On a Typic Ustipsamment (pH 8.0) upland rice suffered severely from Fe deficiency, but wheat did not (observations by Katyal). As compared with other cereals, including wheat, legumes exhibit a higher response to applied Mo.

Among the crops, particularly temperate cereals, the response of wheat to a Cu deficiency is generally greater than that of barley, oats, or rye (52, 73). In fact, rye shows the greatest tolerance to low concentrations of available Cu in soils. Wheat produced no grains without supplementary Cu on Cu-deficient sandy soils in Australia (Table 3) (21). In contrast, rye and hexaploid triticale were remarkably tolerant of this soil, producing as much grain in untreated soil as when Cu was added. The unusually low yield of rye in this study was due more to its poor adaptation to the environment (late maturity and high temperatures) than to low Cu. Clearly hexaploid triticale has similar tolerance to low Cu supply as its rye parent. The difference in tolerance of wheat and rye on Cu-deficient soils is due to the ability of rye to maintain a high concentration of Cu in the shoot (52, 73).

In several studies wheat has exhibited high sensitivity to Mn deficiency in soils (44), a characteristic shared by oats (50).

Like interspecies differences, genetic variations (Table 4) within each species are undoubtedly important to micronutrient stresses. At times the genotypes chosen will influence the order of sensitivity observed in crops. For example, in several studies (23, 52) tetraploid wheats (*Triticum durum*) were more sensitive to Cu deficiency than hexaploid wheats (*T. aestivum*). Important differences in vulnerability to Cu deficiency exist within hexaploids (1). Cu deficiency is known to reduce grain yield more severely than the straw yield (14); therefore, genotype differences will be more distinct in grain yield than in vegetative yield. Nambiar (52) reported that deferred supply of Cu to deficient wheat plants increased the grain yield more than the straw yield. A decrease in the number of grains per head seemed to be the major factor for the yield depression in Cu-inefficient types.

The relative tolerance of wheat to Zn deficiency has already been mentioned. With this micronutrient, choosing genotypes on the basis of their response to Zn will be a viable strategy in avoiding the need for Zn fertilizers. Shukla and Hans Raj (67) reported that susceptibility to Zn deficiency among the Indian wheats was related to their capacity to utilize soil Zn; varieties differed in time of onset and intensity of symptoms, tissue Zn concentration, and relative yield depression. Their findings pointed out that the response of a cultivar to Zn deficiency increased as its inefficiency in utilizing soil Zn increased. This relationship was confirmed in the studies of Alam et al. conducted on some Pakistan wheats (3). The depression in yield due to Zn deficiency was inversely related to Zn concentration in the plant. Although differential susceptibility of wheat varieties to low Zn has been established beyond doubt, rarely has this relative tolerance been confirmed in the field. Field validation of results obtained from pot studies conducted either in soil (3, 4, 67); or in sand/solution (1, 2) culture becomes important, in that Randhawa and Takkar (62) reported a profound influence of growth media on the grouping of relative susceptibility/tolerance of a genotype to Zn deficiency.

Similar to variability in responses to micronutrient stresses, interspecies and intraspecies differences in tolerance of micronutrient toxicities also exist (18). Rice is known to be more tolerant of excess Mn. Some varieties of wheat tolerate higher levels of Mn in their tops than others. Cultivation of tolerant varieties is a practical way of solving Mn toxicity problems in acid soils.

Plant micronutrient contents
Based upon the values given by several researchers and compiled by Katyal and Randhawa (35), approximate micronutrient contents in wheat plants have been determined (Table 5). Judgment of micronutrient deficiency, sufficiency,

Table 3. Effect of copper supply and genotype on yield of grain in a copper-deficient sandy soil

Genotype	Ploidy	Copper supply (mg/pot) 0	0.1	0.4	4.0
		Grain yield[a] (g/pot)			
Triticum durum cv Cocorit	Tetraploid	0	0.1	5.6	12.5
Triticum aestivum cv Chinese Spring	Hexaploid	0	3.5	12.9	13.7
Secale cereale cv Imperial	Diploid	2.1	2.4	2.4	2.1
Triticale cv Beagle	Hexaploid	14.3	13.8	14.3	14.5
Triticale Chinese Sp.-Imperial	Octoploid	4.6	6.5	7.4	7.5

[a] Each value is the mean of three replicates. Plants were grown in a copper-deficient siliceous sand from Tintinara, South Australia (Laffer Sand) in an evaporatively cooled glasshouse

Source: Graham (21)

or excess by this table alone may be dangerous because of year-to-year and location-to-location variations as a result of soil-plant-climate interactions. The soil-plant relationship is complicated further by genetic composition, selectivity, antagonism, and other external factors. Shukla and Hans Raj (67) reported that tissue concentration of Zn in wheat cultivars ranged from 4.2 to 28.3 ppm under Zn-deficiency conditions. Excess availability of P is widely known to interfere with Zn and Fe nutrition. Elemental composition is also modified by the plant part sampled and the age of the plant at sampling. For example, younger plant parts generally contain more Zn and less Fe than older plants. By and large, Zn concentrations decrease with age.

Plant micronutrient concentrations are a reflection of the available micronutrient levels in soil, as well as the influence of soil environment. Thus, plant tissue tests can be of real aid in diagnosing or confirming a micronutrient deficiency if due consideration is given to variables mentioned earlier. In fact, a quantitative relationship exists between tissue micronutrient concentrations (except Fe) and growth and yield of crops. Figure 1 represents the relation between wheat yield and tissue Zn content. It is evident that at values lower than 20 ppm Zn, wheat yield is likely to be limited; thus, this value is referred to as the critical Zn concentration. Critical concentrations of micronutrients are used to indicate the level below which a

Table 4. Sensitivity of wheat varieties to micronutrient deficiencies

	Sensitivity			
Micronutrient	Low	High	Country	Reference
Cu	Gabo Glaive Pinnacle Choti Lerma UP301 Duramba	Halbred	Australia	52
Mn	WG357 WL410 TL419 HD2009	DWL5023 WL1562	India	33
B	Sonalika	Janak UP262	India	13
Zn	WG377	Hira	India	33
	WL212	HD1944		
	UP301	Safed Lerma		
	WL334	Choti Lerma		
	UP368	C306		
	UP262	Kalyansona		

deficiency condition exists and a sharp reduction in growth/yield is noticed. The values of micronutrient contents listed as deficient in Table 5 may be regarded as the critical limits of deficiency.

The critical limit of Fe, which distinguishes deficient plants from the sufficient, is not presented in Table 5. This is largely due to a general lack of close relationship

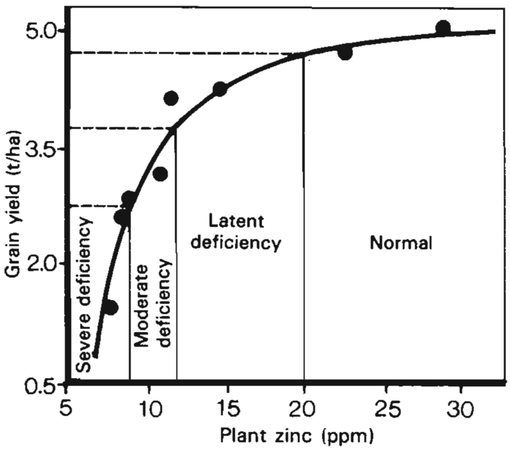

Figure 1. Relationship of plant Zn and wheat yield. Source: Takkar and Randhawa (76)

between total Fe content of plants and yield (37), which suggests that plant analysis for total Fe may not be a reliable index of Fe deficiency. To resolve this problem, Katyal and Sharma (36) suggested analyzing plants for Fe^{2+} fraction rather than total Fe. In their subsequent studies (37), yield of sorghum and tissue Fe^{2+} concentrations were significantly correlated.

Apart from a lack of a universal correlation between total concentration of an element and occurrence of a deficiency, another problem with diagnosis of micronutrient deficiencies by plant analysis is that it is often too late for correction of a deficiency. Assays of micronutrient-containing enzymes have been designed to overcome this difficulty.

Deficiency symptoms

Micronutrient deficiencies may inhibit or stimulate production of certain chemical and biochemical constituents. Depressed or increased accumulation of these substances leads to the development of certain symptoms related to a specific micronutrient deficiency such as 1) abnormal coloration or discoloration

Table 5. Approximate micronutrient concentrations in wheat tissue which may be classed as deficient, sufficient, or excess

		Concentration (ppm)	
Micronutrient	Deficient	Normal range	High
B	<4	5	–
Cu	<4	5-15	>20
Fe	?	50-250	?
Mn	<20	25-250	>400
Mo	<0.1	0.5-5	–
Zn	<20	21-40	41-150

of leaves, 2) reduction in the normal size of the plant organs (malformed and/or reduced size of leaves, shortening of stalk internodes), 3) death of the affected tissues/plants, 4) uneven crop stands, 5) delayed maturity, and 6) sterility. At times there may be qualitative alteration in biochemical processes before the visual symptoms can be seen. Such a situation is referred to as "hidden hunger" and is only possible to diagnose by plant analysis. Multinutrient deficiencies or disease syndromes obstruct the development of specific symptoms and thus lead to complications in diagnosing a deficiency disorder.

Specific symptoms of micronutrient deficiencies in wheat are described in the following sections (1, 5, 12, 22, 35).

Copper—Symptoms of Cu deficiency begin at around mid-tillering as limpness or wilting (loss of turgor). At tillering the tips of leaves become pale yellow and curled (wither tip); the leaf tips then die (whip-tail). Stem elongation of Cu-deficient plants is retarded, and there is excessive late tillering and high mortality on late tillers. Heading is delayed. Spikelets are devoid of grain, and the ears are mostly empty. The few grains that are formed are shriveled and have blackened endosperm. A Cu deficiency may lead to total grain loss, but the loss in straw yield may not exceed 20% of the normal yield.

Zinc—Symptoms of Zn deficiency are generally seen in 3- to 4-week-old plants. The third leaf from the top develops brownish-gray or bronze necrotic lesions near the base of the lamina. The necrotic areas coalesce, and the affected tissue becomes discolored. Finally, the leaf collapses. The plants are stunted, and many die; thus, the wheat stand is uneven. If the deficiency is unattended, the crop duration is prolonged and the yields are severely reduced.

Manganese—Symptoms of Mn deficiency are seen first as white or buff necrotic streaks on the lamina of young leaves. These lesions enlarge and coalesce, resulting in long irregular necrotic bands. The symptoms are very conspicuous in the flag leaf at heading.

Iron—The most common Fe deficiency symptom is the chlorosis of the young leaves. First effects of Fe deficiency can be seen within 2 weeks of sowing. Typically, Fe chlorosis begins as pale leaf color followed by chlorosis or yellowing of the interveinal areas of the new leaves. In some wheat varieties, (e.g., UP301) (2), the veins remain green and turn chlorotic only as the deficiency becomes severe.

Boron—Boron deficiency symptoms appear as small chlorotic patches on young and middle leaves of 3-week-old plants (grown in sand culture). Later the chlorotic spots become pronounced and develop bright orange coloration. The inflorescence is improperly developed (zig-zag axis, short awns, apical part discolored), and thus grain formation is poor.

Molybdenum—Since Mo is intimately involved in N metabolism of plants, its deficiency resembles N deficiency. Molybdenum-deficient plants exhibit restricted growth, and their leaves become pale.

Symptoms of Mn and Cu (and B) toxicities have frequently been recorded. Manganese toxicity, a problem of acid soils (pH < 5.5), is characterized by marginal chlorosis, cupping of young leaves, and brown speckling of older leaves. The most prominent symptom of Cu toxicity is chlorosis, superficially resembling Fe deficiency.

Distribution of micronutrients in soils

Total contents—Total micronutrient contents vary in soils. The variations may be attributed to the composition and nature of the parent rocks, the weathering process, and the age of the soil. Information on total micronutrient contents of soils has been compiled by Katyal and Randhawa (35) and shows the following:

- Boron levels of most soils range from 2 to 100 ppm with an average of about 30 ppm. The lowest values are found in soils derived from acid igneous rocks and fresh water sedimentary deposits (coarse textured) and in soils with low organic matter. Soils formed from shale, loess, and alluvium (fine textured) show higher values of total B.

- Copper contents in soils vary between 10 and 200 ppm with an average value of around 55 ppm. Soils derived from basalt are richer in total Cu than those originating from granite. Total Cu increases with the fineness of soil texture.

- Total Mn contents in soils can vary from a trace to as high as 10% or even more. However, Mn contents between 200 and 3000 ppm are most common.

- Total Mo contents in soils range between 0.6 and 3.5 ppm. with an average value of around 2.0 ppm.

- Among the micronutrients, Fe has the distinction of being most abundant in soils. On an average, soils contain around 5% Fe by weight. Ferruginous soils contain a higher amount of Fe ($>10\%$). Sandy soils contain low amounts of total Fe ($= 1\%$) and leached acid sands the least ($< 1\%$).

- Total Zn in soils varies from 10 to 300 ppm, with an average of around 80 ppm. Some highly leached acid sands are unusually low in total Zn.

Total micronutrient contents are generally of geochemical interest. They are of little or no biological or ecological significance since they are, by and large, poorly related to plant growth and yield. Because of this poor relationship and the need to match the levels of micronutrients supplied by the soils with the crop needs, the plant-available micronutrient contents of the soil must be determined.

Available contents—Plant available micronutrient contents, representing only a fraction of the total, are determined by extracting soils with one of a number of extractants (41) which generally include water (cold or hot), inorganic salts, acids, and chelating agents. Extractions with water, except to determine plant-available B and Mn in acid soils (to assess Mn toxicity), are generally not used since water extracts too little to determine accurately with the instrumentation available in most laboratories. Contamination can bring about serious errors in interpreting results of water extracts. Acid extractants are generally less successful in arid and semiarid soils, which invariably are calcareous. Chelating agents are relatively more successful on a wide variety of soils because the extraction pH can be adjusted to the normal pH of soils.

The extractants more commonly used to estimate plant-available micronutrient contents are listed in Table 6. For estimating availability of Zn, Cu, Mn, and Fe, the DTPA (diphenyl-triamine penta acetic acid) extraction method of Lindsay and Norvell (42) has been adopted in many countries of the world. The advantage of this method is that in a single extraction all four micronutrient cations can be determined. Ammonium oxalate (pH 3.3) is the most extensively used soil test for Mo. The popular method to assess B availability in soils involves extraction with boiling water.

Critical limits of micronutrient availability, below which deficiencies can be expected, are also presented in Table 6. It is evident that values of critical limits change if the extractant is changed. Even with the same extractant, critical values will not be uniform since several soil properties are known to modify micronutrient availability. For instance, soil pH strongly influences the availability of Mn. Therefore, the critical limit of Mn availability becomes higher if the soil pH increases. In fact, the superiority of an extractant as a soil test becomes less important if the contribution of soil factors affecting nutrient availability is taken into account (41).

Several soil factors, management practices, and climatic conditions lead to insufficiency of micronutrients in soils. For example:

- Zinc availability is low in soils with high pH ($>$7.0), soils with low ($<$0.5%) or very high ($>$5%) organic matter, sandy soils, and poorly drained soils. Excessive P and lime applications and removal of topsoil aggravate Zn deficiency. Zinc deficiency in wheat can be expected if soils test less than 0.5 ppm DTPA-extractable Zn.
- Manganese becomes less available in the presence of lime at higher pH and under dry conditions, low light intensity, and low soil temperature. Regular leaching of sandy soils can lead to Mn deficiency (53). Manganese deficiency in wheat is expected if soils test below 2.0 ppm DTPA-extractable Mn. An Mn toxicity may occur if wheat is grown on acid soils (pH $<$5.5). Such soils test $>$2 ppm water-soluble Mn.
- Calcareous soils, soils with low organic matter, compacted soils, and exposed subsoils are generally deficient in Fe. High soil moisture, low soil temperature, liberal use of phosphatic fertilizers, and indiscriminate use of heavy metals are associated with low Fe availability.
- Copper is strongly immobilized by organic matter. As a result, peat and muck soils are generally Cu deficient. A Cu deficiency can be encountered in alkaline calcareous soils and acid sandy soils. Copper-deficient soils test less than 0.2 ppm DTPA-extractable Cu.
- Boron is less available at increasing pH, perhaps due to Ca antagonism (alkaline calcareous soils). Sandy acid soils, podzols, and areas of heavy rainfall represent B-deficient conditions. Dry weather, high light intensity, and liming of acid soils provoke deficiency. If hot water-soluble B in a soil is less than 0.3 ppm, B deficiency can be suspected. If soils test more than 5 ppm hot water-soluble B, a B toxicity will occur.
- Molybdenum availability, contrary to that of B, Cu, Mn, Zn, and Fe, is restricted to acid soils.

Table 6. A list of common extractants for micronutrient analysis of soils and critical limits of micronutrient availability for wheat

Extractant	Soil (g): extractant (mL) ratio	Shaking time (min)	Critical limit (ppm)
	Boron		
Hot water	10:20	5[a]	0.3
	Copper		
N NH_4OAc (pH 4.8)	50:100	60	0.2
DTPA[b]	10:20	120	0.3
0.05 *N* HCl + 0.025 *N* H_2SO_4	5:20	5	0.4
	Iron		
N NH_4OAc (pH 4.8)	2.5:50	30	2.0
DTPA	10:20	120	2.0
	Manganese		
N NH_4OAc (pH 7.0)	10:100	30 min + 180 min (intermittently)	3.5
0.05 N HCl + 0.025 *N* H_2SO_4	5:20	5	–
DTPA	10:20	120	2.5
	Molybdenum		
24.9 g $(NH_4)_2C_2O_4$ + 12.6 g $C_2O_4H_2$ dissolved to make 1 L of pH 3.3	25:250	600	0.1
	Zinc		
0.1 *N* HCl	2:20	5	1.0
0.05 M EDTA (pH 7-9)	15:75	Three successive extractions of 25 mL each	–
0.01% dithizone in CCl_4, *N* NH_4OAc (pH 7.0)	2.5:50 (25 mL of each reagent)	60	0.5
0.05 *N* HCl + 0.025 *N* H_2SO_4	5:20	5	1.0
DTPA	10:20	120	0.3-0.5
2 *N* $MgCl_2$	10:50	45	–

[a] A soil is extracted by boiling water for 5 minutes

[b] DTPA = 0.005 *M* diethylene triamine penta acetic acid + 0.1 *M* triethanol amine + 0.01 *M* $CaCl_2$(pH 7.3)

Source: Katyal and Randhawa (35) and Lindsay and Cox (41)

Regions of micronutrient deficiency

According to research data generated thus far, deficiency of Zn can be suspected somewhere in every wheat-growing country. Alkali soils in general show an inadequacy of Zn for normal plant growth. In India Zn application is considered critical for reclamation of 2.5 million ha of alkali and saline-alkali soils of the Indo-Gangetic alluvium (8). So severe is the deficiency that, despite amendments with gypsum, annual applications of Zn are necessary for obtaining optimum wheat (and rice) yields (72). More than 50% of the soils in the main wheat-growing states of India are suspected of suffering from a Zn deficiency (34). Entisols (Fluvents, Calcifluvents, Psamments), Inceptisols (Ustropepts, Ustochrepts, Eutrochrepts, Halaquepts), Alfisols (Natraustalfs, Haplustalfs, Ochraqualfs), Aridisols (Salorthids, Natrargids, Camborthids, Calciorthids), and Vertisols (Chromusterts and Pellusterts) are the dominant soil orders covering the wheat-growing areas in India, Pakistan, and Bangladesh. Analyses of 49 benchmark soils of India (33) (Table 7) and 152 soil samples from four provinces of Pakistan (39) confirm the probability of a wide incidence of Zn deficiency.

A generally low level of all nutrients including Zn in sandy soils, a high pH arising either from calcareousness or saline-alkali conditions, and unusually low levels of organic matter are the key factors leading to Zn deficiency. Prevalence of these conditions in the soils of arid and semiarid regions makes them more prone to Zn deficiency than are the soils of humid and subhumid regions (38). In a study by Singh et al. (71), a significant increase in wheat yield was noticed in 50 of 55 wheat-growing districts in India. Irrigated wheat appeared to benefit more from Zn treatment than nonirrigated wheat (Table 8). A need for Zn fertilization has been established for wheat grown on floodplain soils of Bangladesh (26, 60). Although an economic response of wheat to Zn application has been

Table 7. Zinc-deficient (%) benchmark soils of India

Soil order	No. of soils	Available Zn (ppm)[a] Range	Available Zn (ppm)[a] Mean	Zinc Deficiency (%)
Entisols	5	0.28-0.96	0.54	60
Inceptisols	16	0.19-1.54	0.58	69
Vertisols	12	0.15-1.27	0.41	83
Alfisols	15	0.19-2.28	0.55	87
Ultisols	1	0.28	—	100

[a] By DTPA extraction
Source: Katyal (32), Katyal and Vlek (38)

noticed in Pakistan (6), effects of Zn application are no doubt less widespread than those observed in India.

As in Asia, Zn deficiency seems to be a major soil constraint in tropical Latin America. According to Lopez (43), 50% of the soils (Brazilian Cerrado and Venezuelan and Colombian Llanos, highly weathered, acid, low-CEC soils) suffer from low Zn. Response of wheat to Zn applications has, however, rarely been investigated (40). In Africa, Zn may be a major nutrient deficiency for cereals in the Chad basin (70) and on Vertisols of the Sudan Gezira (28).

Copper deficiency in wheat is common in strongly leached, young acid sandy soils derived from pumice and ash (Rift Valley area in Kenya) and granite (northern Zimbabwe) (56, 78). Coarse-textured ferrallitic and ferruginous soils that have gone through extensive weathering and leaching are another group of soils that are mostly Cu deficient. Examples of this type of soil are found widely in Australia, Latin America, and Southeast Asia (20, 22). Calcareous soils formed on chalk, crystalline limestone, and calcite-cemented sandstones are Cu deficient because of low total Cu, high pH, and dominance of Ca^{2+} in the exchange complex (5). Such soils fringe the Western Australian coast (20).

Peats and mucks are well known for producing Cu-deficient crops in Malaysia and elsewhere. Even mineral soils with more than 10% organic matter, and particularly with alkaline reactions, are prone to Cu deficiency.

Indiscriminate use of Cu fertilizers (see a later section) and a regular use of Cu fungicides and pesticides can lead to high amounts of Cu in the soil, which may prove toxic to plant growth.

Low availability of Mn is usually associated with high pH. Probability of Mn deficiency is therefore high in countries with generally alkaline soils—India and Pakistan. Recently in India, Mn deficiency has been observed in heavily percolating sandy soils (pH = 8.0) where wheat follows lowland rice. Leaching losses of Mn due to unusually frequent irrigation of rice result in Mn deficiency in wheat (53). Excess Mn may be a problem in acid soils of countries in Africa and Latin America.

Table 8. A comparison of response of irrigated and nonirrigated wheat to Zn application (farmers' field experiments, India)

	No. of experiments	Yield response to Zn application	
		Range	Mean
		(additional kg grain/ha)	
Irrigated	3702	79-1162	287
Nonirrigated	223	172-253	234

Source: Singh et al. (71)

From a global study of micronutrients, Sillanpaa (69) reported that a deficiency of Mo seems to be most widespread in African countries with acid soils — Sierra Leone, Zambia, Nigeria, and Ghana. In his survey, low Mo values were recorded in soil and wheat tissue samples from Brazil and Nepal.

Boron deficiency can be suspected in countries with alkaline calcareous soils and acid leached sandy soils. Boron deficiency in wheat seems to be relatively more common in India, Nepal, and Thailand in Asia, and Nigeria and Malawi in Africa (69). Boron toxicity occurs in soils developed on marine deposits, arid soils, soils irrigated with high-B (>0.5 ppm) waters, or those excessively fertilized with B carriers. Examples of such soils can be found in Pakistan and India.

Iron deficiency is a problem of calcareous soils and in alkaline sandy soils with low organic matter. Iron deficiency has not been commonly recorded in wheat.

Amelioration of micronutrient deficiencies

Micronutrient deficiencies are corrected by application of carriers either as chemically pure salts (e.g., zinc sulfate, copper sulfate, manganese sulfate, ammonium molybdate, etc.), as chelate compounds (Fe-EDDHA, Zn-EDTA, etc.) or as fertilizers that have been fortified with micronutrients. Small amounts of micronutrients get inadvertently added when present as contaminants in the N-P-K fertilizers or when soils are treated with organic manures. Irrigation waters (particularly underground) can be a potent source of some micronutrients (like B and secondary nutrient S). The more common micronutrient fertilizers are listed in Table 9.

On the basis of economic considerations in alleviating deficiency problems, the application of pure salts should be preferred. In some cases the addition of micronutrients to N-P-K fertilizers may be advantageous because the method may give optimum balance between the various nutrients applied. Cost of application is reduced, although at times nondeficient nutrients also get added. A summary of methods, rates (Table 10), and times of application is given below for each of the micronutrient elements. Details are discussed in several publications (5, 22, 31, 35, 47, 51).

Zinc—Application of Zn to the soil at the time of seeding (late applications are less efficient) is the most satisfactory way to cure Zn deficiency in wheat. Zinc can be applied either broadcast (followed by incorporation) or placed beside and below the seed. Less soluble sources of Zn (ZnO, $ZnCo_3$) perform as well as soluble sources ($ZnSO_4$) if they are broadcast and incorporated. One soil application of Zn can last for 6 to 8 seasons. Duration of the residual effect increases with the level of application, particularly if wheat is rotated with an upland crop like groundnut (75). In variance, if wheat is rotated with lowland rice, the length of residual effect is shortened, and frequency of application has to be increased. In the studies of Pathak et al. (55) and Bhardwaj and Prasad (7), significant residual effect of Zn (10 kg Zn/ha as $ZnSO_4$) was not noticeable after two crops (one rice and one wheat). Recently Singh and Abrol (72) suggested making annual applications to wheat (and rice) immediately after reclamation of alkali soils in India.

Table 9. A list of common micronutrient sources

Common/trade name	Chemical formula	Element (%)
Zinc		
Zinc sulfate	$ZnSO_4.7H_2O$	23
	$ZnSO_4.H_2O$	36
Zinc oxide	ZnO	60-80
Zinc chelate	Na_2-ZnEDTA	14
Zinc frits	—	4 (variable)
Iron		
Ferrous sulfate	$FeSO_4.7H_2O$	20
Ferric sulfate	$Fe_2(SO_4)_3$	20
Fe-EDDHA	—	6
Manganese		
Manganese sulfate	$MnSO_4.3H_2O$	26-28
Manganese oxide	MnO_2	63
Manganese chelate	Mn-EDTA	12
Copper		
Copper sulfate	$CuSO_4.5H_2O$	25
	$CuSO_4.H_2O$	35
Cuperous oxide	Cu_2O	89
Copper chelates	Na_2-CuEDTA	13
	Na-CuEDTA	9
Boron		
Borax	$Na_2B_4O_7.10H_2O$	11
Sodium tetraborate		
fertilizer borate 46	$Na_2B_4O_7.5H_2O$	14
fertilizer borate 65	$Na_2B_4O_7$	20
Solubor	$Na_2B_4O_7.5H_2O +$ $Na_2B_{10}O_{16}.10H_2O$	20
Molybdenum		
Sodium molybdate	$NaMoO_4.2H_2O$	39
Ammonium molybdate	$(NH_4)_6Mo_7O_{24}.4H_2O$	54
Molybdenum trioxide	MoO_3	66

Foliar applications of Zn are made to prevent Zn deficiency in a growing wheat crop. Foliar treatment, however, produces less response than preplant soil application. This is evident from the comparative data on response of wheat to soil and foliar applications of Zn (Figure 2); except on 2 of the 12 sites, foliar-applied Zn was inferior. Foliar sprays are to be made 2 to 4 times at biweekly intervals. Foliar applications leave no residual effect and have to be repeated each season.

Copper—Copper deficiencies can be prevented by soil or foliar applications of $CuSO_4$ (or other carriers). Soil application of Cu is made at the time of seeding either through broadcast (incorporated) or band placement. Band placement is generally more efficient, so the application rates are reduced (Table 10). Rates of Cu application higher than those given in Table 10 may produce toxic effects and should be avoided. For organic soils, rates of Cu application can be as high as 20 kg Cu/ha without ill effects. The usefulness of one soil application of Cu lasts at least for 2 to 8 years. Repeat applications may cause toxic accumulations of Cu. Banded Cu applications produce relatively short residual effect.

Copper deficiency in wheat can be effectively controlled through foliar application (Table 10). In order to avoid leaf scorching, the spray solution should be neutralized with lime. For maximum response, multiple sprays spaced at biweekly intervals may be needed (first spray is made as soon as symptoms are seen).

Table 10. Methods and rates of micronutrient application for wheat

Deficient element	Source	Suggested application rates		
		Broadcast	Band	Foliar
		(kg element/ha)		(g element/ha)
Zn	$ZnSO_4$	5-20	3-5	15-250
Cu	$CuSO_4$	4-15	1-4.5	100-500
Mn	$MnSO_4$	20-130	6-11	500-2,000
Fe	$FeSO_4$	—	—	5,000-10,000
B	Fertilizer borate ($Na_2B_4O_7.SH_2O$)	0.6-1.2	—	—
Mo	$NaMoO_4.2H_2O$	0.07-0.2	—	100-150

Source: Murphy and Walsh (51), Katyal and Randhawa (35), and Alloway and Tills (5)

Manganese—Manganese is applied to soil through broadcast or band placement at the time of seeding. Band applications are more efficient (Table 10). Foliar application of Mn is the most effective method of correcting Mn deficiency. At relatively low rates of application, foliar-fed Mn is often as effective as much higher rates applied to the soil (53). Two to three sprays at 14-day intervals often are sufficient to cure Mn deficiency disorder completely.

Iron—The most common of the Fe sources — sulfates — are not very effective when applied to soil. Foliar sprays are generally made to correct Fe deficiency. Economics favor their use. Multiple sprays of 1 to 3% $FeSO_4$ solution are made during the growing season. First spraying should be done as soon as symptoms are noticed. Subsequent sprays, depending upon the need, are made at 10- to 14-day intervals. Iron sulfate solution should be fresh, unneutralized, and preferably sprayed in the morning hours.

Boron—Boron may be applied to the soil either broadcast or banded at the time of sowing. The rate of B (Table 10) should not be exceeded; otherwise, B toxicity may occur. Foliar applications of B are generally preferred if deficiency occurs during the growing season. Solubor is widely used for foliar application (0.2 to 0.5% solubor in water), and multiple sprays are needed for complete cure.

Molybdenum—Molybdenum deficiency can be prevented by liming acid soils to a pH above 6.0. However, if this procedure is impractical, Mo deficiencies are corrected by soil, foliar, or seed application of Mo carriers. Molybdenum deficiency can also be overcome by sowing seeds enriched with Mo. The levels of Mo needed to check the deficiency are very small (70-200 g Mo/ha) even when applied to soil either through broadcast or band placement. One soil application produces residual effect if crops with high Mo requirements are not rotated with wheat.

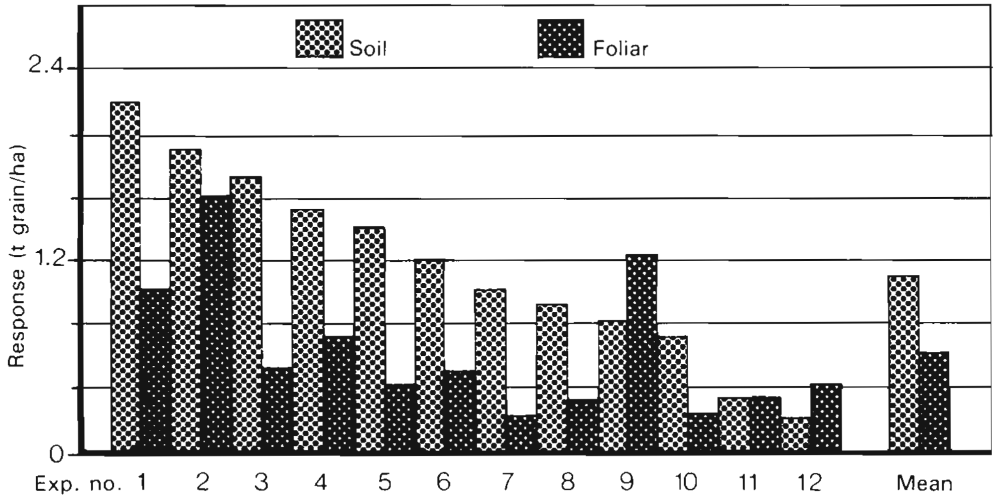

Figure 2. Response of wheat to soil (10 kg Zn/ha) and foliar (1.5 kg Zn/ha) applied zinc. Source: Katyal and Randhawa (35)

The most common method to overcome Mo deficiency is to apply Mo salts (equivalent of 50 to 100 g Mo/ha) to seed in a liquid or slurry form. This method of application allows a uniform distribution of small amounts of Mo, which otherwise is difficult to achieve. Seed treatment avoids waste of Mo through soil fixation; thus it is more efficient. Foliar sprays (0.1 to 0.3% solution of a soluble salt) can effectively control Mo deficiency. They produce responses comparable to those with seed treatment.

High intake of Mo by wheat, caused by excessive applications of Mo carriers, may not upset its growth. However, if straw analyzing more than 15 ppm Mo is ingested by cattle (straw is a staple food of cattle in India, Pakistan, and Bangladesh), it can harm their health (molybdenosis or teart disease). Therefore, optimum levels of Mo application should not be exceeded.

Sulfur

Role of sulfur

Sulfur is involved in several functions in plants (9). Among these are the synthesis of the essential S-containing amino acids, cysteine, cystine, and methionine. The protein quality, and hence the nutritive value, of cereal grain is determined by the proportion of S-amino acids present. Sulfur is also required for the formation of chlorophyll and ferredoxin, both essential to the photosynthetic process. The synthesis of certain vitamins (biotin, thiamine, and B1), glutathione, and coenzyme A also requires sulfur, as does the activation of proteolytic enzymes such as papainases.

Deficiency symptoms

Since sulfur is involved in the formation of chlorophyll, its deficiency results in reduced chlorophyll production and a general and interveinal chlorosis of the leaves. In this sense S deficiency resembles N deficiency. However, because S in high-S proteins is not as readily remobilized as N, the older leaves of wheat plants growing into a deficiency remain green while younger growth experiences yellowing — in contrast to N deficiency where the reverse occurs.

Sulfur requirements of wheat

In general, the sulfur content of plants is similar to that of phosphorus. S:P ratios of 0.3 to 0.4 at 30 days after sowing, 0.5 to 0.6 at 60 days after sowing, and 0.64 to 0.89 at maturity have been reported for whole wheat plants grown at optimal levels of S and P fertilizers (27, 46). The S concentration in wheat grain grown under field conditions where S is nonlimiting ranges from 0.12 to 0.19% (63). A wheat crop yielding 3 t/ha of grain (8 t/ha total dry matter) extracts approximately 14 kg S/ha from the soil (46). This amount may be considered the S requirement of the crop at this particular yield level; the S fertilizer requirement, on the other hand, would depend on the soil S reserves, natural accessions of S from the atmosphere, rain, and irrigation water, losses by leaching and erosion, and the fertilizer use efficiency factor for the crop, most of which are location-specific. Atmospheric accessions of S are approximately 2 to 3 kg S/ha (based on data from northern Nigeria, Kenya, India, and Australia summarized by Kanwar and Mudahar [29]), and leaching losses, which depend on soil properties and water received, are generally an unknown quantity.

Table 11 provides estimates of S removal by wheat and crops commonly grown in rotation with wheat at various yield levels (29). Clearly, under more intensive modern agricultural practices, S exports from the soil can be substantially greater than inputs. An analysis by Kanwar and Mudahar (29) of S inputs and exports under various cropping scenarios indicated the need for substantial inputs of S fertilizer in the intensive cropping systems. Deficiencies may not be apparent in many of these systems as yet since soil reserves have not been fully exploited; however, it is clear that deficiencies must eventually develop and will lead to reductions in both yield and crop quality. Effect of S deficiency on wheat quality Although the requirement of a crop for a specific nutrient has been defined as the minimum concentration of nutrient in the plant that is associated with maximum (grain) yield, for a nutrient such as S, which affects crop quality as well as yield, such a definition may be inadequate. Under conditions of balanced nutrient supply, organic S in grain constitutes 80 to 95% of the total S, the remainder being sulfate (64). The essential amino acids, methionine and cysteine, account for most of the organic S. In wheat, as in other cereals, deficiency of S leads not only to a reduction in grain yield but also to sharp decreases in grain S-amino acid content and in the proportion of S-amino acids in relation to total amino acid content (Table 12) (11). Even where yields are not reduced as a result of S deficiency, reduced S-amino acid contents may occur (so-called "hidden hunger"). Since nonruminant mammals are incapable of synthesizing methionine from inorganic S, the reduced content of S-amino acids in grain reduces the nutritive value of the crop (68). Moreover, dough formation and hence baking quality of wheat flours is considered to depend strongly on the presence of

Table 11. Sulfur removal in wheat and wheat rotations

Crop species	Yield component	Dry matter yield (t/ha)	S content (kg/ha)
Wheat	Grain	3.0	5
	Total	8.0	14
	Grain	5.4	6
	Total	—	23
Rice	Grain	3.0	4
	Total	8.0	9
	Grain	7.8	6
	Total	—	14
Groundnuts	Nuts	3.0	8
	Total	9.0	24
Soybeans	Grain	3.0	6
	Total	9.0	23

Source: Kanwar and Mudahar (29)

sulfhydryl and disulfide groups associated with the S-amino acids (48, 81). Increased toughness and reduced extensibility of dough have been found in S-deficient wheat flour samples (48).

Content and distribution of sulfur in soils

Soil sulfur occurs in both organic and inorganic forms with organic forms generally predominating. The common inorganic forms are 1) water-soluble sulfates; 2) sulfate adsorbed onto the surfaces of clay minerals, Fe and Al oxides, and hydrous oxides; 3) insoluble sulfates of Ca, Fe, and Al; and 4) sulfides. Surface and subsurface accumula-tions of soluble sulfates are common in the soils of arid and semiarid regions while insoluble sulfates are generally associated with calcareous soils. Sulfides may be present in waterlogged soils that have undergone severe reduction.

The amount of adsorbed sulfate in the soil is related to the amounts and forms of oxidic colloids present and to soil pH, which affects the anion exchange capacity (and hence adsorption of sulfate) by these variable charge colloids. Adsorbed sulfate thus tends to accumulate in the subsurface horizons of Oxisols, Ultisols, and Alfisols that have an enrichment of adsorbing colloids and/or an acidic reaction.

Since adsorption of sulfate by colloidal minerals decreases with increasing pH, neutral or alkaline soils contain little or no adsorbed sulfate.

While accumulated sulfates may predominate under arid conditions, in humid regions organic S may constitute from 70 to 98% of the total soil S (9). Organic S accumulates in the surface soil and is directly correlated with soil organic matter content. It may be

Table 12. Effect of S deficiency on yield and S-amino acid content of wheat grain

Rate			S-Amino Acid Concentration	
N	S	Grain yield	% AA[a]	% Grain
(mg/pot)		(g/pot)		
60	0	3.00	3.6	0.065
	15	3.28	5.1	0.080
	30	2.99	5.3	0.085
240	0	0.67	1.8	0.079
	15	5.71	2.8	0.085
	30	6.32	3.5	0.104

[a] AA = Amino acids (total)
Source: Byers and Bolton (11)

broadly classified into two forms: S in the sulfate esters and carbon-bonded S. Although the proportions of each vary widely in soils, they are of a similar magnitude.

Table 13 lists the sulfur content of soils from some tropical and subtropical regions where wheat is presently or may in the future be grown. It can be seen that a tremendous range in total S content exists. Although S deficiencies can logically be expected on soils with a very low total S content, high total S does not necessarily imply adequacy of S. Indeed, total S levels in the Indian soils, where wheat responses to S-fertilizers have been observed, are among the highest in the group.

Diagnosis and prediction of sulfur deficiency

Soil tests—Soil testing for sulfur is complicated by the several forms in which S occurs in soils, the often rapid transformations of S from one form to another, and the distribution of the various forms within the soil profile. Consequently, it is not possible to generalize with respect to extractants, extraction methods, critical levels, or sampling methods for estimating plant-available S in soils. Specific methods and associated problems have been reviewed in detail elsewhere (9, 29, 59) and will only be briefly discussed here.

Table 13. Sulfur content of soils in tropical and subtropical wheat growing regions

Country/location	Total S (ppm)	Available S (ppm)
India: Andhra Pradesh	112-275	—
Uttar Pradesh (surface)	93-189	9-52
Uttar Pradesh (subsoil)	102-169	5-42
Punjab, Haryana, Himachal Pradesh	99-308	1-41
Rajasthan	91-386	22-83
Malawi	35-139	—
Zambia/Zimbabwe	60-100	—
Zimbabwe: coarse-textured		
0-30 cm	30-60	1-9
30-60 cm	36-56	3-12
fine-textured		
0-20 cm	116-144	4-41
20-40 cm	93-157	3-50
Kenya: Mt. Kenya	263-540	3-25
Kitale	105-187	1-17
Lake Victoria	99-225	4-23
Nigeria: Northern	38-52	—

Source: Kanwar and Mudahar (29)

Plants absorb sulfur from soil solution as sulfate ions. Consequently, most soil tests are based on the extraction of sulfate forms of S. In soils that may contain a higher proportion of soluble sulfates, cold water or weak salt solutions such as neutral 0.15% $CaCl_2$ or 0.1*M* LiCl generally give satisfactory results. In soils containing significant proportions of adsorbed sulfate, solutions containing phosphate (e.g., 0.01M $Ca(H_2PO_4)_2$ or 500 ppm $K[H_2PO_4]$) or acetate (e.g., 1*M* NH_4OAc), which are able to extract adsorbed sulfate, are preferred. However, high levels of adsorbed sulfate do not necessarily imply adequacy because the very presence of adsorbed sulfate in large amounts suggests that it is strongly held by soil colloids and may not be readily released to plant roots (59). Thus, Fox (17) has suggested the use of soil solution concentration of sulfate to determine the need for S fertilization. The fact that adsorbed sulfate tends to accumulate in subsurface layers of many well-weathered tropical soils must also be considered when sampling soil for S soil tests. The common practice of sampling only the surface layer would overlook the larger amounts of available S at greater depth.

Transformations of organic S further complicate the estimation of available S in soils. Although some extractants purportedly attempt to estimate mineralizable organic S, they are limited by the inability of chemical procedures to assess the influence of external/environmental variables on organic S mineralization rates or the possibility of sulfate immobilization under certain conditions.

Plant tissue tests—Several indices have been evaluated as possible diagnostic criteria for S deficiency in wheat. Concentrations of total S and sulfate S in the tissue have been found to be of limited value since both are greatly affected by plant age (Table 14) and, in the case of sulfate-S, plant part and N supply (19, 74). Although the limitation of plant age can be overcome by appropriate timing of crop sampling, results of Rasmussen et al. (63) suggest that critical concentration may vary from year to year.

The ratio of sulfate-S to total S (expressed as a percentage) has also been assessed as a measure of S deficiency (19, 74). Of all the indices compared, this was found to be the least affected by plant age (Table 14) or N supply.

Table 14. Effect of plant age on critical values of sulfur deficiency indices in whole wheat plants

Sampling stage	Days after sowing	Sulfate-S/ total-S (ratio)	Sulfate-S conc. (ppm)	Total-S conc. (%)	Total N/ total S (ratio)
Fourth leaf	61	14	460	0.30	15
Maximum tillering	92	12	360	0.28	16
Early jointing	134	11	190	0.15	19
Combined		13			16

Source: Spencer and Freney (74)

The intimate relationship of N and S in plant protein has led several researchers to evaluate the ratio of N:S in plant tissue as a diagnostic tool for S deficiency. Critical ratios of about 16/1 have been obtained by both Rasmussen et al. (63) and Spencer and Freney (74). Moreover, the ratio was not greatly affected by plant age (Table 14) (74). Nevertheless, as pointed out by Blair (9), the difficulty in using this ratio on its own is that increases above the critical value could be due to either a deficiency of S or an excess of N. He suggests the use of multiple criteria (N:S ratio and S concentration) to overcome these difficulties.

Similar tissue tests have been used in retrospectively diagnosing S deficiency and assessing the quality of wheat grain. Under adequate N supply, the critical concentration of S in wheat grain is about 0.12% (61,63). However, this criterion must be used in conjunction with the N:S ratio since the grain S concentration of wheat grown under N deficiency is also less than 0.12% (61). Thus, as in the case of tissue testing, each sample requires at least two determinations. A rapid and simple test which depends on the coloration of S-deficient whole wheat grains soaked in glutaraldehyde solution has been developed by Moss et al. (49). Such a test is useful for screening large numbers of grain samples for S deficiency and baking quality.

Regions of actual and anticipated S deficiency in wheat

Responses to sulfur fertilizer applications have been reported for numerous crops in many countries in the tropics and subtropics (9, 29). However, only a small proportion of these reports concern wheat. Sulfur responses ranging from 9 to 186% have been observed on light-textured soils in the northwest of India (Punjab, Madhya Pradesh, Uttar Pradesh, Rajasthan) (Table 15). In Bangladesh, where it is estimated that some 70 to 80% of rice soils are S-deficient (57), wheat is being increasingly planted on these soils as an off-season crop. While S deficiency is expected to be less severe when soils are in the oxidized state, responses to S fertilizer have already been reported in both rainfed and irrigated wheat in that country (Table 15) (60).

Although there have been no reports of S deficiency in wheat in other countries, responses in other crops suggest that deficiencies may be expected where, as in Bangladesh, wheat is introduced as an alternative or dry season crop. Examples include Thailand, where sulfur deficiency in maize and pastures has been reported on the coarse-textured soils in the north and northeast (25), and eastern and southern Africa where maize responses to S fertilizer have been observed (24, 45). Wheat production in Zambia and Zimbabwe has increased tremendously in recent years, probably onto soils similar to those planted to maize. Similarly, in northern Nigeria where responses by groundnuts to S fertilizer are common, wheat production on irrigated sandy soils is also likely to encounter S deficiencies.

Amelioration of sulfur deficiency

There are a great many alternative sources of fertilizer S (Table 16) (29, 54) although the availability of any particular one will depend on the local market. Agronomically, the choice is essentially between a sulfatic source or an elemental S source. Sulfatic sources, which are the most common, provide S that is immediately available to the crop, whereas elemental S sources must first be oxidized to sulfate before they can be taken up. The rate of oxidation of elemental S depends on such factors as particle size, soil moisture and temperature (54). Fine particle sizes (100 mesh or smaller) well dispersed in the soil are usually required for the source to be effective for the crop to which it is applied. The advantages of elemental S are that leaching losses can be reduced and that it can be introduced into high-analysis fertilizers without substantial dilution of their N or P contents. Rates of application of fertilizer-S to S-deficient soils may range from 5 to 40 kg S/ha. However, actual requirements must be developed for particular soil types in each agroclimatic zone.

Future Research Needs

In addition to the sensitivity of wheat and its genotypes to micronutrient stresses, factors that govern decisions related to supplemental nutrient additions are 1) the specific beneficial or deleterious effect of a preceding crop on the nutrient needs of a succeeding wheat crop; 2) contributions of micro- and secondary nutrients from manures, fertilizers, and irrigation waters as well as atmospheric accessions of S; and 3) nutrient mobilization/ immobilization caused by the cultural environment. Response studies will be more meaningful if the influence of these factors on

Table 15. Responses of wheat to S-fertilizer applications

Location	Soil type	Yield without S (t/ha)	Increase due to S (%)
India			
Delhi	Alluvial	4.3	9
Madhya Pradesh	Black	2.7	16
Punjab	Alluvial	2.4	30
Punjab	Alluvial	0.7	186
Punjab	Arid brown	2.7	69
Rajasthan	Clay loam	2.8	9
Uttar Pradesh	Alluvial	2.8	39
Bangladesh (rainfed)			
Narsingdi	Sandy clay loam	2.9	14
Panba Kotwali	Sandy clay loam	2.4	5
Jessore Kotwali	Clay loam	3.0	10
Kushtia Sadar	Clay loam	3.0	10
Bangladesh (irrigated)			
Narsingdi	Sandy clay loam	3.0	–
Panba Kotwali	Clay loam	3.1	24
Jessore Kotwali	Silty clay loam	3.2	8
Kushtia Sadar	Sandy clay loam	3.2	8

Source: Tandon (77) and Rahman et al. (60)

micro- and secondary nutrient needs is a part of future studies. Specific questions that must be addressed with respect to sulfur deficiencies in crop rotations involving wheat include the following:

- Is it more efficient to fertilize each crop in the rotation or only one, leaving the other to rely on residual S?

- If only one is fertilized, which crop should it be? This is especially important when elemental S sources are used in rice-wheat rotations because elemental S will be less available to rice under flooded conditions.

- What are the effects of residue management on the availability of S to subsequent crops in the rotation?

Thus far, the differential sensitivity of wheat genotypes to micronutrient stresses has largely been investigated in pots under controlled greenhouse conditions. Future studies in the field are needed to validate these results. In the pursuit of breeding for tolerance of nutrient deficiencies, crop scientists and soil scientists should work together. The objective should be to breed varieties that can efficiently utilize low levels of applied nutrients to deficient soils. Breeding for tolerance of micro-

Table 16. Sulfur-containing fertilizer materials (commercial and experimental)

S-fertilizer material	% S	S-fertilizer material	% S
Sultafe-containing		**Elemental S-containing**	
		Elemental S	100
Ammonium sulfate	24		
		Sulfur bentonite	88
Ammonium sulfate nitrate	5-12[a]		
		Urea-sulfur	20[a]
Ammonium phosphate sulfate	14-20		
		Diammonium phosphate-sulfur	12-15
Urea-ammonium sulfate	4-13		
		S-coated urea	15
Superphosphate, single	10-12		
		S-fortified single superphosphate	27-45[a]
Superphosphate, double/ enriched	7-9[a]		
		S-fortified triple superphosphate	10-20[a]
Partially acidulated phosphate rock	2-8[a]		
		S-fortified PAPR	a
Potassium sulfate	18		
		Phosphate rock-sulfur	5-50[a]
Magnesium sulfate (kieserite)	20-23		
Potassium-magnesium sulfate (langbeinite)	22		
Calcium sulfate (gypsum)	13-18		

[a] Variable
Source: Kanwar and Mudahar (29) and Palmer et al. (54)

nutrient toxicities is more profitable because it is less expensive to cure a deficiency than to ameliorate a toxicity.

In the past, soil tests have been used widely to isolate deficient soils. Seldom has the role of soil properties known to influence a deficiency been considered. As a result, considerable time spent in search of a universal extractant for diverse soils has yielded limited success. In the future, a soil test procedure may be standardized, and interpretations of the extractable amounts should include key soil properties that affect plant-available micronutrients. The work on delineation of micronutrient deficiencies in soils has mostly been done without considering the influence that parent material, climate, and other soil-forming processes have on total and plant-available micronutrient contents. Even information on well-defined classification units is lacking. A knowledge of micronutrient distribution on this basis will enable researchers to delineate geographical areas where micronutrient deficiencies are likely to constrain crop production. This in turn will help in assessing micronutrient needs of a crop in a country.

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Insect Problems of Rice-Wheat Cropping Patterns

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Abstract

Rice and wheat have almost 200 insect pests in common on a worldwide basis, and these are described in terms of habitat, life cycle, and pest status. An analysis of potential pest problems in rice-wheat cropping systems is given and control measures are discussed. The primary control strategy is to limit the carrying capacity of the environment for insect buildup, in tropical environments by community-wide crop scheduling. Wheat has relatively fewer pests than rice as rice is often double- or triple-cropped, but wheat will likely develop more new pest problems as more ecological niches are open. The potentially most serious pest problem in short-season environments is a virus or other disease common to rice and wheat transmitted through a common vector. Comprehensive lists of rice-wheat pests and shared diseases are included.

Ecologically rice and wheat have been isolated in time and space (Figure 1, patterns 1 and 2). Before early-maturing rices and wheats were bred and expanded irrigation systems developed, only some temperate areas were suitable for both crops to occur together. Consequently there have been few opportunities for pests to adapt to both crops.

In the short-season temperate regions, winters are too long to allow wheat and rice to be grown sequentially in a single year, but they can be found in adjacent fields in diversified dryland (wheat and rice) or transitional dryland (wheat) and wetland (rice) areas. Traditional photoperiod insensitive japonica rices are adapted to temperate regions. They tolerate cold, drought, and pest stresses — traits lacking in the wetland indica rices adapted to flooding and long monsoon seasons. Wheats, in contrast, are ill-adapted to the tropics.

In warmer temperate climates, growing seasons are sufficiently long to allow rotation of early-maturing rices and wheats (Figure 1, pattern 3). The association of rice and wheat will increase as new wheat varieties are bred for more tropical environments, changing the status of insect pests.

In the wetlands, crop intensification — more crops per year and more area planted — brought about by the modern rices and irrigation, has led to severe pest problems of rice in recent decades (68, 102). A method to counterbalance these problems is to break the rice cycle by community-wide adoption of crop rotation, early maturing varieties, strict planting schedules, and crop residue destruction.

As with rice, the wheats were accused of being highly susceptible to pests as outbreaks accompanied their spread across Asia (29, 33). It was not the varieties themselves that were responsible, but the change in ecological availability of the crop to pests by increased area planted per year. Traditional varieties would have led to these problems if they had been as widely planted over the dimensions of space and time.

Introducing wheat into rice-based systems increases the cropping intensity on the one hand, but also fosters crop rotation, a form of pest control. In Japan, a change from rice-wheat to rice-fallow increased *Nephotettix cincticeps* and virus diseases of rice because more favorable grassy weed hosts grew in the uncultivated fallow (58). But in certain circumstances, crop rotation may increase pest problems (105). In India, a rice-wheat rotation in the Punjab increased pink stem borer, *Sesamia inferens*, over the population that would have developed in a rice-fallow pattern (66). Crop rotation as a method of controlling phytophagous insect pests involves two biological principles. First, insect populations increase exponentially with each succeeding generation if natural enemy pressure is constant and the physical environment is favorable for insect growth and development. Second, phytophagous insects are limited to a range of host plant species.

Insects with the narrowest host range are monophagous and develop on species within a genus (107). Polyphagous insects have wide host ranges and develop on plants

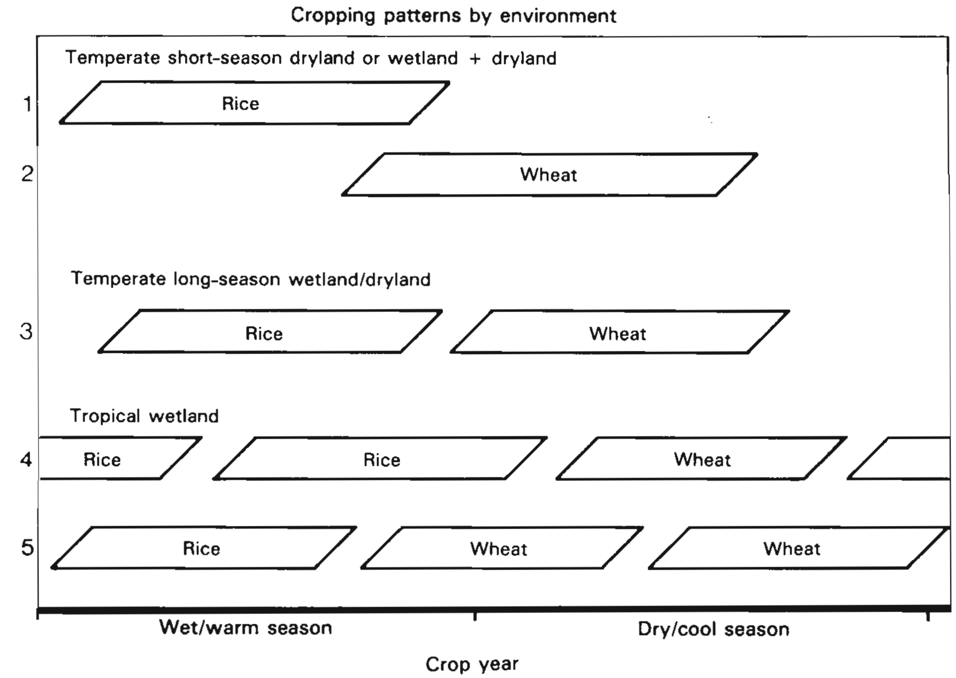

Figure 1. Wheat and rice cropping patterns in temperate and tropical environments.

belonging to more than one family. Oligophagous insects fall in between, developing on plants within a single family. In biological terms, an insect plant host is a species or a local population of species that can sustain development from egg to egg.

Insect pests that can develop on both rice and wheat are necessarily oligophagous or polyphagous as each crop belongs to a different genus within the grass family Poaceae. Rice belongs to the subfamily Oryzoideae, tribe Oryzeae and wheat to the subfamily Festucoideae, tribe Horbeae.

Crop rotation in the same field is particularly effective against pests with narrow host ranges, low dispersive powers, and long life cycles (50). Crop scheduling should be carried out over a wide area to be effective. The size of the area should have a radius larger than the effective dispersal range of the pest

Rotating a host with a nonhost will mean the death of the pest unless it disperses or physiologically enters dormancy until the host reappears. High pest mortality usually accompanies dispersal or dormancy. By definition, monophagous pests will be harmed most by rotation of rice and wheat, and polyphagous pests least.

The host range of a pest is not limited so much by the food value of the plant, as by its defensive system. Plants fend off insect pests by producing toxic chemicals called allelochemics. Morphological defenses such as pubescence or silica-rich stems are less significant.

Pests overcome chemical defenses by possessing enzymes specific to each toxic allelochemic. As it takes energy to produce these enzymes, each pest is limited to how many enzymes it can efficiently produce, set against other uses for that energy such as reproduction or dispersal. With exceptions, the more closely related plants are botanically, the more similar are their chemical and morphological defense systems. Most pests are oligophagous. In areas where irrigated rice can be grown year-round, monophagous species become major pests. Wheat is not grown year-round and therefore is similar to upland rice in having oligophagous or polyphagous major pest species (67).

Shared Pests

Rice and wheat have almost 200 insect pests in common on a worldwide basis (Appendix). These records are not necessarily from the same location or from a rice-wheat rotation.

Termites
Termites utilize dead plants and would not be expected to be agricultural pests. But a number of grassland-adapted species harvest young plants, which they take to underground chambers to be inoculated with fungi. The fungi break down the plant tissues, and the termites feed on the fungi. In the absence of dead plants, termites will harvest living ones, particularly at the beginning of a crop cycle where land preparation has turned under plant residues, which become difficult for termites to locate. Termites will be more attracted to a crop that is not growing vigorously, perhaps one suffering from water stress.

In the Philippines, *Macrotermes gilvus* selectively decimated wheat plots in an upland rice field. The wheat crop literally disappeared, while the rice crop was hardly damaged. Wheat was growing less well on the acid soil than the rice.

In India termites were emphasized more as pests of wheat. None of the termite species mentioned attacked both rice and wheat (88).

Flooding normally controls termites, but *Microtermes* spp. damaged rice seedlings in a wetland seedbed soil in India. In this case, greater damage was done to rice.

Minimum tillage methods leave plant residues on the surface of the field to divert termites from attacking a young crop. Agronomic practices that produce vigorous growth allow crops to resist termite damage.

Mole crickets and field crickets
Mole crickets are omnivorous, tunneling with their front legs in the soil during the day to locate roots and foraging at night on the surface as insect predators. They cannot live in flooded fields, but exist in the dry bunds of wetland rice fields. They thrive best in moist soil that can be easily dug. Damage is more severe on a young crop, as a mole cricket can eat the entire root system, killing the plant. They are cannibalistic and never become extremely abundant. Many species of mole crickets are reported from both wheat and rice.

Field crickets live in the soil, but do not tunnel extensively. They roam the soil surface eating seeds and young seedlings. Some species cause deadhearts while others defoliate. Crickets as a group are highly polyphagous and many species would attack both wheat and rice.

Both mole crickets and field crickets seek shelter under plant residue, either 1) weeds removed during weeding and piled or 2) in heaps of straw after threshing. Their populations will be minimized by spreading piles of weeds or crop residue, otherwise they are controlled by insecticide-poisoned bait.

Meadow grasshoppers and katydids
Meadow grasshoppers and katydids feed on foliage and, more importantly, on rice grains, but are also effective egg predators of stem borers and seed bugs. They are more adapted to wetlands as their common name, meadow grasshopper, implies, because they lay eggs in leaf sheaths and not in the soil, as do most grasshoppers. Because they are omnivorous, they could readily attack both rice and wheat. However, they rarely become abundant and their role as predators at least partially outweighs any potential pest problem they may pose.

Grasshoppers
Except for wetland-adapted species, shortfaced or shorthorned grasshoppers lay eggs in soil and therefore are adapted to drylands. Grasshoppers are highly polyphagous and readily feed on both wheat and rice. Their low status as pests of wetland rice stems not from a difference in food quality between wetland and dryland rice, but from the detrimental effects of flooding on most grasshopper species. Grasshoppers have no distinct preference for either wheat or rice, so normally they are unimportant to either crop. Locust outbreaks, however, continue to exist worldwide. Locusts are best controlled by altering the habitat where they breed or by using insecticide-treated bait against immatures in their breeding grounds before they migrate. Because of their egg laying habits, wheat following wetland rice should have fewer grasshopper problems in wetlands than drylands.

The wetland-adapted *Oxya* species lay their eggs behind leaf sheaths of rice, but they rarely become sufficiently abundant to pose any problem. Grasshoppers are more a pest problem in low rainfall areas, which allow a greater egg survival. They tend to build up in perennial grasses before moving to annuals. Farm areas near extensive grasslands have a greater chance of being damaged than in areas with minimal grasslands. Adoption of a rice-wheat rotation in itself implies small farm sizes and intensive cropping as a result of population pressure and encroachment of grassland fallows.

Root aphids

Winged root aphids invade newly planted fields soon after crop emergence. Subsequent generations are wingless and individuals feed underground on roots of dryland plants. They remove plant sap from the roots, which causes the plant to turn yellow and become stunted. They attack rice from a newly emerged crop until harvest. None of the several species found on both wheat and rice transmit viruses. Ants care for root aphids by transporting them from plant to plant as well as fending off natural enemies. In return, ants receive the sugary honeydew secreted by aphids. Root aphids are more abundant in grassland areas, as perennial grasses are important alternative hosts. In temperate regions, root aphids pass the winter on trees.

Aphids reproduce parthenogenetically without the benefit of males. This adaptation allows for a high rate of population increase, which is further enhanced by the protection from natural enemies afforded by ants.

Flooding kills root aphids, therefore they are only found in dryland fields. Soft-bodied root aphids also perish from tillage operations after harvest during early land preparation for the following crop. Root aphids are difficult to control.

Shoot aphids

Aphids feeding on shoots and leaves are much more prevalent on wheat than either wetland or dryland rice. Rice is traditionally grown in the wet season summer and wheat in the low rainfall winter. Heavy rainfall is detrimental to aphid population buildup and aphids may have adapted better on a crop more suited to low rainfall conditions.

Shoot aphids are highly dispersive, travelling tens of kilometers with the wind. They are highly attracted to yellow, indicating they are day flying and locate the crop by sight.

Shoot aphids remove plant sap and produce copious amounts of honeydew, which falls onto the foliage, turning black with fungal infection. Colonies rapidly develop around the colonizing mother aphid. Aphids give birth to only females during their multiplication phase. Eggs are not laid until the population is ready to disperse to another host. Aphids typically have broad host ranges. The rice shoot aphid, *Rhopalosiphum padi*, is more prevalent on wheat than rice despite its name. *Hysteroneura setariae*, frequently recorded on wheat and rice, is a dryland pest.

Of great concern is the propensity of shoot aphids to transmit virus diseases (Table 1). *H. seteriae*, *R. maidis*, and *Schizaphis graminum* are recorded on both wheat and rice and vector sugarcane mosaic virus. The other aphid vector, *Dactynotus ambrosiae*, is not recorded on wheat or rice. Aphids are readily controlled with insecticides, but prevention of virus disease transmission requires expensive repetitive applications.

Planthoppers
Planthoppers are known for their ability to disperse long distances and to multiply rapidly. They feed during all crop growth stages and remove phloem sap from the base of plants. The proteinaceous feeding sheaths they leave in plant tissue while feeding block the flow of phloem sap, causing wilt or hopperburn.

Planthoppers have become major pests of wetland rice as a result of multiple rice cropping in irrigated areas. Their habit of living at the base of the plant protects them from pelting rain in monsoon Asia. Natural enemies play a pivotal role in containing their numbers even with favorable year-round availability of rice. Broad spectrum insecticides applied against other pests kill natural enemies, unleashing the planthoppers to hopperburn extensive areas.

The brown planthopper, *Nilaparvata lugens*, is a major rice pest in Asia, causing hopperburn and transmitting three virus diseases; none however occurs on wheat. It cannot overwinter in cold climates. It is considered to be monophagous, but it is known to be able to quickly

Table 1. Insect-vectored virus diseases shared by rice and wheat

Disease	Vectors	Location	Reference
Rice gall dwarf virus	*Recilia dorsalis* *Nephotettix cincticeps*	China	94
Rice hoja blanca virus	*Sogatella orizicola*	Latin America	5
Rice dwarf virus	*Recilia dorsalis* *Nephotettix cincticeps* *Nephotettix nigropictus*	Japan, Korea, China, Nepal	96
Rice black streaked dwarf virus	*Laodelphax striatellus* *Muellerianella fairmairei* Unkanodes albifascia Unkanodes sapporonus	Japan, Korea, China	96
Rice striped virus	*Laodelphax striatellus* Muellerianella fairmairei Unkanodes albifascia	Japan, China, Korea	96
Oat pseudo-rosette virus	*Laodelphax striatellus* *Unkanodes albifascia* *Unkanodes sapporonus*	Siberia, Japan	96
Wheat streaked virus	*Toya catilina*	East Africa	96
Sugarcane mosaic virus	*Hysteroneura setariae* *Rhopalosiphum maidis* *Schizaphis graminum* *Dactynotus ambrosiae*	Worldwide	96

adapt to new rice genotypes. A local population in the Philippines, for example, lives on a rice field weed, *Leersia hexandra*, in waterways surrounding rice fields (28). This sympatric population is reproductively isolated from the general population, which feeds on rice. The single record in the literature of its feeding on wheat is highly suspicious as it was reared on wheat in a test tube.

Two other rice planthoppers, one in Latin America, *Sogatella orizicola*, and one in temperate Asia, *Laodelphax striatellus*, are potentially more of a threat to wheat. *S. orizicola* is the vector of hoja blanca, which is a major rice virus disease in tropical Latin America. The virus and vector were reported on wheat in Colombia. *Laodelphax* can overwinter in the subfreezing climates of Japan, China, and Korea.

It also occurs in the mountainous regions of the northern Philippines. It is not a pest of rice in the Philippines because the rice area in mountainous regions is very small — only one annual rice crop — and no alternative host such as wheat or barley is grown. It is, however, a major pest in temperate Asia, where it transmits three virus diseases — rice black streaked dwarf, rice stripe, and oat pseudo-rosette — common to both rice and wheat. The other planthopper vectors of these same three viruses are rarely encountered on either crop. Rice black streaked dwarf and rice stripe are serious virus diseases of rice in Japan.

Peregrinus maidis transmits plant diseases but prefers maize. Planthoppers and the viruses they vector are most effectively controlled by resistant varieties.

Leafhoppers

Leafhoppers are cousins of planthoppers, but are less dispersive and rarely become sufficiently abundant to cause direct damage from feeding. Leafhoppers also vector virus diseases. Most species feed from the phloem but others, notably *Thaia oryzivora*, remove patches of mesophyll, producing a chlorotic, stippling appearance on the leaves. Leafhoppers feed on leaves during all growth stages and occur on the topmost portion of plants.

The green leafhoppers *Nephotettix cincticeps* and *N. nigropictus* are virus vectors and are more important to rice than wheat. *N. virescens* is considered to be monophagous and vectors important diseases to rice, but not wheat.

The zigzag leafhopper, *Recilia dorsalis*, is potentially more serious, as it feeds readily on both rice and wheat and vectors several virus diseases. The blue leafhopper, *Zygira maculifrons*, can cause hopperburn on young rice.

The rice leafhopper, *Cofana spectra*, and orange leafhopper, *Thaia orizivora*, are minor pests of rice; wheat is a less preferred host. The remaining leafhoppers prefer neither rice nor wheat and none is a known vector.

In contrast to planthoppers, leafhoppers are density dependent and regulate their own populations. When they become abundant, the females produce relatively fewer eggs. As with planthoppers, leafhoppers are best controlled by resistant varieties.

Root bugs

Bugs in the family Lygaeidae feed as nymphs and adults on the sap of roots in the crown of the plant. They only occur in dryland habitats. The chinch bug, *Blissus leucopterus*, is more a pest of wheat than rice and when abundant its damage can cause the plants to wilt. Chinch bugs migrate on the ground to adjacent fields at harvest and can severely damage younger crop borders. They hibernate over the winter in grasses.

The other recorded species prefer grasses to either wheat or rice. Synchronous planting helps control their population buildup.

Plant bugs
Mirid and pentatomid plant bugs remove sap from leafsheaths, leaves, and culms. *Scotinophara lurida* is known as the Japanese black bug of rice and causes hopperburn by its removal of sap from the phloem, much the same way as rice planthoppers. Wheat is of minor importance to this pest. Black bug pests of rice are notably aquatic, but there are related species that prefer dryland areas. Plant resistance would be the most practical control tactic.

Seed bugs
A number of hemipterous seed pests are adapted to a wide range of grasses. They puncture developing seeds with their sucking mouthparts to inject an enzymatic saliva to predigest endosperm. They not only prevent grain filling but, when the damage occurs after the grains are developed, blemished grains result from bacterial infection.

The most serious seed pest of wheat, *Eurygaster integriceps*, is not recorded on rice, but the most important seed pests of rice, *Leptocorisa oratorius*, *Oebalus pugnax*, and *Nezara viridula*, feed on wheat. The rice bug, *L. oratorius*, is not readily attracted to wheat and the record on wheat is infrequent. *Oebalus* and *Nezara* can readily move from crop to crop.

Adult seedbugs are highly mobile and long-lived and each crop is receptive for only a few weeks during grain filling. They must continuously move from older to younger fields. Planting so that grain filling occurs within a few weeks in all fields is a practical control method.

Thrips
Plant thrips can feed on mesophyll of young leaves or within flowers on developing grains. The recorded *Haplothrips aculeatus* feeds on developing grains, preferring wheat to rice. Their small size and secretive habits allow them to usually go unnoticed. If grain sterility is encountered, then thrips would be candidates for causing such damage. They feed by rasping plant tissue with their asymmetrical mouthparts. Rainfall normally physically controls them and they become most abundant during dry spells.

Ground beetles
Gonocephalum ground beetles are omnivorous as adults, in that they feed on decaying vegetation, prey on other insects, and eat plant tissue. Accordingly, they have wide host ranges and feed on the roots of young plants, often killing seedlings. As soil pests they occur only in dryland habitats. Tillage disturbs their habitat.

White grubs
White grub larvae prefer the fibrous root systems of grasses in dryland habitats. Plants having tap roots are readily killed and are not suitable. The large larvae can consume the entire root system of a young plant, causing death, or only part of the root system, causing stunted growth. Both wheat and rice are readily attacked. In the tropics, the larvae mature slowly; one generation occurs per year. White grubs normally pass

the winter or dry season fallow in dormancy as larvae in the moist soil profile. They emerge as adults after the onset of the rainy season to lay eggs in tilled soil. White grub species are highly indigenous, but their life cycles and larval food preferences vary little from region to region. *Holotrichia consanguinea* in India has caused high yield losses on both wheat and dryland rice (100).

Because of the winter/dry season dormancy, white grubs are only active half the year. It is important to avoid planting a crop when the larval population is in the large third instar. Planting should be timed during dormancy or when the larvae are young and cannot consume much root mass.

Root beetles
In Latin America, a number of *Diabrotica* species feed in the soil on the roots of a young crop, particularly fibrous root systems. The adults are highly mobile and feed on pollen, laying eggs in the soil. The eggs can undergo dormancy to pass a winter underground. Eggs hatch with warmer weather and the young larvae feed on roots. As root pests they prefer grasses, but show little preference between grass species. Crop rotation with a nonhost is effective to control them.

Flea beetles
Adult flea beetles defoliate seedlings by eating small holes in the leaves. What they lack in size as individuals they make up in numbers. The larvae feed on roots of grasses. *Chaetocnema basalis* is a minor pest of rice and occurs only in the drylands, probably because of the larval soil habits as well as the habit of the adults to seek shelter under soil clods. Adults are dispersive, but are restricted to a young crop, therefore synchronous planting is effective in controlling them.

Leaf beetles
Adults and larvae of leaf beetles feed on the soft tissues of leaves, producing a scraping injury and leaving only the white epidermis of the leaf showing. *Oulema oryzae* is adapted to temperate climates of Asia and *Chnootriba similis* is found in the warmer climates of Africa. They feed on the crop for a longer period than flea beetles. High numbers are required before economic damage occurs, as crops normally can withstand high levels of defoliation. They can only be controlled by foliar insecticides.

Wireworms
The elongated larvae of wireworm beetles are hard as wire, hence their name. The larvae are long-lived and feed on roots of a wide range of crops in dryland soils. As with most soil pests, many species occur worldwide. They are more damaging to tuberous crops than grasses. Their numbers are reduced by crop rotation.

Cutworms, armyworms, and headworms
Noctuid larvae that live in the soil and feed at the base of young plants, often severing them, are called cutworms. The black cutworm, *Agrotis ipsilon*, occurs worldwide and attacks more than 100 plant species. It is migratory and has a high reproductive rate. Air currents concentrate their numbers, and infestations usually are localized. Eggs are laid in masses of several hundred, further concentrating the attack.

Armyworms are also migratory and highly fecund noctuid moths. Their larvae feed on all stages of a wide range of hosts. They often prefer grassy weeds, moving to a crop after the weeds are removed by the farmer. At harvest, they move to a neighboring field in mass, giving them the name armyworms. Armyworms sever the panicle or spike, causing high yield loss of both rice and wheat when abundant at heading. The rice ear-cutting caterpillar, *Mythimna separata*, has been frequently reported attacking both wheat and rice, causing damaging outbreaks in both crops.

Heliothis species are known as headworms because they prefer developing grain, but they are defoliators on a younger crop. They are cannibalistic and do not become as abundant as armyworms. *Heliothis* is more common in wheat and rarely attacks rice. Because of their high reproductive powers and large voracious larvae, armyworms and headworms are a threat to both wheat and rice. They can be controlled by chemical or microbial insecticides, sprayed in the late afternoon before the larvae climb up the plants to feed at night.

Loopers, leaffolders, skippers, and caterpillars

Larvae of moths (loopers and leaffolders) and butterflies (skippers and caterpillars) defoliate during all crop growth stages. Except for leaffolders, they have low reproductive rates and rarely cause economic damage. Butterfly larvae grow large, but slowly, making them ready targets for parasites and predators. Leaffolder larvae tie the edges of leaf blades together and, as the silk contracts upon drying, the edges close to form a shelter. The larvae scrape leaf tissue from within the feeding chamber, giving the leaves a whitish appearance. The folded leaf offers protection from many parasites and predators. Leaffolder populations are normally held in check by egg predators, larval parasites, and pathogens. Damaging numbers usually result from a combination of high levels of nitrogen fertilizer plus application of broad-spectrum insecticides directed at other pests earlier in the season. Insecticides selectively kill predators and parasites of the leaffolder, allowing greater leaffolder survival, leading to damaging populations — a phenomenon known as resurgence. Microbial insecticides spare natural enemy populations.

Stem borers and webworms

Stem borers lay their eggs in masses on foliage and the larvae hatch in unison to tunnel into stems within hours. The crop is most susceptible to entry by these small larvae during two elongation growth phases — active tillering and panicle exertion. Damage at these stages can result in the death of a tiller or panicle, creating deadhearts or whiteheads, respectively. Deadheart damage can be somewhat compensated for by increased tillering in high tillering plant types.

Stem borers can attack all stages of the crop as soon as the seedlings develop a hollow pith large enough to accommodate small larvae. After harvest, stem borer larvae and pupae remain in the stubble left in the field. Some stem borer species can pass a cold winter or dry summer in dormancy in the stubble. None of the monophagous rice stem borers — yellow rice borer, *Scirpophaga incertulas*; Asian white rice borer, *S. innotata*; African white rice borer, *Maliarpha separatella*; Latin American white rice borer, *Rupela albinella*; or the African stalk-eyed flies, *Diopsis* spp. — attack wheat.

In Asia the polyphagous pink stem borer, *Sesamia inferens*, readily attacks wheat and both wetland and dryland rice, and repeatedly has been reported causing losses on both crops. It is most known as a sugarcane pest and will be more numerous if sugarcane fields are nearby. *Chilo partellus* and *C. auricilius* attack most cereals including wheat and rice, predominantly in dryland environments.

Diatraea saccharalis fills the same niche as *Sesamia* in Latin America, but the highly polyphagous lesser cornstalk borer, *Elasmopalpus lignosellus*, which also attacks seedlings of both crops, has been reported as a pest more often. Young *Elasmopalpus* larvae spin silken tunnels on the outside of the tillers allowing them to colonize a young crop. These webworms sever seedlings at the base. *Herpetogramma licarsisalis* in Asia has much the same habits as *Elasmopalpus* and also occurs only in drylands.

Several chloropid stem maggots in Japan including *Chlorops oryzae*, a noted rice pest, are reported on both wheat and rice. They are temperate species and prefer dryland environments. The dipterous stem borers *Oscinella frit* and *Phytophaga destructor* do not attack rice.

Stem borers and webworms are controlled by early-maturing varieties, community wide crop scheduling, and crop residue destruction. Zero tillage practices in wheat following rice result in an appreciable increase of monophagous rice stem borers that survive during the wheat crop to reinfest the subsequent rice seedbed (48). Zero tillage also favors oligophagous stem borers that attack both wheat and rice (66).

Seedling maggots
Seedling maggots are Asian and African dryland species that lay eggs on newly-emerged plants. The maggots sever tillers causing deadhearts and feed on decaying tissue. The taxonomy of this group has been confused over the years and many plant host records are erroneous.

The important sorghum shoot fly, *Atherigona varia soccata*; wheat bulbfly *Leptohylemyia coarctata*; and *Hylemyia cilicrura* are reported from wheat but not rice. *A. naqvii* in India is known only from wheat. The rice seedling maggot, *A. oryzae*, which is an important pest on dryland rice, maize, and sorghum, is recorded at low levels on wheat.

Seedling maggots are highly cyclic in occurrence. They probably aestivate over the dry season in grasses and emerge in low numbers with the onset of rains, becoming very abundant several months later, then decline once more. Damage is most severe in low tillering crops which cannot compensate for loss of tillers. Adjusting the time of planting even by as little as two weeks is an important control method.

Leaf miners
Several species of agromyzid flies lay eggs on foliage and the larvae tunnel within leaf blades. Leaf miners are small and each one causes insignificant loss of photosynthetic tissue. Their populations are normally held in check by larval parasites. At times, often as a result of the use of broad-spectrum insecticides directed against other pests, the parasite populations become selectively reduced, causing resurgence. *Pseudonapomyza spicata* has reached economic levels on wheat in the Philippines. It also occurs on both dryland and wetland rice but at much lower levels. They can be controlled by minimal use of insecticides.

Gall and blossom midges
Gall midge larvae feed on primordial tissues of young tillers. Damaged tillers emerge but do not bare panicles. Blossom midges develop with young seed. The rice gall midges in Asia *Orseolia oryzae* and Africa *O. oryzicola* do not attack wheat. The only record of a midge from both wheat and rice comes from dryland rice in temperate Japan by the orange wheat blossom midge *Sitodiplosis mosellana*. It does not attain economic numbers on rice.

Leaf cutting ants
Numerous species of ants in Latin America feed on young plants by cutting sections of leaves and carrying these to underground nests. Large colonies of ants near cropped fields can be highly destructive. These ants only occur in dryland areas and feed on a wide array of plant species. They live in permanent nests deep in the soil often in fallow areas. Intensive cropping, minimizing perennial field border habitats, will reduce their populations.

Seed harvesting ants were not recorded for rice and wheat but certainly exist. Species of fire ants *Solenopsis* specialize in gathering fallen seeds in grassland environments. They are particularly important during times when there is a delay in crop emergence after seedings. Normally, more wheat and rice seed is sown than required and ant damage is insignificnt. But if ants cause stand reduction, future crops can be protected by treating the seed with kerosene, an inexpensive control practice of farmers.

Sawflies
Hymenopterous stem borers, *Cephus* spp., are major pests of wheat in North America and Europe, but not Asia or Latin America. Only two species have been recorded on rice, both in Japan. *Dolerus* spp. however, are insignificant on either wheat or rice.

Control Strategies

The first control strategy is to lower the carrying capacity of the environment to insect buildup by community-wide adoption of crop schedules and crop residue management (68, 102). These cultural control tactics vary with each environment. The basic objective in the tropics is to create the effect of a winter to stop pest buildup favored by year-round optimal temperatures.

Temperate short-season environments
Diversified cropping areas typical of colder temperate mountain valleys (Figure 1, patterns 1 and 2) are more isolated in space and time and generally support lower pest populations than warmer alluvial plains with expanses of contiguous fields planted to rice and wheat. The short growing season and long winter itself produce a high pest mortality. This beneficial effect is offset by the high synchronization of the pest population when it emerges from overwintering, concentrating the attack. Pests in short-season areas 1) specialize either in the warm or cool season crop and lie dormant in the opposite season, or 2) disperse from an older crop at harvest to a nearby overlapping young crop. Pests which either aestivate or hibernate will not be influenced by the presence of the nonhost crop.

Specialized pests are controlled by stubble plowdown after harvest of only the host crop. Pests which disperse will transfer crops and will survive in proportion to area cropped. Those species that will be favored can readily disperse and attack rice or wheat at any crop growth stage and must be managed in both crops. Overlapping pests can be minimized by creating a break in the pest cycle by 1) delaying the planting of rice in the spring as long as possible, 2) minimizing the period of crop overlapping (wheat stubble and young rice; maturing rice and young wheat), by plowing under rice and wheat stubble after harvest and repeated plowings to eliminate weedy fallows.

The potentially most serious pest problem in short-season environments is a virus or mycoplasma disease common to rice and wheat transmitted through a common vector (Table 1).

Temperate long-season environments

A warmer climate allows crops to grow faster, and with a longer season, rice and wheat can be rotated in the same field (Figure 1, pattern 3). In dryland areas, two gramineous crops following one another will allow some soil pests to increase over time. The problem will be less if both crops are established with deep, frequent tillage to disturb the soil habitat. Most soil pests are controlled by flooding.

Foliar pests are important in both the drylands and wetlands. Community-wide crop scheduling will be important in creating breaks in the crop cycle. Monophagous pests pass the nonhost crop period in dormancy and are controlled by stubble plowdown. Zero tillage benefits these pests. Oligophagous and polyphagous pests transfer during crop overlaps and are controlled by synchronous planting and stubble plowdown.

Tropical environments

In irrigated environments with year-round temperatures favorable for development, community-wide crop scheduling is the foundation of pest control. Wheat introduced into a rice-rice cycle to allow three crops per year is helpful in breaking the rice cycle (Figure 1, pattern 4). Also, theoretically, rice introduced into a wheat-wheat cycle would have the same effect in reducing wheat pests (Figure 1, pattern 5).

Year-round growing cycles create pest problems when farmers plant independently from their neighbors. Staggered planting allows pests, particularly viruses, to become continuously abundant. This bitter lesson was learned by large-scale farmers who attempted to grow continuous rice. Four crops per year on the same land are possible. Two rice crops however are optimal, leaving sufficient time to grow a second or third nonrice crop to break the cycle.

An exponential human growth rate has forced increased cropping intensity. Organization of crop scheduling is a necessary step societies must adapt to counteract a more favorable environment to pests accruing from expanding the spatial and temporal availability of their crop hosts. China (102) and Indonesia (69) have adopted irrigation-system-wide crop scheduling as a first step in pest control.

A rice-rice-fallow pattern should have fewer pest problems than a rice-rice-wheat pattern. But rice-rice-wheat should have fewer pest problems than rice-rice-rice. If the third crop were not in the grass family, pest problems would even be lower. Greater pest stability would accrue from rice-wheat-legume or other nongramineous species as a third crop. In the three-crop patterns, the time of planting of each crop is dictated by water availability, solar radiation, and temperature more than whether some insect pests will be favored or not; but at least this outcome should form part of the information used in decision making, as it can be very powerful in controlling pests.

Resistant varieties and insecticides are considered as the second line of defense in a pest management program because the pests can readily develop biotypes to counterbalance these measures. Cultural methods are broad spectrum in effect and are difficult for pests to evolve biotypes in response, and therefore are a first line of defense.

Natural enemies normally keep pest numbers in check and must be protected from broad spectrum insecticides. Minimal perturbation of natural enemy numbers will occur if insecticides are applied only when populations become economically threatening. Replacing synthetic insecticides with biologically based materials — microbial or plant origin — will spare more natural enemies and be safer to farmers and the environment.

Analysis of Potential Pest Problems

Rice and wheat are sufficiently distantly related and ecologically separated that few major pests shared by rice and wheat occur at economic levels on both crops. Most of the species we listed are highly polyphagous and have low pest potential on either crop. More revealing is not which pests were mentioned, but which major pests were not recorded on both crops. The serious pests of rice — with the exception of pink stem borer, *Sesamia inferens*; earcutting caterpillar, *Mythimna separata*; smaller brown planthopper, *Laodelphax striatellus*; and leaffolder, *Cnaphalocrocis medinalis* — do not readily develop on wheat. Wheat has fewer insect pest problems than rice. The shoot aphids, sawflies, blossom midges, and seedbugs occur only sporadically on rice even in the temperate zones where both crops overlap.

The potentially most serious insect pest problems would be viruses vectored by aphids, leafhoppers, or planthoppers. Thirteen species vector eight virus diseases common to both crops (Table 1). None is important now but could become important as the area of rice-wheat rotation increases.

Soil pests — termites, ants, mole crickets, field crickets, white grubs, ground beetles, root beetles, wireworms, root aphids, root bugs — only pose a problem in dryland habitats, particularly in regions with extensive uncultivated grassland areas, which are a perennial source of this pest group. As grasslands disappear with intensive cropping, so do many of these pests. Tillage exposes soil pests to desiccation as well as to their natural enemies and reduces their food supply. The more the soil is turned over, the lower is the biomass of roots, crop residue, and seeds upon which they feed. Establishing rice and wheat with several plowings and harrowings of each will decrease soil pests. Soil pest numbers often are low at the beginning of the crop year, therefore early planting would assure greater crop vigor to tolerate damage.

Among soil pests, root aphids and white grubs are the most difficult to control. Root aphids are more mobile and can colonize from farther away. They would be less affected by tillage operations, but their damage is less on a well established crop. They are difficult to control by any known method, particularly in response to damaging populations detected after the crop has established. White grubs, because of their large size, are difficult to control with insecticides and can be serious problems in areas where high numbers exist.

Shoot pests that are restricted to a young crop — flea beetles, seedling maggots, and gall midges — are also only abundant in dryland habitats. Rotating another crop should not affect this group of pests, which depends on finding young crops continuously. Flea beetles and seedling maggots have short life cycles to match the small window of time open to them for colonization and development. Synchronous planting will be very important in keeping their numbers down. Staggered planting between fields allows more of them to find young crops. Adjusting planting times may reduce these pests, otherwise insecticide seed treatment will be necessary.

Shoot pests that are not restricted by crop growth stage — grasshoppers, leaf beetles, armyworms, loopers, leaffolders, leafminers, webworms, skippers, stem borers, and sawflies — will more readily be able to span the bridge between crops, particularly if they are planted close together. It is important to create a break in the crop cycle as many times in a year as possible, by first selecting early-maturing varieties. Rotating wheat and rice, of course, has a more beneficial effect in controlling pests than if rice followed rice or wheat followed wheat. But with this group of pests, it is necessary to maintain natural enemy populations, which are also favored by the extended crop season and availability of hosts. Minimizing broad-spectrum insecticides will conserve natural enemies that regulate these pests. This group of pests increases in severity with increased use of nitrogen fertilizer. Therefore, using only optimal amounts of nitrogen will temper their population increase.

The sap feeders—shoot aphids, planthoppers, leafhoppers, plant bugs, and thrips—are more important as vectors of diseases than as causing direct feeding damage. Heavy rainfall is a natural controlling mechanism to these exposed soft-bodied insects. The role of natural enemies is less helpful to prevent insect vectors from transmitting diseases. Plant resistance to both the vector and the disease becomes an important control method along with breaking the crop cycle during the year.

Seed pests—seed bugs, blossom midges, and meadow grasshoppers—will be helped if an additional crop is grown, but the major pest species for either rice or wheat do not readily feed on both crops. Polyphagous species will benefit most. Seed pests are generally difficult to control. Insecticides have to be used repeatedly, especially if rainfall is frequent. Synchronous planting and particularly synchronous flowering is important to minimize the time available for these pests to undergo more than one generation each crop. The availability of other flowering hosts when rice or wheat is not flowering is also important. These pests are highly mobile and can locate small isolated fields.

Conclusion

Pests are highly adaptable to changing crop production practices. We can expect pest problems to develop in proportion to the ecological apparency of suitable crops for pest development (21). Of the two ecological parameters — time and space — the former is more important to sustain pest populations. An excellent example of this is wheat. Large areas of monoculture wheat exist in various parts of the globe, but insect problems are relatively few. This is because wheat is grown as a single crop.

It is not by chance that relatively fewer wheat pests than rice pests appeared on the list of species shared between the two crops. The number of species attacking rice is more than wheat because rice is double- and even triple-cropped. Five of the eight shared viruses are rice viruses and only one is a wheat virus. Host range increases as a pest becomes more abundant. Rice pests increase to high levels and many individuals will accept less preferred host plants (53, 77).

Wheat will more than likely have more new pest problems because fewer pests now attack wheat and more ecological niches are open. Phytophagous pests are highly adaptable and can transfer to new plant hosts as the area planted expands into new environments. This phenomenon is documented for soybeans in North America (59) and sugarcane worldwide (99). Pest species are highly endemic, transferring from less abundant weeds onto crops. As the area of rice-wheat rotation expands, new endemic pests will transfer from related grassy weeds to wheat, particularly in regions where the rice-wheat pattern replaces a rice-fallow or wheat-fallow pattern. If rice-wheat replaces a rice-rice, then the overall pest problems on rice will lessen. Wheat will still have potentially more problems than it would in a wheat-fallow rotation.

Few new problems will appear in the first decade of introducing tropical wheats. Many pests have wide host ranges but locally specialize in only a few. Initially a new crop is colonized by polyphagous species, which later become replaced by more efficient host-specific species.

Appendix

Insect pests recorded in the field worldwide on both rice and wheat

Pest	Environment	Distribution	Reference
Isoptera (termites)			
Hodotermitidae			
Hodotermes mossambicus (Hagen)	Dryland	South Africa	43
Termitidae			
Microtermes obesi Holmgren	Dryland	India	36,43,83
Microtermes vadschaggae (Sjostedt)	Dryland	Tanzania	43
Microtermes sp.	Wetland	India	72
Procornitermes triacifer (Silvester)	Dryland	Brazil	43
Trinervitermes isiformis (Wasmann)	Dryland	India	43
Trinervitermes rubidus (Hagen)	Dryland	India	43
Macrotermes gilvus (Hagen)	Dryland	Philippines	a
Orthoptera			
Gryllotalpidae (mole crickets)			
Gryllotalpa africana P. de B.	Dryland	Africa, Asia	36
Gryllotalpa orientalis Burmeister	Dryland	Philippines	a
Gryllidae (field crickets)			
Acheta domesticus (Linnaeus)	Dryland	Asia, Africa	36
Brachytrupes megacephalus (Lef.)	Dryland	Asia, Africa	36
Gryllus bimaculatus De Geer	Dryland	Asia	35
Gryllus campestris Linnaeus	Dryland	Asia, Africa	36
Oecanthus pellucens (Scopoli)	Dryland	Asia, Africa	36
Teleogryllus testaceus (Walker)	Dryland	Asia	35
Plebeiogryllus plebejus (Saussure)	Dryland	Asia	a
Tettigoniidae (meadow grasshopers, katydids)			
Mecopoda elongata (Linnaeus)	Wetland	Asia	35
Phaneroptera furcifera (Stal)	Wetland	Asia	35
Euconocephalus varius Walker	Wetland	Asia	35
Decticus albifrons (Fabricius)	Wetland	Asia, Africa	36
Decticus annaelisae Ramme	Wetland	Asia, Africa	36
Tettigonia caudata (Champ.)	Wetland	Asia, Africa	36
Tettigonia viridissima (Linnaeus)	Wetland	Asia, Africa	36
Pyrgomorphidae (slant-faced grasshoppers)			
Atractomorpha psittacina psittacina (de Haan)	Dryland	Philippines	35
Atractomorpha crenulata (Fabricius)	Dryland	Thailand	87
Acrididae (short-horned grasshoppers)			
Locusts			
Schistocerca gregaria (Forskal)	Dryland	India, Africa, Asia	36,61,103
Locusta migratoria manilensis (Meyen)	Dryland	Philippines	35
Locusta migratoria migratorioides (R. and F.)	Dryland	Africa	36,61
Nomadacris septemfasciata (Audinet-Serville)	Dryland	Africa	36,61
Zonocerus variegatus (L.)	Dryland	Africa	36
Grasshoppers			
Arcyptera labiata (Brulle)	Dryland	Middle East, Asia	36
Calliptamus italicus (L.)	Dryland	Middle East, Asia	36
Chrotogonus homalodemus (Blanch.)	Dryland	Middle East, Asia	36
Chrotogonus trachypterus robertsi Kirby	Dryland	Middle East, Asia	36
Dociostaurus maroccanus (Thunb.)	Dryland	Africa	36
Oedaleus decorus (Germ.)	Dryland	Africa	36
Oedaleus nigrofasciatus (De G.)	Dryland	Africa	36
Oedaleus senegalensis Krauss	Dryland	Africa	36
Oedipoda caerulescens (L.)	Dryland	Africa	36
Phymateus aegrotus (Gerst.)	Dryland	Africa	36
Phymateus pulcherrimus I. Bol.	Dryland	Africa	36
Poekilocerus hieroglyphicus (Klug)	Dryland	Asia, Africa	36
Pyrgodera armata (Fischer-Waldheim)	Dryland	Middle East	36
Sphingonotus carinatus Sauss.	Dryland	Asia	36
Sphingonotus azurescens (Ramb.)	Dryland	Africa	36

Appendix (continued)

Pest	Environment	Distribution	Reference
Thisoecetrinus pterostichnus (Fischer-Waldheim)	Dryland	Africa	36
Thisoecetrinus littoralis (Ramb.)	Dryland	Africa	36
Notostaurus anatolicus (Kr.)	Dryland	Asia	36
Ramburiella turcomara (Fischer-Waldheim)	Dryland	Asia	36
Oxya sp.	Wetland	Asia	56
Oxya velox (Fabricius)	Wetland	Asia	6
Oxya hyla intricata (Stal)	Wetland	China	21
Cyrtacanthacris tatarica (Linnaeus)	Wetland	Pakistan	52
Ailopus thalassinus (Fabricius)	Wetland	Egypt	41
Ailopus thalassinus tamulus (Fabricius)	Dryland	Philippines	35
Gastrimargus transversus marmoratus (Thunberg)	Dryland	Philippines	35
Melicodes tenebrosa tenebrosa Walker	Dryland	Philippines	35
Chilacris (=? Dichroplus) maculipennis (Liebermann)	Wetland	Chile	39
Hemiptera			
Aphididae (aphids)			
Root Aphids			
Anoecia fulviabdominalis (Sasaki)	Dryland	Asia	101,109
Tetraneura nigriabdominalis (Sasaki)	Dryland	Asia	7,8,101
Rhopalosiphum rufiabdominalis (Sasaki)	Dryland, Wetland	Asia, Latin America	36,38,101,110
Geoica lucifuga (Zehntner)	Dryland	Asia	35,38
Shoot Aphids			
Rhopalosiphum maidis (Fitch)	Dryland, Wetland	Cosmopolitan	38,61,110
Rhopalosiphum padi (Linnaeus)	Dryland	Asia	7,8,16,36,38,45, 47
Sitobion akebiae (Shinji)	Wetland	Asia	109
Sitobion avenae (Fabricius)	Wetland	Asia	36,109
Sitobion (= Macrosiphumc) graminis Takahashi	Dryland	Asia	16,109
Longiunguis sacchari (Zehntner)	Dryland	Philippines	35
Hysteroneura setariae (Thomas)	Dryland	Asia	7,8,38,109
Schizaphis graminum (Rondani)	Dryland	Asia, Africa	35,61
Sipha flava (Forbes)	Dryland, Wetland	Latin America	110
Macrosiphum miscanthi	Wetland	Asia	38
Delphacidae (planthoppers)			
Sogatella furcifera (Horvath)	Dryland, Wetland	Asia, Egypt	2,73,75
Javasella pellucida (Fabricius)	Dryland	Japan	35
Peregrinus maidis Ashmead	Dryland	Philippines	35
Sogatodes oryzicola (Muir)	Dryland, Wetland	Asia, Latin America	64,86
Sogatodes pusanus (Distant)	Dryland	Philippines	a
Laodelphax striatellus (Fallen)	Dryland, Wetland	Japan, Korea, China, Philippines	40,60,74,78 75
Nilaparvata lugens (Stal)	Wetland, Dryland	Asia	75
Cicadellidae (leafhoppers)			
Erythroneura truncata Ahmed	Wetland	Pakistan	1
Typhlocyba jaina Distant	Wetland	Asia	57
Empoascanara (= Zygina = Typhlocyba) maculifrons (Motschulsky)	Wetland	Asia	30,57,84
Cicadulina bipunctella (Matsumura)	Wetland	Asia	57
Cicadulina mbila (Naude)	Wetland	Africa	57,93
Balclutha hebe Kirk	Wetland	Asia	57
Thaia subrufa (Motschulsky)	Wetland	Asia	57
Nephotettix cincticeps (Distant)	Dryland, Wetland	Japan, Korea, China	60,62
N. virescens (Distant)	Dryland, Wetland	Philippines, Asia	35,57
N. nigropictus (Stal)	Dryland, Wetland	Asia	20,22,49,57

Appendix (continued)

Pest	Environment	Distribution	Reference
Recilia dorsalis (Motschulsky)	Dryland, Wetland	Asia	54,60,78,106
Thaia oryzivora Ghauri	Wetland	Asia	46,54
Scaphoideus morosus Melichar			17,57
Scaphoideus sp.	Dryland	Asia	35
Cofana spectra (Distant)	Wetland, Dryland	Asia	35
Cofana yasumatsui Young (= *Kolla mimica* Distant)	Wetland	Asia	57
Yanocephalus yanonis Matsumura	Dryland	Japan	4
Lygaeidae (bugs)			
Root Bugs			
Blissus leucopterus (Say)	Dryland	Latin America	70
Elasmolomus sordidus (Fabricius)	Dryland	Philippines	35
Paromius piratoides (Costa)	Dryland	Philippines	35
Miridae (plant bugs)			
Stenodema calcaratum Fallen	Wetland, Dryland	Japan	4
Trigonotylus coelestialium Kirkaldy	Wetland	Japan	81
Trigonotylus ruficornis (Geoffr.)	Wetland	Asia	36
Pentatomidae (bugs)			
Plant Bug			
Scotinophara lurida (Burmeister)	Wetland	Japan	40,62
Seed Bugs			
Pygomenida varipennis (Westwood)	Dryland	Philippines	35
Oebalus pugnax (Fabricius)	Wetland	Latin America	12,79
Eysarcoris ventralis (Westwood)	Dryland	Philippines	35
Nezara viridula (Linnaeus)	Dryland, Wetland	Cosmopolitan	42
Acrosternum armigera (Stal)	Wetland	Brazil	9
Alydidae (seed bugs)			
Leptocorisa oratorius (Thunberg)	Wetland	Asia	54
Thysanoptera (thrips)			
Thripidae			
Haplothrips aculeatus (Fabricius)	Dryland	China	24
Coleoptera			
Tenebrionidae (ground beetle)			
Gonocephalus simplex (Fabricius)	Dryland	Africa	11,95
Scarabaeidae (white grubs)			
Phyllophaga sp.	Dryland	Latin America	70
Holotrichia consanguinea (Blanchard)	Dryland	India	100
Holotrichia spp.	Dryland	Philippines	35
Anomala sp.	Dryland	Philippines	35
Adoretus sp.	Dryland	Philippines	35
Autoserica spp.	Dryland	Philippines	35
Leucopholis irrorata (Chevrolat)	Dryland	Philippines	35
Chrysomelidae (beetles)			
Root Beetles			
Diabrotica speciosa (Germar)	Dryland	Latin America	9
Diabrotica balteata LeConte	Dryland	Latin America	70
Flea Beetles			
Epitrix cucumeris (Harris)	Dryland	Latin America	
Chaetocnema basalis (Baly)	Dryland	India, Philippines	89

Appendix (continued)

Pest	Environment	Distribution	Reference
Leaf Beetles			
Monolepta bifasciata (Hornstedt)	Dryland	Philippines	35
Oulema oryzae (Kuwayana)	Dryland, Wetland	China	108
Oulema erichsoni sapporensis Matsumura	Dryland	Japan	4
Coccinellidae (beetles)			
Leaf Beetle			
Chnootriba (= *Epilachna*) *similis* (Mulsant)	Dryland, Wetland	Africa	65,93
Elateridae (wireworms)			
Ectinus sericeus Candeze	Dryland	Japan	4
Lepidoptera			
Noctuidae (moths)			
Cutworms			
Agrotis ipsilon (Hufnagel)	Dryland, Wetland	Cosmopolitan	10
Mesapamea concinnata Heinicke	Dryland	Japan	4
Apamea sordens Hufnagel	Dryland	Japan	4
Armyworms/Headworms			
Mythimna separata (Walker)	Dryland, Wetland	Asia	19,20,37, 40,60
Mythimna loreyi (Duponchel)	Dryland	India	71
Mythimna unipuncta (Haworth)	Wetland	Chile	3
Euxoa spinifera (Hubner)	Dryland	India	71
Spodoptera mauritia acronyctoides Guenee	Dryland	Asia	37
Platysenta (= *Mythimna*) *compta* (Walker)	Wetland	India, Bangladesh	19,20
Spodoptera frugiperda (J.E. Smith)	Dryland	Chile, USA	3,25
Spodoptera exigua (Hubner)	Dryland, Wetland	India	103
Spodoptera litura (Fabricius)	Dryland, Wetland	Asia	76
Spodoptera exempta (Walker)	Dryland, Wetland	Africa	13,14,61
Faronta (= *Protoleucania*) *albilinea* (Hubner)	Wetland	Chile	3,39
Pseudoleucania impuncta (Guenee)	Wetland	Chile	3
Peridroma saucia (Hubner)	Wetland	Chile	3
Heliothis armigera Hubner	Dryland	Philippines	35
Heliothis zea (Boddie)	Dryland	Chile	3
Loopers			
Mocis latipes (Guenee)	Dryland, Lowland	Brazil	9
Mocis frugalis (Fabricius)	Dryland	Philippines	a
Rachiplusia ou (Guenee)	Wetland	USA	31,32
Neoplusis acuta (F.) (= *Chrysodeixis chalcites*)	Dryland	Philippines	35
Autographa californica (Speyer)	Wetland	USA	31,32
Stem borers			
Sesamia inferens (Walker)	Dryland, Wetland	Asia	37,49,51,53, 55,61,94
Sesamia calamistis Hmps.	Dryland	Africa	61
Pyralidae (moths)			
Webworms			
Herpetogramma licarsisalis (Walker)	Dryland	Philippines	a
Leaffolders			
Marasmia patnalis Bradley	Dryland, Wetland	Philippines	a
Marasmia trapezalis (Guenee)	Dryland, Wetland	East Africa	11

Appendix (continued)

Pest	Environment	Distribution	Reference
Cnaphalocrocis medinalis (Guenee)	Wetland, Dryland	Asia	22,35,37,66, 91,104,106
Stem borers			
Elasmopalpus lignosellus (Zeller)	Dryland	Latin America	90,92,98
Diatraea saccharalis (Fabricius)	Dryland, Wetland	Latin America	9
Chilo partellus (Swinhoe)	Dryland, Wetland	Asia	93
Chilo auricilius Dudgeon	Dryland	Philippines	[a]
Hesperiidae (skippers)			
Pelopidas mathias (Fabricius)	Dryland	Philippines	35
Parnara guttata mangala Moore	Dryland	Africa	18
Parnara guttata (Bremer and Grey)	Dryland	Philippines	35
Satyridae (green-horned caterpillars)			
Melanitis leda ismene Cramer	Dryland	Philippines	35
Melanitis leda leda Linnaeus	Dryland	Philippines	35
Mycalesis mineus (Linnaeus)	Dryland	Philippines	35
Diptera			
Chloropidae (flies)			
Stem borers			
Chlorops oryzae Matsumura	Dryland, Wetland	Japan	80
C. mujivorus Uishijima and Kanmiya	Dryland, Wetland	Japan	4
Meromyza nigriventris Macquart	Dryland	Japan	4
Meromyza orientalis Fedoseeva	Dryland, Wetland	Japan	4
Muscidae (flies)			
Seedling Maggots			
Atherigona oryzae Malloch	Dryland		26,63,85,97,106
Atherigona nudiseta megalaba Fan	Dryland	Japan	4
Agromyzidae (leafminers)			
Pseudonapomyza spicata (Malloch)	Dryland, Wetland	Asia	33
Phytomyza nigra Meigen	Dryland	Japan	4
Cecidomyiidae (gall and blossom midges)			
Sitodiplosis mosellana Gehin	Dryland	Japan	4
Hymenoptera			
Formicidae (ants)			
Leafcutting ants			
Atta spp.	Dryland	Latin America	23
Acromyrmex spp.	Dryland	Latin America	23
Tenthredinidae (sawflies)			
Dolerus ephippiatus Smith	Dryland	Japan	4
Dolerus lewisi Cameron	Dryland	Japan	4

[a] Observation by authors.

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Sclerotium rolfsii: Potential Impact on Wheat Production and Possible Means of Control

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Abstract
The soil-inhabiting plant pathogenic fungus Sclerotium rolfsii *causes considerable losses to a wide number of plant species, particularly in the tropics and subtropics. Sclerotia produced by this pathogen represent the resistant structures by which the fungus survives in soil. They germinate under optimal conditions of 27 to 30°C, in moist to wet soils, at pH 2.0 to 4.0, and in the upper 8 to 10 cm of the soil profile. Infection of host tissue is facilitated by the production of oxalic acid, which sequesters calcium to form calcium oxalate and also lowers the pH, and by production of endo-polygalacturonase. The pathogen can spread from plant to plant via root contact during one growing season. To reduce the disease, planting in fields containing low levels of inoculum, deep-plowing of infested fields to bury inoculum and organic debris, and application of nitrogen and calcium containing compounds, such as urea, ammonium bicarbonate, or gypsum, are recommended and may decrease losses. Of numerous fungicides, PCNB and vitavax have the best potential. Use of biocontrol agents may be worthy of further investigation. Plant tissues that are lignified or suberized are more tolerant to the action of oxalic acid and/or polygalacturonase and may be more tolerant to the organism. A simple technique to screen for resistance to* S. rolfsii *could be developed by utilizing fungal metabolites.*

The soilborne plant pathogenic fungus, *Sclerotium rolfsii* Sacc., infects an extensive number of crops comprised both of dicotyledonous and several monocotyledonous species. It has been estimated that the host range of this pathogen includes well over 500 plant species (1). In the United States, crops that have been most severely affected in recent years include carrot, pepper, tomato, and annual bluegrass-bentgrass golf greens. Initial symptoms of infection usually are wilting and severe necrosis, which are followed by the death of the plant due to stem and primary root infections. Most initial infections occur close to or at the soil surface, where saprophytic growth of the fungus and sclerotial germination are the greatest. *S. rolfsii* can become a serious problem during storage and in nursery beds where planting densities are high.

Diseases caused by *S. rolfsii* are especially rampant in the tropics and subtropics and in areas of the southern and southeastern United States. These areas are characterized by hot, humid climates, which are conducive to growth and survival of the pathogen. Under optimal conditions of temperature and moisture, mycelial growth rate is prolific and may range from 1 to 3 cm per day. Sclerotia produced by the fungus represent the overwintering or survival structures and generally constitute the primary source of inoculum for disease initiation (Figure 1). The sclerotia measure 0.5 to 2.0 mm in diameter, are dark brown in color, and have an outer melanized rind. Sclerotia may survive in the soil for periods of 1 to 3 years. Abundant sclerotial formation usually occurs when nitrogen levels are low or carbon:nitrogen ratios are high (14). Sclerotial germination is enhanced by a period of drying (17) or exposure to volatile compounds emitted from dried and remoistened plant tissues (18).

Abiotic Conditions Influencing Growth of *S. rolfsii*

The prevalence of *S. rolfsii* in the warmer regions of the world is a reflection of the high temperature optimum for growth and sclerotial germination. The growth rate of the fungus and disease progression are highest at 25 to 33°C, with the optimal at 27 to 30°C (Figure 2). The pathogen is rarely found in areas where the average daily minimum winter temperatures drop below 0°C or where the average summer temperatures are less than 20°C.

Germination of sclerotia of *S. rolfsii* and mycelial growth are increased with increasing soil moisture up to saturation (Figure 3); optimal moisture regimes are 0 to -3 bars. In drier soils (-3 to -10 bars), germination is reduced, and below -10 bars, few sclerotia germinate.

Mycelial growth of *S. rolfsii* and sclerotial formation and germination in soil usually are most abundant within the upper 8 to 10 cm of the soil profile. At deeper depths, sclerotial germination is inhibited (Figure 4). Elevated carbon dioxide levels up to 10% do not significantly reduce germination or mycelial growth to account for this inhibition (Figure 5). The increase in pressure imposed on sclerotia by the overlying soil may, in part, account for the reduced germination deeper in the soil (23). Survival of sclerotia is also decreased with increased time of burial in soil. Possibilities for disease control exist following deep burial of sclerotia (8, 16).

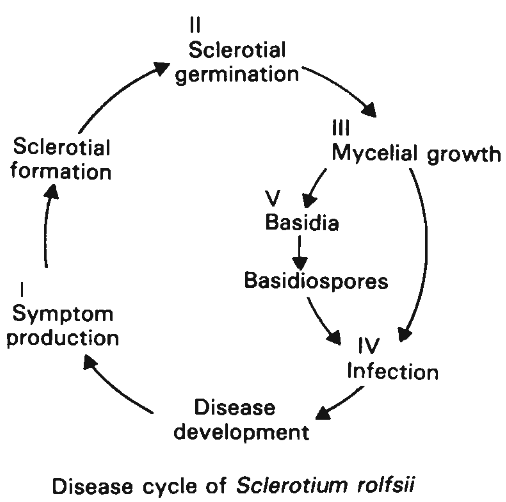

Figure 1. Generalized disease cycle of *S. rolfsii*. The importance of basidiospores has not yet been established.

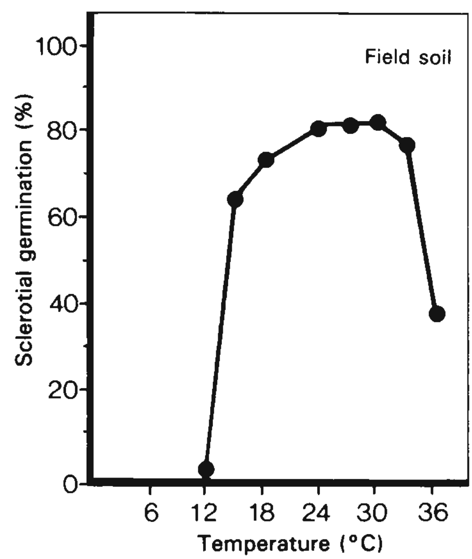

Figure 2. Influence of temperature on germination of sclerotia of *S. rolfsii* in natural field soil.

Sclerotial germination is optimal at low pH, in the range of 2.0 to 4.0 (Figure 6). At pH above 7.0, germination is inhibited. Attempts to control disease by raising soil pH through application of lime have met with limited success, even at high rates of application (21). Application of salts containing the bicarbonate (HCO_3) ion (19), however, have some potential for reducing the disease (16, 20).

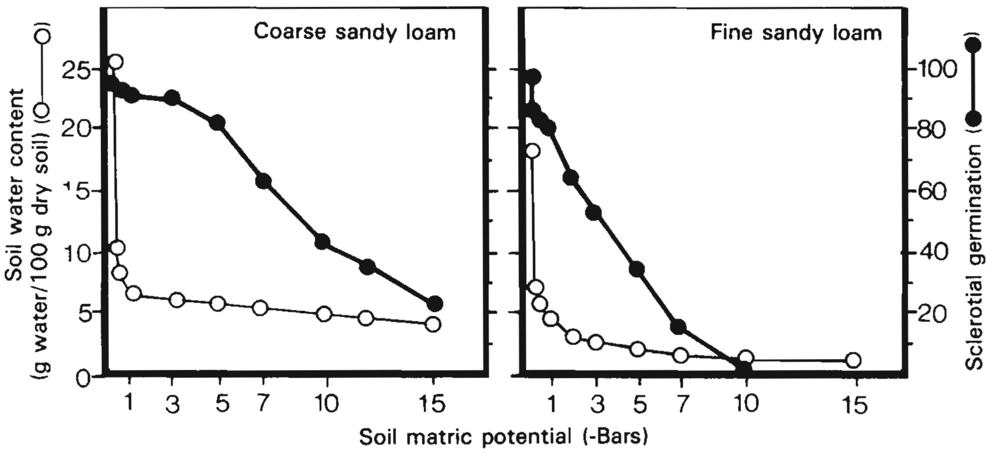

Figure 3. Influence of soil matric potential on germination of sclerotia of *S. rolfsii* in two soil types.
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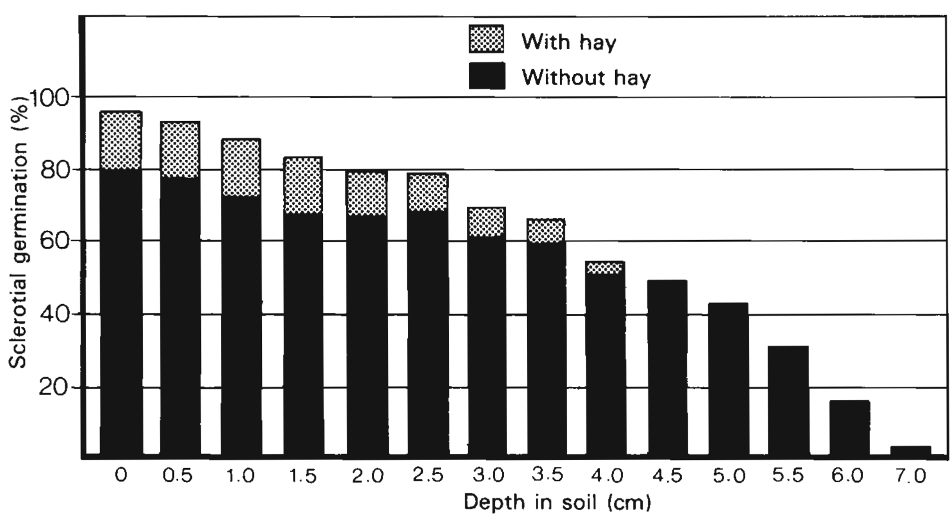

Figure 4. Effect of depth of burial in nonsterile field soil with or without addition of alfalfa hay on germination of sclerotia of *S. rolfsii*.
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A summary of the parameters influencing germination of sclerotia of *S. rolfsii* is given in Table 1.

Biotic Factors Influencing Growth of *S. rolfsii*

Exposure of sclerotia or mycelium of *S. rolfsii* to dried and subsequently remoistened plant tissues of numerous crop species stimulates vigorous growth (Table 2). The distances over which the mycelium can grow to infect a host also are greatly increased (Table 3), especially if sclerotia are dried prior to exposure. These plant tissues emit numerous volatile compounds, primarily alcohols and aldehydes, which trigger germination (18, 25). Due to the nonspecificity and abundance of plant materials in the soil, control measures aimed at removal of the source of volatiles may be impractical.

Microorganisms in natural soil may influence sclerotial germination and survival of *S. rolfsii*. Sclerotia exude sugars and amino acids, particularly after a period of drying or exposure to volatile compounds, and these increase the activities of soil microorganisms (13, 29). The activity of soil microflora may also be increased by adding nitrogenous compounds (9). Enhancing the levels of microorganisms antagonistic to *S. rolfsii* could provide a possible means of disease control.

Infection of Host Tissue by *S. rolfsii*

Growth of *S. rolfsii* is greatly enhanced by the presence of decomposing plant debris at the soil surface. The fungus colonizes the organic matter rapidly and grows from the debris onto host tissue. Senescing lower leaves provide a suitable bridge for infection of healthy tissue. Subsequent maceration and death of the tissue result from the secretion of oxalic acid concomitant with the production of cell wall degrading enzymes, particularly endo-

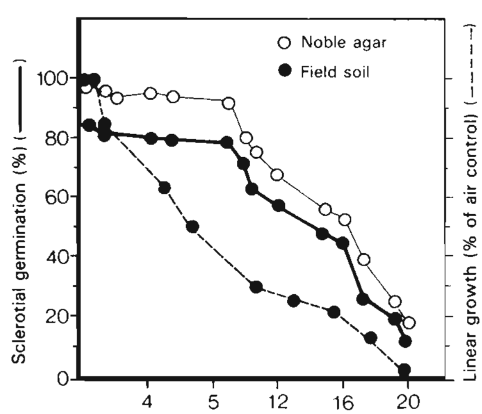

Figure 5. Effect of carbon dioxide concentration on sclerotial germination and linear mycelial growth of *S. rolfsii* on agar and field soil.
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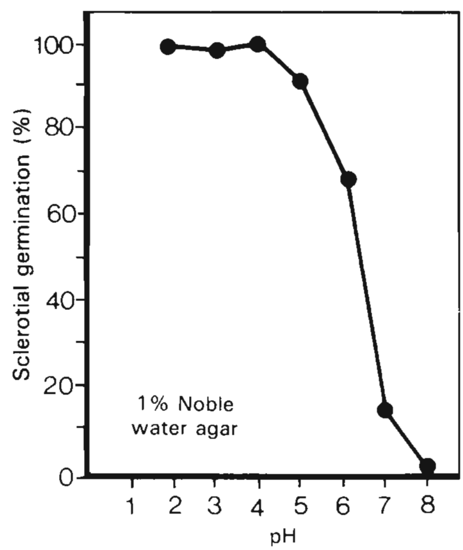

Figure 6. Influence of pH of agar medium on germination of sclerotia of *S. rolfsii*.

polygalacturonase (4, 22). The oxalic acid sequesters calcium present as calcium pectate in the cell walls to form calcium oxalate (4, 24), thus rendering the pectic materials more susceptible to degradation (Figure 7). The oxalic acid also lowers the pH of the tissue to the optimum for enzyme activity (around pH 4.0 to 4.5) (4, 22).

Table 1. Summary of the parameters affecting eruptive germination of sclerotia of *S. rolfsii*

Parameter	Optimum	Limits
Temperature	27-30° C	<12° C
pH	2.0-5.0	6.9-7.1
Solute potential	-2.5 to -8.0 bars	>-38 bars
Matric potential	-0 to -2 bars	-6 to -8 bars
CO_2	0.03-10.0%	>20%
O_2	16-21%	<10%
Depth in soil	0 to 2 cm	>7.0 cm

References: 19, 23

Table 2. Effect of dried and remoistened plant tissues (hay) on germination of sclerotia of *S. rolfsii*

Plant tissues (hay)[a]	Germination (%)[b]
Alfalfa	92
Bean	83
Peanut	89
Sugarbeet	81
Tea	87
Turf	80
Check	25
Alfalfa + activated charcoal (15%, w/w)	29

[a] 50 mg per 60 x 15 mm petri dish
[b] Rated on 1% Noble agar after 72 hr

Table 3. Maximum distances for mycelial growth from germinating sclerotia of *S. rolfsii* on sand or soil

Sclerotial treatment	Distance (cm)[a]	
	Quartz sand	Nonsterile field soil
Nondried	0.5	0.5
Nondried + hay	1.0	3.5
Dried	1.0	3.5
Dried + hay	3.0	6.0

[a] Rated after 5 days of incubation at 27°C

Summarized from Table 2 of Phytopathology 71:1099-1103 (18)

Increasing the calcium level in tissues can delay the rate at which the fungus colonizes the host (16, 22) (Figure 8). Similarly, tolerance of plant tissue to oxalic acid or degradative enzymes may be correlated to resistance of plants to infection by *S. rolfsii*. Lignified or suberized tissues, or tissues with an impermeable layer of phellogen, may be more tolerant of the disease. Thus, plants with woody stems and older tissues of succulent plants tend to be less susceptible to *S. rolfsii*. Selection for the above traits in a breeding program could increase the likelihood of disease resistance if plant quality is not adversely affected.

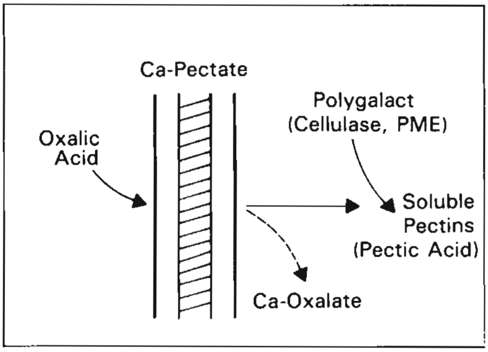

Figure 7. Mechanism of action of oxalic acid and cell wall-degrading enzymes produced by *S. rolfsii* in tissue degradation.

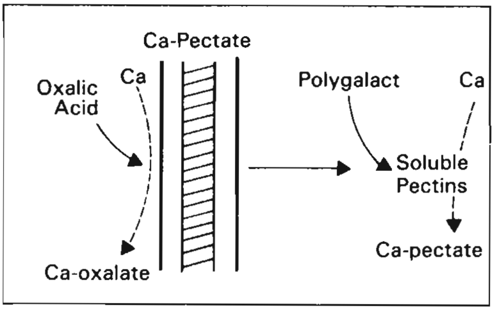

Figure 8. Influence of supplemental calcium on oxalic acid and enzyme activity of *S. rolfsii* in host tissue.

Development of Disease Under Field Conditions

Disease due to *S. rolfsii* is greatly favored by high soil temperatures and moisture. Serious disease outbreaks are usually associated with wet periods, particularly when preceded by a dry spell. On processing carrots grown in North Carolina, the time of disease onset and continued progression in the summer of 1984 was associated with maximum daily air temperatures above 27°C. Close spacing of plants within the row in carrots greatly facilitates secondary plant-to-plant spread of the pathogen via root contact. The extent of spread from initial infection sites or disease foci to adjacent plants during one growing season can be extensive (Figure 9). Disease progress curves on carrot show that over a 70-day period, percentage of dead plants can increase from 0 to 39% (Figure 10). Thus, in a planting bed or in a seedling crop where plant populations are high, *S. rolfsii* has the potential to devastate the entire crop. Sanitation practices and greater plant spacing could reduce the rate at which disease progresses.

Strategies for Disease Control

There are numerous potential disease control strategies for reducing plant mortality due to *S. rolfsii*. Their applicability to wheat would depend on the nature of any limitations, such as cost effectiveness, adverse side effects, practicality, etc. These strategies are described below in detail and summarized in Table 4.

Site selection

Planting wheat in areas without a previous history of disease or avoiding fields infested with sclerotia of *S. rolfsii* could minimize crop losses provided land availability was not limiting and a reliable approach could be developed to assay fields. Sclerotia of *S. rolfsii* in field soil tend to show a clustered spatial pattern, making it difficult to accurately sample a field. By examining various sampling patterns (Figure 11), it was concluded that samples taken along diagonal paths provided an inoculum density estimate within 5% of the population mean (Table 5) (26). This approach could perhaps be used to identify fields with low or no potential for disease development. Soil samples may be obtained with soil probes or other sampling devices.

Once retrieved, various procedures can be used to recover and enumerate sclerotia. These include a wet-sieving procedure (11, 26), a flotation-sieving method using molasses (27), or a methanol germination-stimulation method (28). Comparison of these three assay procedures has shown that recovery of sclerotia and efficiency differed with each procedure (Table 6). With large soil volumes, the wet-sieving assay was the most desirable.

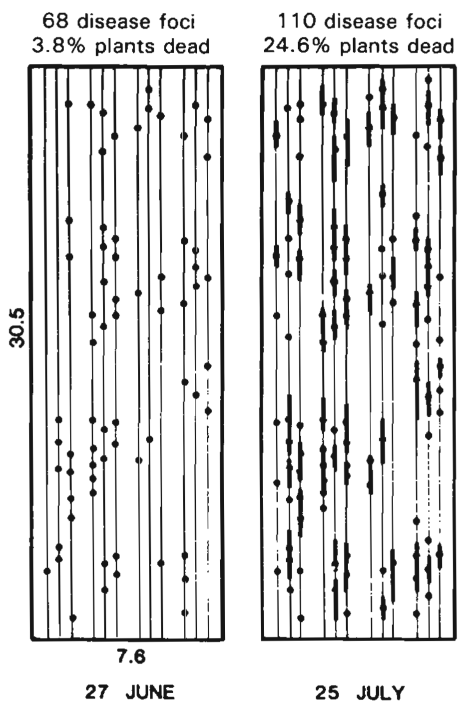

Figure 9. Spatial pattern of disease foci and extent of secondary spread from the foci of *S. rolfsii* on carrots at two evaluation dates.
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To be utilized commercially, the site selection approach requires that the relationship between sclerotial numbers and the potential for disease development be established. On processing carrots grown in Georgia, one or more viable sclerotia per 300 cm^3 of soil is sufficient to cause significant levels of disease (Figure 12). Similarly, with increasing numbers of disease foci in a field, the percentage of plants dead is also increased (Figure 13). Thus, with carrots, only fields with no or extremely low inoculum levels are acceptable for planting (15, 26).

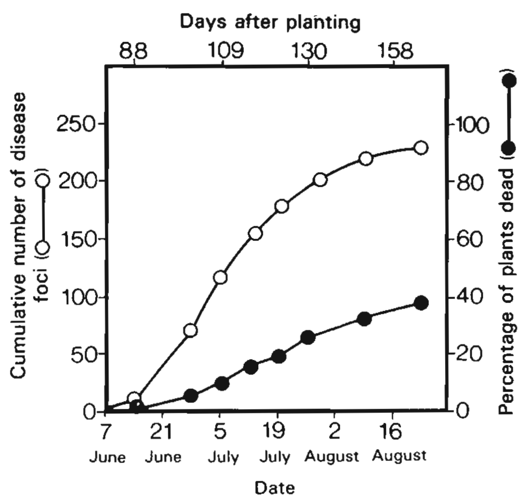

Figure 10. Progression of root rot on processing carrots due to *S. rolfsii* expressed as numbers of foci and percentage of plants dead.
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Table 4. Summary of strategies for control of disease due to *S. rolfsii* and their potential for use on wheat

Method	Reports of success	Potential for disease control	Requirement
Site selection	Avoidance of infested sugarbeet and carrot fields in California (11); N. Carolina (26) made possible.	If land availability is not limiting.	Adequate sampling procedure required; need to establish relationship of inoculum level to disease.
Tillage practice	Deep plowing reduces inoculum levels and disease; survival of sclerotia may be reduced (16, 23).	Only when used in combination with fungicides or fertilizers.	Must be conducted in advance of planting; need to use moldboard plow.
Nitrogen fertilizer applications	Use of urea and ammonium compounds at high rates proved useful on turf, processing carrots, potatoes, (3, 16, 20).	If excess nitrogen is not detrimental and cost of fertilizer not prohibitive. High pH enhances control.	Must be applied prior to onset of symptoms, need repeated applications.
Calcium fertilizer applications	Use of gypsum and calcium nitrate reduces disease on carrots (16).	If high rates are economical and soil calcium availability is low. Levels in tissue should be enhanced.	Not effective under high disease pressure. Used in combination with tillage practice.
Fungicide applications	Several reports of use of PCNB, vitavax, captan (8, 10, 16, 20).	Need several applications, at high rates. Cost probably prohibitive.	Must be applied to soil surface early in season. May not be registered for use.
Fumigation	Several reports of use of methyl bromide, chloropicrin (10, 12).	May be too costly.	Requires early applications, under tarp.
Crop rotation	Disease may be lower after rotation to maize. Few other reports.	Minimal applicability due to prolonged sclerotial survival and wide host range of fungus.	Few crops are completely resistant to disease.
Resistance	Reports of tolerance in pepper, tomato, soybean (5, 10).	Holds some promise. Tolerance to oxalic acid or enzymes may be manifested in resistance.	Mechanism of resistance not evaluated. Requires an efficient screening procedure.

Table 4. (continued)

Method	Reports of success	Potential for disease control	Requirement
Sanitation	Burial of organic residues and removal of weeds and debris can reduce inoculum and energy for fungal growth (1, 8, 10, 16).	Only if used in combination with fungicides and fertilizers.	Need to eliminate all possible sources of inoculum. May be impractical.
Biological control	Application of *Trichoderma harzianum* reported to reduce disease in some experiments (2, 6, 7, 13).	Holds some promise. Biocontrol production may be an involved process. Disease control not total.	Mechanism of action not known. High rates of application may be required.
Soil solarization	Inoculum in soil reduced by high temperatures and by antagonists (7, 10, 13).	If land use not critical and temperatures sufficiently high.	Cost of tarping may be prohibitive. Land not in production for 2-3 months.
Soil flooding	No reports.	If sclerotial survival is reduced; sclerotia may float and be dispersed.	Needs testing.

Table 5. Comparison of simulated sampling patterns for estimation of mean number of sclerotia of *S. rolfsii* in two fields

Sampling pattern	No. of samples	Field A (k-parameter = 0.34) Mean	S.D.	Field B (k-parameter = 4.4) Mean	S.D.
Quadrat	72	5.4	12.1	5.9	4.5
Diagonal	24	5.7[a]	11.2	5.9[a]	4.3
Zig-zag	24	3.0	4.2	4.5	2.7
Parallel verticals	24	8.3	12.1	5.9[a]	4.9
Diamond	24	5.1[a]	11.7	5.3	3.3
Parallel horizontals	36	7.2	16.0	5.9[a]	4.3

[a] Within 5% of the mean in the quadrat method if standard deviation is not considered
Summarized from Table 4 of Plant Disease 69:469-474 (26)

Tillage practice

Deep plowing of infested fields prior to planting has been shown to reduce inoculum levels, compared with disking (16) (Figure 14). Since sclerotia of *S. rolfsii* do not germinate deeper in soil, plowing may reduce disease incidence provided the residual inoculum levels are sufficiently low. Plowing was most effective when used in combination with other control measures, such as fertilizers and fungicides (8, 16).

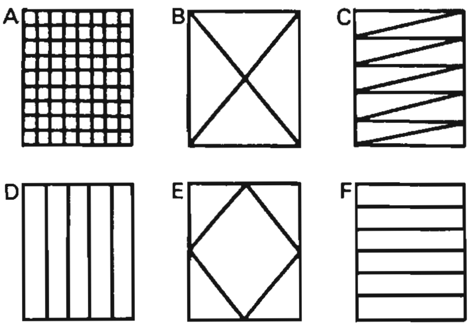

Figure 11. Sampling patterns used to obtain soil samples for estimation of inoculum density of *S. rolfsii* in naturally infested fields. A) Quadrat, B) diagonal paths, C) zigzag path, D) parallel (top to bottom), E) diamond-shaped path, F) parallel (left to right).
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Nitrogen fertilizer application

There are numerous nitrogenous compounds that directly affect sclerotial germination and mycelial growth of *S. rolfsii* (19). Among these, urea and ammonium bicarbonate have been applied in the field and shown to reduce disease on golf greens (20, 21), potato (3), and processing carrots (16) (Tables 7-9). Other compounds, such as calcium nitrate and gypsum, which have no inhibitory effects on the fungus, may also reduce disease under certain conditions (16). Release of ammonia from ammonium fertilizers under alkaline conditions was suggested to be one of the mechanisms by which *S. rolfsii* is suppressed following fertilizer applications (16, 19).

Calcium fertilizer application

Increasing the levels of calcium in tissues by application of calcium nitrate or gypsum has been shown to reduce disease on processing carrots under nonepiphytotic conditions

Table 6. Comparison of three extraction procedures for recovery of sclerotia of *S. rolfsii* from field soil

Assay method	Amount of soil per sample (g)	Average time required per sample (min)[a]	Sclerotial recovery[b] Mean	% CV
Wet sieving	800	13.5	93	17.5
Flotation-sieving	75	2.8	80	25.3
Methanol assay	220	8.5	44	63.9

[a] Mean of 30 samples
[b] Mean recovery of laboratory and soil-produced sclerotia from artificially infested samples. Represents average of four replications and two repetitions in two soil types
Summarized from Table 2 of Plant Disease 69:469-474 (26)

(16). This approach could prove to be effective and economical where calcium supply in the soil is limiting, particularly in light, sandy soils.

Fungicide applications
Numerous fungicides have been reported to inhibit germination of sclerotia or reduce mycelial growth in culture. The most effective of the compounds tested are given in Table 7. A number of these have effectively controlled disease on various crops in the field (8, 10, 16, 20, 21) (Tables 8-10). Several applications of the fungicides usually are required, and frequently they are applied at high rates. Thus, cost may be prohibitive and many compounds may not be registered for use. Treatment of wheat seed would not be expected to provide sufficient carry-over of fungicide for protection against the rapidly growing mycelium of this soil inhabiting fungus.

Fumigation
Treatment of soil prior to planting with fumigants and soil sterilants such as methyl bromide, chloropicrin, or metham-sodium may reduce disease incidence, since these compounds are toxic to sclerotia of *S. rolfsii* (10, 12). However, cost would be a major factor limiting use of these materials on an agronomic crop such as wheat.

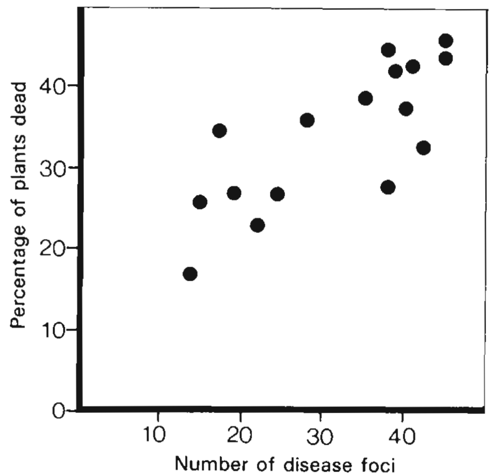

Figure 13. Relationship of percentage of plants dead to the number of disease foci for *S. rolfsii* on processing carrots.
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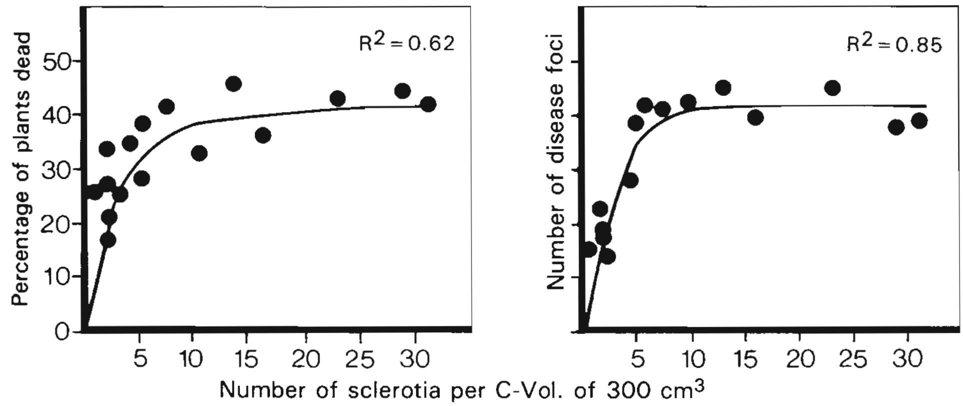

Figure 12. Relationship of percentage of plants dead and number of disease foci to the inoculum density of *S. rolfsii* on processing carrots.
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Crop rotation

Due to the fact that *S. rolfsii* has a wide host range and can persist on virtually all types of crop debris, crop rotation is not likely to be an effective or practical method for disease control. On the other hand, rotating away from very susceptible crops to those less affected by the pathogen, such as maize, may result in lower disease incidence in subsequent years by reducing inoculum levels (10).

Resistance

Susceptibility of host tissue to *S. rolfsii* is influenced by plant age and succulence, Older, woodier tissues tend to be less susceptible than younger, fleshier tissues. In tomato, an accession of *L. pimpinellifolium* possessing tolerance to infection was characterized as having a lignified and thickened stem, which presented a barrier to fungal penetration (1). In pepper, germplasm is available which shows resistance to *S. rolfsii* (5). The prospects for controlling disease through host resistance in a crop such as wheat are promising, and tolerance may be manifested by early development of lignified or suberized stem tissue.

Table 7. Chemical salts and fungicides inhibiting sclerotial germination of *S. rolfsii* in vitro by 80-100%

Carbonates	Fungicides
K_2CO_3	Actidione TGF 2.1
Na_2CO_3	(cycloheximide)
$(NH_4)_2CO_3$	Bravo 54%
	(chlorothalonil)
	Captan 50% (captan)
	Dithane M-45 80%
	(mancozeb)
Bicarbonates	PCNB
	(pentachloronitro-benzene)
$KHCO_3$	Plantvax 75%
$NaHCO_3$	(oxycarboxin)
NH_4HCO_3	Vitavax 75% (carboxin)
	OAG 3890
	(furmecyclox)

Concentrations of salts and fungicides were 50mM and 200 ppm.
Summarized from Figure 2 of Plant Disease 66:108-111 (20) and Table 2 of Phytopathology 72:635-639 (19)

Sanitation

Development of disease may be favored by the accumulation of organic debris around the base of the plant, the presence of weeds, and high plant densities. All of these tend to increase moisture within the canopy, and the organic matter can serve as a substrate for mycelial growth. Deep plowing may eliminate crop debris from the infection court and subsequent cultivations could reduce buildup of weed and debris. Increasing plant spacing, where possible, would reduce the frequency of plant-to-plant spread of the pathogen.

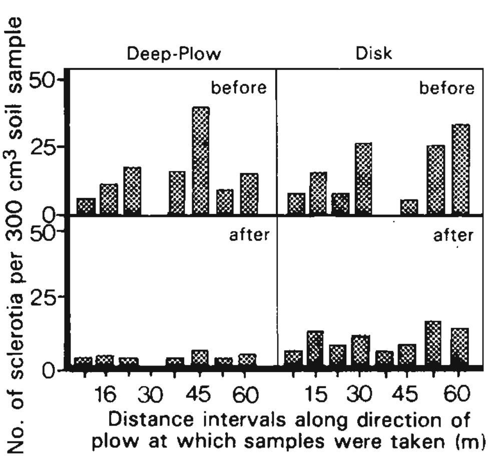

Figure 14. Inoculum density of *S. rolfsii* in soil samples taken before and after deep plowing or disking of field plots.
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Table 8. Effect of five fungicides and two inorganic nitrogen salts on severity of *S. rolfsii* blight on turf in California

Treatment[a]	Rate (kg a.i./93 m^2)	Total diseased spots	Total diseased area (%)[b]
Control	–	20	17.9
Botran + Actidione	0.14-0.04	3	0.9
Captan	0.73	2	0.2
Dithane M-45	0.88	31	13.4
PCNB	0.2	0	0
Vitavax	0.2	3	0.2
NH_4HCO_3	0.18	2	0.8
NH_4SO_4	0.23	2	2.3

[a] Chemicals were applied every 2 weeks starting on May 5, 1980; a total of 7 applications were made

[b] Rated on August 4, 1980. Data are the means of four replicates

Summarized from Table 2 of Plant Disease 66:108-111 (20)

Table 9. Effect of six fungicides and two inorganic calcium salts on severity of *S. rolfsii* blight on turf in California

Treatment[a]	Rate (kg a.i./93 m^2)	Total diseased spots	Total diseased area (%)[b]
Control	–	15	15.4
Botran + Actidione	0.14-0.04	0	0
Captan	0.68	6	1.6
Dithane M-45	0.88	14	8.7
PCNB	0.17	0	0
Vitavax	0.15	1	0.05
Vitavax + NH_4HCO_3	0.1 + 0.085	0	0
Vitavax + Captan	0.1 + 0.34	0	0
Furmecyclox	0.057	3	0.6
$Ca(NO_3)_2H_2O$	0.14	14	12.8
$Ca(OH)_2$	1.8	18	14.3

[a] Chemicals were applied every 2 weeks starting on May 1, 1981; a total of 8 applications were made

[b] Rated on August 24, 1981. Data are the means of two or four replicates

Summarized from Table 1 of Plant Disease 66:1125-1128 (21)

Biological control
Applications in the field of various formulations of the biological control agent *Trichoderma harzianum* have been reported to reduce disease due to *S. rolfsii* (2, 6, 7). High rates of application may be required and disease control may not be complete. The feasibility of producing and applying large volumes of the antagonist could be a problem in its use against *S. rolfsii*. However, amendments to soil may reduce the length of survival of the sclerotia and reduce inoculum levels. This approach to disease control warrants further investigation.

Soil solarization
Solar heating of moistened soils under polyethylene tarp has been reported to reduce both sclerotial numbers and disease due to *S. rolfsii* (7, 10). The pathogen can be effectively eliminated from soil to depths of 6 to 20 cm, depending on location and time of year. Solar heating combined with application of *T. harzianum* may result in less disease than either method alone (10). Sublethal temperatures also may hasten death of sclerotia, possibly by enhancing nutrient leakage and microbial antagonism. This method has applicability where temperatures are sufficiently high and land can be set aside for 1 to 2 months.

Soil flooding
Flooding of soil for a period of time may enhance sclerotial decay and reduce inoculum levels. The potential of this method for disease control has not been investigated.

Conclusions and Need for Research

A diagrammatic summary of the parameters influencing growth and infection of host tissue by *Sclerotium rolfsii* is given in Figure 15. A summary of the strategies for control of disease and their potential for use on wheat is given in Table 4.

Future research should emphasize strategies for disease control. For wheat, a predictive model for the relationship of inoculum density in soil to the potential for disease development needs to be developed. The rate at which disease progresses in relation to stage of development of

Table 10. Efficacy of fertilizers and fungicides for control of *S. rolfsii* root rot of processing carrots under two tillage practices in Maxton, North Carolina, in 1983

	Percentage of plants dead[b]	
Treatment[a]	Disk	Deep-plow[c]
None	18.4	16.8
Calcium		
carbonate	13.1	10.0
hydroxide	14.6	11.7
nitrate	11.2	3.9*
sulfate	17.8	9.8
Ammonium		
bicarbonate	5.6*	1.9*
nitrate	14.2	11.6
sulfate	15.2	10.5
urea	9.0	3.6*
Fungicides		
chlorothalonil	9.6	5.5
TPTH	17.2	10.4
PCNB	3.3*	0.8*
LSD (P=0.05)	6.2	5.1

a Rates of 115 kg/ha Ca or N applied thrice at 3-wk intervals starting on June 7, 1983
b Rated on August 9, 1983. Data are means of four replicates
c Moldboard plowing was done in March 1983
Summarized from Table 1 of Plant Disease 70:819-824 (16)

the host should be determined. The effects of application of calcium and nitrogen fertilizers on host and disease development need to be investigated. Screening of available germplasm for possible tolerance to *S. rolfsii* may provide useful information on mechanisms by which the rate of ingress of the pathogen can be reduced. Finally, the feasibility of applying biological control agents and the use of soil solarization for reducing the disease is worthy of further investigation.

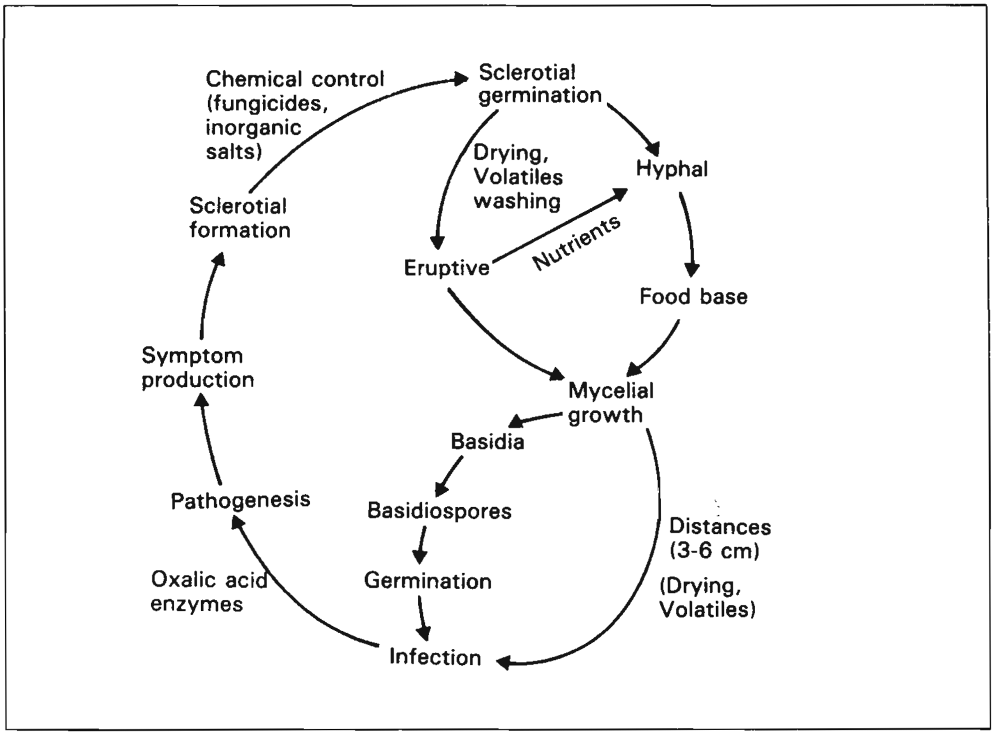

Figure 15. Summary of parameters influencing growth and infection of host tissue by *S. rolfsii*.

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Helminthosporium sativum: Disease Complex on Wheat and Sources of Resistance in Zambia

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Abstract

The environmental conditions in Zambia during the last 2 seasons were conducive to the development of Helminthosporium sativum *diseases on wheat. A disease scoring method has been developed. Double digit scores at specific growth stages are used to identify resistant germplasm. A correlation matrix shows highly significant negative correlation coefficients between* H. sativum *scores, yield parameters, and plant height of entries in the 1986 national and advanced tests. Tropical wheat varieties resistant to* H. sativum *are being developed with germplasm from Brazil, CIMMYT, and local crosses. Yields up to 3.3 t/ha have been recorded. Seedborne* H. sativum *is effectively controlled with triadimenol.* Cochliobolus sativum, *the perfect stage of* H. sativum, *occurs in Zambia. Varieties under commercial production include Whydah (PF7748), Hornbill (IAS64/Aldan), PF7339/Hahn'S', and Predg/Nac//PF7748.*

Rainfed wheat or summer wheat production was first explored in Zambia in the period 1957-60, but research was abandoned due to severe disease development and low yields (10). In 1976, research into rainfed wheat production was started again (2). However, crop failures due to *H. sativum* occurred with Mexican varieties and production was discontinued (4).

H. sativum is the major pathogen of rainfed wheat in Zambia. It causes spot blotch, head blight, stem break, and black point (3, 20). In crop loss assessment tests, it was demonstrated that yield losses could be as much as 85%. It was also shown that yields of 3 t/ha were possible in plots with low levels of infection (3, 11, 13).

Various fungicides were tested in the field for the control of spot blotch and head blight. Fentin compounds and triadimenol were effective (3, 12, 17). Propiconazole provides disease control in tests in Brazil (8). Many wheat varieties from different sources have been tested at Mount Makulu Research Station. The vast majority were very susceptible to *H. sativum* diseases and were rejected (3, 16, 18, 19). In 1986, about 1,300 ha of rainfed wheat were grown mostly with the Brazilian selection PF7748 released under the name "Whydah."

This paper discusses some of the epidemiological aspects of the *H. sativum* diseases and the development of improved rainfed wheat varieties.

H. sativum Diseases

Environment

Rainfed wheat is sown at Mount Makulu Research Station during the first days of January. Heading occurs 50 to 60 days later, and harvest is in April-May. Figure 1 shows the average maximum and minimum temperatures at Mount Makulu for the period December to April. The temperatures remained rather constant throughout the growing period at about 26°C and 17°C, respectively (1). In Figure 2, the rainfall data of the last 2 seasons are compared with the 10-year average at the Mount Makulu location. As shown, yield testing and screening during the 1985 and 1986 seasons were done in an environment with above average rainfall. In 1986, 1261 mm were recorded, whereas the 10-year average was 662 mm (1).

The combined effect of high temperatures, high relative humidity, and long periods of leaf wetness due to rainfall and daily dew periods of more than 12 hours meant that there was high *H. sativum* disease pressure, especially in 1986. The temperature range of 17 to 26°C provided optimum conditions for growth, infection, lesion development, and sporulation of *H. sativum* (5, 6, 9). Wheat fields near the research station with the nonrecommended susceptible cultivars, Emu (40 ha) and Veery (70 ha), succumbed to *H. sativum* diseases in 1986. Under these environmental conditions different levels of resistance to *H. sativum* were observed in experimental plots. Testing for straw strength and sprouting was also possible.

Sources of infection

Grasses that are well developed at the time when rainfed wheat is being seeded are considered to be a major source of *H. sativum* inoculum. Spore trapping over land where wheat has never been grown showed that *H. sativum* spores were present in the air prior to seeding and emergence (2). These spores are believed to have originated from the surrounding bush.

In 1985 "black point" grain from Mount Makulu and Mbala (northern Zambia) was examined to determine how much of the symptom was caused by *H. sativum*. Seeds with obvious symptoms of *Fusarium* infection were excluded from the tests. At total of 300 seeds from Mount Makulu and 200 from Mbala, all with various degrees of black point, were surface-sterilized, plated onto potato dextrose agar (PDA) and examined after 10 days at room temperature. *H. sativum* was present in 63% of the grain (65% in Mount Makulu grain and 60% in Mbala grain). *H. urochloae* occurred in 30%

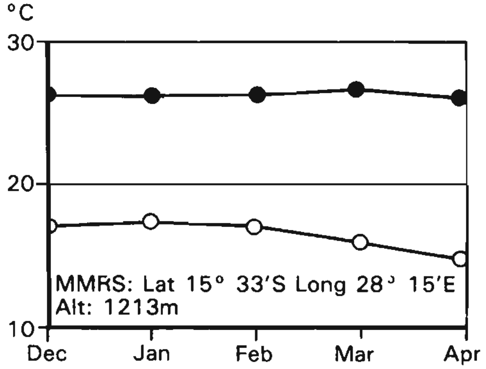

Figure 1. Mean maximum and minimum temperatures at Mount Makulu Research Station.

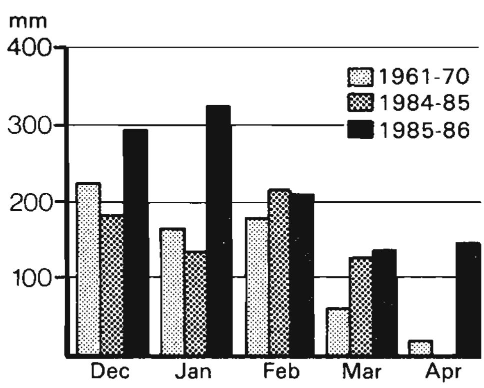

Figure 2. Monthly rainfall (mm) at Mount Makulu Research Station.

Source: Climatological summaries for Zambia. Meteorological Dept. Lusaka. 1975 of the grain (28% Mount Makulu, 32% Mbala). This species, identified at the Commonwealth Mycological Institute, was not recorded previously and does not appear to be a wheat pathogen (7). *Phoma sorghina* and *F. equiseti* were also present.

Seedling blight, stunting, and root rot due to *H. sativum* were observed in 1986 in a field with some stubble residues from the previous crop. The infections were probably due to a combination of seed- and soilborne inoculum and are indications of potentially serious *H. sativum* foot and root rot in a wheat-wheat rotation.

Another possible source of inoculum recently found in Zambia on wheat stubble is *Cochliobolus sativus*, the perfect stage of *H. sativum*. Mature ascospore production coincides with the time of seeding and emergence. Septated ascospores quickly germinate and produce conidia on PDA (Raemaekers, unpublished). Pathogenicity of the ascospores is being tested. Measurements of perithecia, asci, and ascospores are somewhat different from those produced artificially in the laboratory elsewhere (21). Perithecia of *C. sativus* apparently have not been found in nature anywhere else (21). Since *C. sativus* is heterothallic, the presence of two compatibility groups is necessary to produce perithecia and ascospores (21). Both mating types therefore must occur at the Mount Makulu Research Station. The role of *C. sativus* in the epidemiology of *H. sativum* diseases is not yet clear.

Method of disease scoring in the field

A uniform method of disease scoring has been introduced. This method should overcome previous disease assessment difficulties with:

- recognition of the pathogens
- interaction of *H. sativum* and other pathogens
- quick crop and disease development
- escapes due to late maturity
- confusion about interpretation of resistance elsewhere
- various scoring methods

Table 1 shows when various diseases are scored. By using "number of days after 50% heading" rather than referring directly to growth stages, the scoring may be easier to carry out and become more accurate. *H. sativum* is scored at 5 and 25 days after heading. For bread wheat, this corresponds in general with anthesis and the soft dough stage.

Table 1. Time of disease scoring

Pathogen	Days after 50% heading					
	5	15	20	25	30	Grain
H. sativum	•			•		•
X. campestris		•				
Fusarium spp.			•	•		
P. recondita			•			
P. graminis tritici					•	

Table 2 explains the double-digit score. Field scores are on a 0-9 scale and the disease index on grain is expressed on a 0-100 scale. At anthesis, the vertical spread of spot blotch infection (1st digit) and severity (2nd digit) are recorded. At 25 days after heading, spot blotch severity on the flag leaf (1st digit) and head blight severity (2nd digit) are scored.

Black point scoring provides additional information about resistance to the *H. sativum* complex and may lead to the identification of germplasm with better quality grain. Scoring is done on machine-harvested grain and could be different for hand-harvested grain. The factors 0, 1, 2, 4, and 6 were chosen to reflect the increase in severity of infection.

Table 2. Method of disease scoring

1. *H. sativum* (5 days), 0-9 scale

   2-digit score
   - 1st digit: Height of infection (0-9)
     5 = up to mid-plant; 8 = up to flag leaf
   - 2nd digit: Severity on infected foliage (0-9)
     5 = infected foliage is 50% destroyed

2. *H. sativum* (25 days), 0-9 scale

   2-digit score
   - 1st digit: severity on flag leaf (0-9)
     5 = 50% of flag leaf area destroyed
   - 2nd digit: severity on ear (0-9)
     5 = 50% of ear area destroyed

3. *X. campestris* (15 days), 0-9 scale

   2-digit score
   - 1st digit: Height of infection (0-9)
     5 = up to mid-plant; 8 = up to flag leaf
   - 2nd digit: severity on infected foliage (0-9)
     5 = infected foliage is 50% destroyed

4. *Fusarium* spp. (20 & 25 days), 0-9 scale

   2-digit score
   - 1st digit: incidence of scab (0-9)
     5 = 50% of ears are infected
   - 2nd digit: severity of scab (0-9)
     5 = infected ears are 50% destroyed

5. *P. recondita* & *P. graminis tritici*
   See "Rust Scoring Guide" (CIMMYT 1986). Use modified Cobb Scale.

6. *H. sativum* on grain, 0-100 scale
   Classify 200 grains in the following 5 groups: no infection (a grains); black tip (b grains); embryo area discolored (c grains); infection over embryo and part of endosperm (d grains); extensive damage and shrivelling (e grains)

$$\frac{(a \times 0) + (b \times 1) + (c \times 2) + (d \times 4) + (e \times 6)}{12}$$

Stem break caused by node infection of *H. sativum* is not scored each season. Varietal differences are observed under high disease pressure only. Susceptible lines usually break immediately above the top node or the penultimate node (20).

Linear correlation

Table 3 shows the correlation matrix with *H. sativum* scores, yield parameters, and agronomic characteristics of 40 entries that had already been screened and yield-tested during previous rainy seasons. Scoring in 1986 was done according to the methods described above. The factors used in black point scoring were 0, 1, 2, 3, and 4. Tables 4 and 5 show the significance of the correlation coefficients between disease scores and yield parameters and between *H. sativum* scores and plant height as derived from Table 3.

The *H. sativum* scores on foliage, ear, and stem — except severity of infection at anthesis — were negatively correlated with yield, thousand grain weight, and hectoliter weight, and the correlations were highly significant. The correlation between black point and yield was negative and significant at P ≤0.05 only. There was a highly significant negative correlation between plant height and severity of spot blotch on the flag leaf and head blight and incidence of stem break. The correlation coefficients between vertical spread of infection at anthesis and spot blotch and head blight severity at the soft dough stage, stem break, and black point were all highly significant. A significant correlation (P ≤0.05) between spot blotch and head blight at the soft dough stage and black point was recorded.

The scoring method appears to provide reliable information about the interaction of the *H. sativum* syndrome and yield parameters under high disease pressure.

Table 3. Correlation matrix with *H. sativum* scores and yield parameters. National and advanced Tests, Mount Makulu Research Station, 1986

	1	2	3	4	5	6	7	8	9	10	11
1.	—										
2.	0.112	—									
3.	0.704	-0.065	—								
4.	0.542	0.048	0.639	—							
5.	0.585	-0.124	0.404	0.413	—						
6.	0.429	0.133	0.606	0.487	0.034	—					
7.	-0.582	-0.209	-0.631	-0.474	-0.344	-0.732	—				
8.	-0.437	-0.143	-0.511	-0.477	-0.128	-0.741	0.618	—			
9.	-0.357	-0.188	-0.501	-0.621	-0.134	-0.664	0.614	0.591	—		
10.	-0.409	0.031	-0.613	-0.624	-0.218	-0.425	0.374	0.559	0.624	—	
11.	0.316	0.366	0.001	0.005	0.333	-0.032	-0.139	0.063	0.184	0.416	—
12.	0.251	0.267	-0.173	-0.128	0.382	-0.206	-0.075	0.118	0.236	0.438	0.886

*** 0.518
** 0.418
* 0.324

d.f. 38

1. Vertical spread of spot blotch (5)
2. Severity of spot blotch (5)
3. Spot blotch severity on flag leaf (25)
4. Head blight severity (25)
5. Black point
6. Stem break
7. Yield
8. Thousand grain weight
9. Hectoliter weight
10. Plant height
11. Days to heading
12. Days to maturity

Varietal resistance at the Mount Makulu location, which is considered to be a "hot spot" for these diseases, can be detected. Black point and head blight scoring may have to be refined further.

Highly significant correlation coefficients between lesion types (0-5) and *H. sativum* scores at anthesis and soft dough (positive correlation) and plant height (negative correlation) were recorded in the Disease Observation Nursery.

Table 4. Significance of correlation coefficients between *H. sativum* scores, yield parameters, and plant height

	Yield	1000-grain weight	Hectoliter weight	Plant height
1. Vertical spread of spot blotch (5)	***	**	*	*
2. Severity of spot blotch (5)				
3. Spot blotch severity on flag leaf (25)	***	**	**	***
4. Head blight severity (25)	**	**	***	***
5. Stem break	***	***	***	**
6. Black point	*			

* P ≤ 0.05
** P ≤ 0.01
*** P ≤ 0.001

Table 5. Significance of correlation coefficients between *H. sativum* scores

	1	2	3	4	5	6
1. Vertical spread of spot blotch (5)	1		***	***	**	***
2. Severity of spot blotch (5)		1				
3. Spot blotch severity on flag leaf (25)	***		1	***	***	*
4. Head blight severity (25)	***		***	1	**	*
5. Stem break	**		***	**	1	
6. Black point	***		*	*		1

* P ≤ 0.05
** P ≤ 0.01
*** P ≤ 0.001

Present Status of Variety Development

Our present sources of resistance originate from:

- Brazil (Passo Fundo)
- CIMMYT nurseries
- Mount Makulu Station crosses

Yield testing starts with preliminary yield tests (PYTs) and selected lines enter the advanced yield tests (AYTs). Selections from these tests are forwarded to the first year national yield test (NYT). Table 6 shows the entries in the 1987 NYT. The Mount Makulu Station crosses were made with CIMMYT lines that had entered Zambia as F_2s (2, 14, 15, 18). Several promising lines were selected in the cross PF7339/Hahn'S'. Quick generation advancement is possible by growing two or three generations per year under different environmental conditions.

Varieties selected out of 240 entries in the 1986 PYTs at Mount Makulu and now in AYTs are presented in Table 7. The majority of these lines lack tolerance to acid soil conditions and are therefore not as widely adapted as those in the NYT. Pvn'S'/Bjy'S', IAS54/Ald'S' and Vee'S'/Cep7731 were selected from the *Helminthosporium* screening nurseries. The other lines are derived from local crosses between CIMMYT lines and PF7748. Fahari is a Kenyan variety. Predg/Anza, Predg/Nac, Predg/Kavco, and Pel73280/5/Atr71/4/Tzpp//IRN46/Cno67/3/Protor were all selected from F_2 nurseries.

Table 8 presents 1986 Mount Makulu Research Station data on some of the rainfed wheat lines in the 1987 NYT. These observations indicate the yield potential, resistance to *H. sativum* diseases, and straw strength under abnormally high rainfall and high disease pressure. All lines produced grain with 14 to 15% protein content and good baking quality (National Milling Co. tests). Table 9 shows *H. sativum* scores and agronomic data of some lines that are at present in AYTs. The agronomic data were recorded in the 1986 PYTs and the *H. sativum* scores are from the Disease Observation Nursery. The results show the trend in variety development: shorter plant types, earlier maturity, strong straw, resistance to the *H. sativum* complex, and better yield.

Table 6. Wheat materials included in national yield tests in 1987

Code	Cross No.	Cross
B59	F3750	ND81/IAS59//IAS58(PF7748)
B213	CM47207	IAS64/ALDAN'S'
G74, H31, H34	MM8101	PREDG/NAC//PF7748
G82, G85	MM8124	PF7748/5/PEL73280/ATR/4/ TZPP//IRN46/CNO67/3/PROTOR
G92, H37, H38, H39, H41, H42, H44, H45	CM70377	PF7339/HAHN'S'

Table 7. Wheat materials included in advanced yield tests in 1987

Entries	Cross	Cross
1	MM8204	PEL73280/ATR71/4/TZPP//IRN46/CNO67/3/ PROTOR/5/PREDG/NAC//PF7748
7	MM8210	PEL73280/ATR71/4/TZPP//IRN46/CNO67/3/ PROTOR/5/PREDG/NAC//FAHARI
1	MM8220	KVZ/HD2009/3/TOB/CNO//TOB/ERA/4/ PREDG/KAVCO
1	MM8230	PF7748//PREDG/KAVCO
1	MM8231	PF7748/4/PREDG/NAC//PREDG/ANZA/3/ PREDG/KAVCO
2	MM8236	PREDG/NAC//FAHARI/3/PF7748
1	MM8246	PREDG/NAC/6/PF72640/5/PEL73280/ATR/4/ TZPP//IRN46/CNO67/3/PROTOR
1	CM52326	PVN'S'/BJY'S'
1	CM56805	IAS54/ALD'S'
1	OC3597	VEE'S'/CEP7731

Table 8. High yielding varieties in 1986 national and advanced tests at Mount Makulu Research Station

					H. sativum score		
Code	Yield t/ha	Height cm	D.H.	LDG	5	25	Grain
G74	2.8	122	54	93	34	42	10
G85	2.3	118	54	83	35	44	10
G92	2.3	125	58	00	54	33	18
H37	3.2	125	56	21	34	33	10
B213	1.8	115	54	88	34	46	20
B59[a]	1.8	125	59	86	45	41	8

D.H. = Days to 50% heading, LDG = Lodging on 0-9 scale (extent, degree), *H. sativum* - Grain: Factors 0,1,2,3,4 and denominator 8 in disease index.

[a] B59 = Whydah

The rainfed wheat varieties that are being grown commercially in 1987 are shown in Table 10. A pre-release phase was introduced in the variety release procedures in 1986. A minimum of 2 years of on-farm production tests is required before release can be considered. G92 is less uniform than H37 but has similar disease resistance. C6, although no longer in tests, yields around 2 t/ha and has tolerance to acid soils.

Foot and Root Rots and Seed Treatment

Foot and root rots are minor problems in Zambia at present. There is no intensive production with wheat-wheat rotations, and soil-borne diseases causing common foot and root rots have not built up. Seedborne inoculum of *H. sativum* and *Fusarium* spp. is excluded by seed production under irrigation in the cool season. Disease-free seed provides an ideal start for a crop, but its production is extremely costly due to the low yield capacity of the tropical wheat varieties under irrigation.

Occasionally, damping-off and die-back occur. *Rhizoctonia* spp. are most often isolated from roots and crowns of such plants. Other pathogens are *H. sativum* and *Fusarium* spp. Hand-seeded plots (shallow seeding) appear to be more prone to attacks than machine-seeded plots.

Sclerotium rolfsii infections have been observed during the stem elongation stage, and the pathogen was isolated from the occasional plant with "whitehead" symptoms. *Rhizopus* spp. caused pre-emergence damping-off at the Mount Makulu station in plots seeded with untreated seed in 1986.

Table 9. High yielding varieties in 1986 preliminary yield tests at Mount Makulu Research Station

Code	Yield t/ha	Height cm	D.H.	LDG	*H. sativum* score		
					5	25	Grain
MM8210	3.3	96	49	00	43	63	15
MM8236	2.9	134	53	51	32	31	5
CM56805	2.4	97	53	00	33	63	8
OC3597	2.9	86	48	00	32	55	10
CM52326	2.5	105	51	00	33	64	8
B59[a]	1.6	121	61	63	44	51	6

D.H. = Days to 50% heading; LDG = lodging on 0-9 scale (extent, degree), *H. sativum* - Grain: Factors 0,1,2,3,4 and denominator 8 in disease index

[a] B59 = Whydah

Laboratory tests have shown that Baytan 15SD (triadimenol) at 200 g/100 kg of uninfected seed provides good protection against *Rhizoctonia* spp., *Fusarium graminearum* and *H. sativum*. Furmecyclox was effective against *Rhizoctonia* spp. (14, 17).

Triadimenol was tested for the control of seedborne *H. sativum*. PF7339/Hahn'S' seeds with black point were selected. Each "plot" was made up of five separate flat bottom test tubes with one seed on water agar per test tube. The following treatments were used: standard seed treatment Captasan at 250 g/100 kg,

Table 10. Rainfed wheat varieties on farms in 1987

Code	Cross/Pedigree	Status
B59	ND81/IAS59//IAS58(PF7748) F3750-56F-0R-2F-0R-2F-0R-0F-2F-11R-0F	Released 1984
B213	IAS64/ALDAN'S' CM47207-16M-2Y-3F-702Y-12F-0Y	Released 1986
G74	PREDG/NAC//PF7748 MM8101-79MM-0MM-3MM-0MM	Pre-release 1986
H37	PF7339/HAHN'S' CM70377-3MB-0MM-1MB-0MM-2MM-0MM	Pre-release 1986
G92	PF7339/HAHN'S' CM70377-3MB-0MM-4MB-0MM	
C6	PEL73280/5/ATR71/4/TZPP// IRN46/CNO67/3/PROTOR CM50321-2MM-0MM-1MM-1MM-0MM	

Table 11. Control of seedborne *H. sativum* under laboratory conditions

Treatment	Infection at 20 days after seeding (0-5 scale)	
	Coleoptile	Roots
1. Unsterilized	4.51	3.95
2. Surface sterilized	3.83	3.87
3. Captasan[a]	3.45	3.58
4. Triadimenol	0.04	0.36

[a] Captan + Malathion

Baytan 15SD at 250 g/100 kg, surface sterilized, and unsterilized seed. The treatments were replicated 5 times. The infection on coleoptiles and roots was scored at 10 and 20 days after seeding. The results are presented in Table 11. Captasan was not effective but triadimenol was highly effective in controlling seed-borne *H. sativum*. All treatments except seeds treated with triadimenol had very little root development due to early fungal infection. The root score of 0.36 on the triadimenol treatment is due to infection by *F. graminearum*, which was not completely controlled.

Conclusions

The major constraint to wheat production under rainfed conditions in Zambia is the high disease pressure caused by the *H. sativum* disease complex. The threat of total crop failure due to disease has been removed by the development of resistant varieties. Tropical wheat varieties with resistance to *H. sativum* diseases have now been released for commercial production in Zambia. Seed requests from neighboring countries demonstrate the need for rainfed wheat production in the region. However, to boost production the tropical wheats need further improvements: higher yield, better plant type, and resistance not only to *H. sativum* but to many other pathogens as well. A reliable disease scoring method allows for the identification of resistant varieties in the field. Tests at other "more tropical" locations should be done with this germplasm to provide further evidence of resistance. Fungicide use is restricted to seed treatment for the control of seed- and soilborne diseases which cause only minor damage at present.

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Breeding and Testing Strategies to Develop Wheats for Rice-Wheat Rotation Areas

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Abstract

The rice-wheat rotation is practiced on more than 20 million ha worldwide and involves two crops with opposite agronomic requirements. The prevalent rice-wheat rotations are analyzed and classified into three different situations based on agroclimate, agronomic practices, and production constraints: i) the Indian Subcontinent; ii) the Yangtze River Basin of China; and iii) the tropical rice-wheat rotation in countries such as Thailand, the Philippines, and Indonesia. Breeding and testing strategies for the major production constraints in rice-wheat rotations — heat tolerance and resistance to Helminthosporium *spp. and fusarium scab — are discussed. A combination of these characters in a suitable agronomic background will be required to exploit the location-specific yield potential of wheat grown in a rice-wheat rotation, and additional progress can be expected by exploring different combinations of early, medium, and late maturing wheat and rice to optimize the output of the system.*

It is my great pleasure to speak at this conference on Wheat Production Constraints in Tropical Environments. Not fully conversant with the rice-wheat rotation, I find myself not fully qualified to deal with this important agricultural system. My comments may not be completely authoritative; for that, I ask for your forbearance. However, the synthesis of this paper involves a careful consideration of the constraints prevalent in a rice-wheat rotation, and how they can be overcome to enhance the total production of the system.

The rice-wheat rotation is a commonly practiced agricultural system, especially in the Indian Subcontinent, the Yangtze River Basin of China, Korea, Japan, the Fuerte River Valley of Mexico, and in Egypt. It involves more than 20 million ha. The requirements of agronomy, especially land preparation and soil structure, are so different for each crop that without a proper management system, yields can be very low. The rices, in general, require puddled conditions, with standing water in the field — an anaerobic situation in which rice thrives. Completely opposite conditions are necessary for growing wheats.

Environmental Classification of Rice-Wheat Rotation Areas

The rice-wheat rotation areas can be roughly classified into three different situations — the Indian Subcontinent, the Yangtze River Basin, and the tropics — based on latitude, climate, and the growth cycles of both species. The varieties of one situation are generally not suitable for the others, and separate breeding objectives will be needed for each situation.

The Subcontinent

On the Subcontinent, wheat is planted after the rice is harvested. There is great urgency in regard to land preparation and the planting of wheats on time. The optimum time frame would be to have the rice harvested by mid-November, and the land prepared and the wheat planted by early December. But because of the lateness of most rice varieties, and, in certain situations, because of the wetness of the land, wheat is more often planted in late December or early January. This late planting results in yield losses for the wheat varieties currently available. Thus, heat tolerance is a major prerequisite for wheat varieties in this region. After the wheat is harvested, there is little haste to prepare the land for rice planting because, in most parts of the Subcontinent, this operation starts after the monsoon begins. The lag period varies from 1 to 3 months depending on the location.

Breeding objectives for this environment include heat tolerance, earliness, leaf rust resistance, and in certain places *Helminthosporium* spp. resistance. Most rice-wheat areas of this type lie between 23 and 30°N latitude.

Yangtze River Basin
In the Yangtze River Basin, rice is planted after the wheat is harvested. The time frame is so critical that even a delay of 1 week in maturity may upset the system. The varieties of both species are so precisely tailored that they must mature in an exact time frame. The agronomic operations have to be done so fast that, in certain situations, the wheat is harvested and the rice is planted the same day.

The varietal characteristics of this region are completely different from the Subcontinent. The major difference is the requirement for some cold tolerance, followed by heat tolerance. Most of the Yangtze region, with the exception of the coastal areas, experiences cold temperatures in the winter after the wheats have been planted, and very high temperatures after flowering and before maturity. Because of this, the recommended varieties must have a very long vegetative period to avoid the frost, and once they flower, must mature very fast (sometimes in 30 days) to avoid high temperatures in late spring and early summer.

The breeding objectives must include cold and heat tolerance; resistance to powdery mildew, fusarium head scab, and helminthosporium; lodging resistance; and, most importantly, tolerance to waterlogging. Rusts generally are not a problem except in isolated cases. Major selection emphasis should be placed on rapid grain filling after flowering.

The tropical region
The tropical region includes Thailand, the Philippines, Sri Lanka, Indonesia, and other countries, where wheat is not commercially cultivated now, but could become an important food crop if grown in a rice-wheat system. The problems of varietal production are surmountable, but there are many other production constraints. I personally believe that varieties can be tailored to suit tropical environmental situations. What I am not sure about is whether agricultural authorities of the region will maintain viable breeding and production programs long enough to achieve the required results. The gathering at this conference is a positive sign.

Because of numerous environmental constraints (such as temperatures), the growth of wheats and hence total biomass production are going to be limited even with the best agronomic practices. It will not be possible to achieve the 12 t/ha yield of Western Europe or the 6 t/ha yield of Sonora, Mexico. However, with extensive efforts (both in breeding and production), economic yield levels can be achieved. What is that yield potential? We do not know yet. What we know is that, because of high temperatures, the yield potential will not be comparable to yields of subtropical or temperate regions.

I do not want to appear too pessimistic in regard to wheat for this area. However, the task will be difficult. Diseases such as helminthosporium, fusarium head scab, and leaf rust could be devastating. In certain situations, *Sclerotium rolfsii* may be a serious problem. In addition, drought and heat tolerance will be needed to stabilize production.

Breeding and Testing Strategy

There are ongoing breeding and production programs in each of the above regions. The scope of this paper does not provide an opportunity to discuss the details of each. Nonetheless, I will attempt to provide a constructive and positive analysis related to each region. The basis of my suggestions assumes that in each situation, proper agronomy in relation to wheat cultivation is employed. That is, wheat would not be grown in puddled soils, oversupply of moisture would be controlled, and recommended amounts of fertilizers would be used. Breeding wheat for puddled soil situations (anaerobic) is an exercise in futility. Agronomic methods should be employed to correct the conditions that are deleterious for wheat growth and development. The following varietal characters are the most important for areas with a rice-wheat rotation.

Heat tolerance
High temperatures are responsible for yield losses in the late-planted situations of the Subcontinent and in the tropical situations of Southeast Asia. High temperatures reduce tillering, head size, size of grain, test weight, and in effect total biomass and yield. There is an optimum temperature for wheat growth and development, and a reduction in yield in proportion to the higher heat units above the optimum. Table 1 illustrates the effects of higher temperatures on yield. Mexicali is subtropical, while Tampico is tropical in the wheat growing season (winter months in Mexico). Tampico has a higher mean daily temperature than Culiacan, Cd. Obregon, Los Mochis, and Mexicali. In general, provided there are no soil problems, Mexicali is a site with higher yield potential than Cd. Obregon, which in turn is superior to Culiacan and Los Mochis, all within the Mexican wheat belt. Tampico is outside of the Mexican wheat region, but wheat is being grown on a limited scale in this area.

Table 1. Yield response of Seri 82 at five different latitudes in Mexico in 1984

Locations	Latitudes	Yield (kg/ha)	Maturity (days)
Mexicali	30°53′N	8544	140
Cd. Obregon	37°20′N	7053	123
Los Mochis	25°48′N	6216	119
Culiacan	24°48′N	6111	105
Tampico	22°12′N	3778	98

I would like to point out that late planted wheat in the Subcontinent, in general, experiences exposure to high temperatures in the latter part of the growth cycle, generally from flowering to maturity. However, in the tropical areas of Southeast Asia the wheat crop is exposed to high temperatures from planting to maturity.

Genetic variability exists in regard to tolerance to high temperatures and recently, both at CIMMYT and elsewhere, attempts are under way to identify the best genotypes. An Indian variety, Sonalika (originally bred in Mexico by CIMMYT), is an example of a variety suitable for late-planting in the Subcontinent. This variety escapes heat exposure because it matures very early. However, because of its earliness, it has less biomass production and less yield potential than other varieties (Table 2). Based on data from the Subcontinent and tropical locations, it can be concluded that a suitable variety for rice-wheat rotations would be one that has medium maturity with a high degree of heat tolerance (China excluded). Medium maturity would permit manipulation of higher biomass and yield potential, while heat tolerance would protect that yield from being eroded. I am pleased to see that Pakistan has applied this hypothesis with good results.

Selection methodology and criteria should ensure development of varieties of wide adaptation and acceptance. I personally do not see a need to have two separate programs, one for optimum planting and another for late planting conditions. These two characteristics can be combined in a single breeding program; perhaps in a scheme like the following:

F_2 Optimum planting date, environmental conditions of nursery should include high fertility and well-watered conditions, with artificially created disease epidemics.

Table 2. Highest yielding varieties of 20th International Spring Wheat Yield Nursery (ISWYN) compared to Sonalika in certain locations of the Subcontinent

Location	Highest yielding variety	Yield (kg/ha) Variety	Yield (kg/ha) Sonalika	% of Sonalika
Ishurdi (Bangladesh)	Ures 81	2444	2074	117
Ye-u (Burma)	BAW 28	1547	1432	108
Pirsabak (Pakistan)	Nacozari 76	4675	2874	162
Islamabad (Pakistan)	MN7357	4888	4555	107
Faizalabad (Pakistan)	Seri 82	4911	4177	117
Sind (Pakistan)	Ciano 79	5815	4815	120
Average		4046	3321	121

F_3 Late planting, environmental conditions of nursery to be kept as desired, e.g., selection for drought tolerance, etc. Suggest utilization of bulk selection method.

F_4 Same as above.

F_5 Optimum planting date to facilitate selection for good agronomic types and disease resistance.

F_6 Outstanding lines bulked under optimum planting conditions.

F_7 Yield trials under both optimum and late planting. Best lines selected on the basis of yield and disease performance.

It should be emphasized that the breeding programs of the Subcontinent should place high priority on leaf rust resistance, in addition to heat and drought tolerance. An epidemic of leaf rust in the Gangetic and Indus Valleys would be disastrous to the region. A reduction of 10% in production would mean ± 6 million t less wheat for the area. Sonalika, a susceptible variety, is currently grown on approximately 10 million ha in the region, and this constitutes a precarious situation.

Helminthosporium resistance

We still do not have a good picture of the distribution of *Helminthosporium* spp., i.e., *sativum*, *tritici repentis*, or *giganteum*. However, it is my belief that *H. sativum* is the most widely distributed in the rice-wheat areas. It flourishes in conditions of high temperature and high humidity. *H. tritici repentis* requires cooler temperatures, and can be a problem in the Tarai of the Subcontinent in the early stages of growth. *H. sativum* is also the main limiting factor in wheat cultivation in the Philippines. Because of its complex distribution, resistance to helminthosporium would not be required uniformly across the rice-wheat areas. Nevertheless, in certain areas, such as the eastern part of the Subcontinent, it would be highly beneficial to wheat culture. Without this resistance and in the absence of suitable fungicides, it is not possible to consider growing wheat in the Philippines, Indonesia, or Sri Lanka.

CIMMYT's own germplasm is weak in the desired combination of heat tolerance and helminthosporium resistance. We have tested germplasm for these constraints for the last 10 years with variable success. Helminthosporium resistance has been difficult to stabilize, and I personally sympathize with my colleagues in the Philippines. However, we have identified some materials with resistance (Table 3), which if employed with one application of a fungicide could provide adequate protection. Chinese varieties from the Yangtze Basin and Brazilian varieties are the best sources of *H. sativum* resistance identified to date.

It is important to point out that helminthosporium resistance alone would not make a variety suitable for rice-wheat areas. Other characteristics such as heat tolerance, leaf rust resistance, and yield potential must be combined with proper maturity and height genes to make it acceptable to farmers. With this aim, we have started a breeding program to develop varieties for the rice-wheat systems. In 1987, CIMMYT will distribute a new nursery, tentatively named the Warmer Areas Wheat Screening Nursery (WAWSN). Heat tolerance and helminthosporium resistance will be cornerstones of this nursery.

Table 3. Twenty-five varieties of bread wheat resistant or moderately resistant to *Helminthosporium sativum* in Poza Rica, Mexico, in 1986

Variety or line	Pedigree
V81623	CM43903
NINGMAI # 4/ON//ALD/YANGMAI # 3	NING 8201
SHANGHAI # 4	-15B-0Y
SUZHOE # 1	-5B-0Y
SUZHOE # 8	-12B-0Y
SUZHOE # 10	-31B-0Y
YMI # 6	-40B-0Y
LIRA	CM43903-H-4Y-1M-1Y-3M-3Y-0B-0E
PRL/TONI	CM67360-2Y-3M-4Y-1M-1Y-2M-0Y
COOK/VEE//DOVE/VEE	CM69279-C-2Y-1M-1Y-1M-0Y
MN72131	
BJY/COC	CM55651-4Y-2Y-1M-4Y-0M
LAJ2514	
TRT	CM40610-33M-500Y-500M-500Y-0M-PURAT
ALD//CNT7/PF70354/3/PAT24//BB/KAL	F11687-2L-9L-12L-0L
PF7035/BOW	CM67910-7Y-1M-4Y-0Z-2Y-2Z-0Y
BH1146*3/ALD	F16896-6F-701Y-1F-702Y-1F-0Y
ALDAN/CNT9	CM53512-2MM-2MM-1MM-1MM-0MM
COQ/F61.70//CNDR/3/OLN/4/PHO	CM60907-K-1Y-2M-1Y-2M-0Y-1PTZ-0Y
MN72131	
WRM/PTM//COC	CM43558-N-6Y-1M-2Y-6M-2Y-1M-0Y
ALD/PVN	CM49901-14Y-2Y-6M-4Y-0M
KEA	CM21335-C-9Y-3M-1Y-1Y-1Y-0B
CI14227/TRM//MAD	CM47943-V-5M-3Y-1M-1Y-0Y
RRV/WW15/3/BJ/2*ON//BON/4/NAC	CM65202-3M-2Y-3M-4Y-0M

We firmly believe that it is necessary to amplify bilateral cooperation through shuttle breeding activities to produce varieties for rice-wheat rotations. We are already shuttling germplasm with Tarai, Nepal (for heat and helminthosporium), Sudan (for heat), and Paraguay and Brazil (for heat and helminthosporium). The performance of the lines in the first WAWSN may be less than satisfactory, and we ask for time and support to make it successful. Please remember that the International Bread Wheat Screening Nursery (IBWSN), a highly sought nursery worldwide (250 locations), was not successful in its first year.

Fusarium head scab resistance
Fusarium head scab is one of the major disease problems in the Yangtze River Valley of China. The disease is so severe in some years that without fungicide applications, wheat cultivation would be next to impossible. Yield losses up to 30% have been reported. Scab is endemic in the region and takes on epidemic proportions almost every other year. Part of the problem lies with the commonly utilized rice-wheat rotation, because the causal organism survives in rice also.

Chinese scientists have been able to breed a good level of scab tolerance into their varieties. Some of this resistance traces back to the old improved variety Su Mai 3. A partial list of varieties resistant to scab is given in Table 4. Chinese varieties appear frequently in this list. There is no doubt that they have made good progress in scab tolerance. Further progress can be made by maintaining this resistance in a suitable agronomic background. The typical Yangtze plant type is characterized by low tillering potential and small heads, which need to be modified to realize higher yields.

It is suggested that the Chinese introduce more variability into their breeding programs by crossing to wheat varieties from other parts of the world. Some progress is evident in Nanjing and Sichuan Provinces. While changing the architecture of the wheat plants for this area, we must remain vigilant not to disturb the early maturity of their varieties. The earlier the variety, the better it will be for the cropping system.

At CIMMYT, we believe a shuttle breeding program between Mexico and Chinese research centers in the Yangtze River Valley involving crosses of CIMMYT germplasm x Yangtze germplasm may enhance the process of increasing yield potential while maintaining or improving scab tolerance. The strategy of this shuttle program should be examined in great detail. For the time being, certain seed quarantine problems exist that should be removed or minimized in the near future.

Maturity Requirements for Rice-Wheat Rotations

It must be re-emphasized that the breeding programs in the Subcontinent should be flexible enough to explore the maturity issue intelligently and realistically. The rice breeders of the region should be prepared to produce rice varieties of medium-maturity to permit rotation with medium-maturing wheat varieties. In this way, the yield potential of both crops could be realized. At the present time, it is not economically sound to rotate late rice with early wheat.

The International Rice Research Institute (IRRI) and CIMMYT can serve as catalysts in motivating this change. We must investigate on a large scale the best economic rotation package, i.e., early/early, early/medium, early/late, medium/early, medium/medium, medium/late, late/early, late/medium or late/late varieties of rice and wheat, respectively. The current large-scale practice is a late or medium variety of rice rotated with an early variety of wheat. This may not be the best varietal combination economically.

The maturity requirement of wheats for the Yangtze Basin is even more difficult to satisfy. The vegetative period must be long enough to avoid cold damage. Cold tolerance genes need to be incorporated to achieve this. Meanwhile, heat tolerance and a early maturity are needed to accommodate subsequent rice planting.

In closing, I want to state that I have not touched all the facets of breeding for the rice-wheat rotation. In addition to the above points, yield potential, quality characteristics, agronomic suitability, and resistance to other stresses would be required for satisfactory results.

Table 4. Varieties resistant to scab in Mexico

Variety or cross and pedigree	Scab score 0 - 5
ALDAN/IAS 58 CM53481-6Y-1Y-4M-1Y-1M-14-0M	2
BR1/3/KVZ/GV//KA/EMECK 132/4/PAT70402/ALD//PAT72160/ALD CM57595-A-2Y-1Y-103F-701Y-1F-700Y-0Y	1
F6.74/BUN//SIS CM60042-M-1Y-2M-2Y-1M-1Y-0M	1
MRL/BUC CM61949-13Y-1M-2Y-1M-1Y-1M-0Y-1B-0Y	2
MOR/VEE # 5 CM67443-12Y-1M-3Y-1M-0Y	2
PF70354/BOW CM67910-17Y-1M-4Y-2M-1Y-2M-0Y	2
MRNG/BUC//BLO/PSN CM69191-A-5Y-1M-1Y-2M-2Y-2M-0Y	2
PF70354/ALD//YACO CM74339-043Y-013M-04AL-4Y-2AL-0Y	1
THB/KEA CM74376-(1-9) M-07Y-032M-0Z-0Y-2M-0Y	1
GEN/3/GOV/AZ//MUS CM77851-17Y-025H-0Y-2M-0Y	2
URES/BOW CM78108-3M-02Y-02M-7Y-1B-0Y	2
TUNGURAHUA//IAS20/H567-71 CM78179-1M-07Y-05M-1Y-8B-0Y	2
VEE # 5/3/GOV/AZ/MUS CM79961-18Y-02M-0Y-9M-0Y	1
ALD/IAS58.103A//NOB/3/CEP 76148/4/GEN CM81573-4Y-025H-0Y-7M-0Y	1
SNB//ALD/PVN CM81598-26Y-025H-0Y-1M-0Y	2

Table 4. (continued)

Variety or cross and pedigree	Scab score 0 - 5
KVZ/3/TOB/CTFN//BB4/BLO/5/GLEN/6/BOW CM83225-013TOPM-2Y-02TP-2Y-3M-0Y	1
PF7619/DOVE//CEP7670 B 25813-A-1M-1Y-1M-3Y-7M-1Y-1M-05AL-0Y-2AL-0Y	2
TOB/8156//Y50E/3*KAL/4/MRS//KAL/BB/3/AZ ICW 82383-1Y-02M-0Y-3M-0Y	2
F3. 71/TRM	TR
WHYDAH (PF7748)	2
CAHUIDE	TR
CHINA 7	TR
KAIFENG # 2/SUMAI #3	1
NANJING 7840	1
NING 8331	TR
SHANGHAI # 3 -32B-0Y	TR
SHANGHAI # 4 -23B-0Y	1
SHANGHAI # 5	1
SUZHOU # 4 -24B-0Y	TR
SUZHOU # 6 -6B-0Y	TR
SUZHOU # 8 -28B-0Y	TR
SUZHOU # 9 -37B-0Y	TR
SUZHOU # 10 -38B-0Y	1
YM1 #6 -40B-0Y	1

Data provided by Girma Bekele, CIMMYT plant pathologist.

A Perspective on Research Needs for the Rice-Wheat Rotation

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Abstract

The rice-wheat cropping pattern represents approximately 17.7 million ha or 28% of the cultivated wheat area of South and Southeast Asia. Research needs in terms of crop establishment and land preparation, fertilizer, weeds, irrigation, alternative cropping patterns, harvesting, threshing and storage, integrated disease control of typical hot climate diseases by genetic, agronomic, and chemical means, and varieties with special morphological and physiological characters, are discussed. In conclusion, an integrated, multidisciplinary approach involving biological and social scientists, extension agents, and farmers is proposed to develop recommendations for this cropping pattern that consider the economics and stability of the whole system rather than an individual commodity. A balance of applied on-farm research backed by a well-focused on-station program is a proposed methodology.

This paper will attempt to identify some researchable issues for the rice-wheat cropping pattern, which is regionally important in South and Southeast Asia. Some of these issues are being discussed in this conference, and for some issues results are available. Many of the problems associated with this cropping pattern are common across the region and it is hoped that any available results can be verified by experiments in other countries.

Many farmers, especially in more tropical environments and where irrigation is available, grow two or more crops in their fields. It is essential that researchers take account of this added complexity in designing experiments and developing recommendations. Many agricultural research programs are divided either by discipline or commodity, leading to research being conducted in isolation and not taking due account of significant interactions that occur when crops are grown in double or multi-cropping patterns. The major need for research in the immediate future is an integration of discipline- and commodity-oriented programs to investigate production problems in a cropping system or farming system perspective.

The Extent of the Rice-Wheat Cropping Pattern

The problem of discipline- or commodity-dominated research is amply demonstrated by the statistical reporting of area, production, and yield of major crops in official country statistics. It is not possible to find these data by cropping pattern and only one paper, from China (13), listed any area for rice-wheat.

An attempt was made in Table 1 to estimate the percent of wheat that is grown after rice in the six major wheat growing countries of the region. Any wheat area for the more tropical environments was left out because of the insignificance of the value compared to the 62 million ha of wheat in the six countries listed, but a major proportion of wheat in these areas would also follow rice. One obvious research need is to refine these estimates and convince statistical collection agencies to collect data by pattern as well as by commodity.

Very few data are available on yield for these 17.7 million ha of wheat grown after rice. The literature from India has several figures, but mainly data from cropping pattern trials conducted on-station. Byerlee et al. (6) reported yield of wheat following rice based on crop cuts taken from 152 fields in the rice growing tract of northern Punjab. Average yields were 1.8 t/ha, but quite variable and significantly less than wheat yields measured in other cropping patterns. Accurate estimates of farmer yields and management practices for wheat after rice, plus experimental data on potential yields for this pattern, are needed as a basis for evaluating research results and as a basis for developing recommendations.

Pinkley (24) looked at the variance decomposition of wheat in Pakistan and his data showed that the rice-wheat zone of the Punjab produces about 16% of the country's wheat, but is responsible for over 25% of the year to year variability in wheat production attributable to individual zones. This means that any research that would increase the production and stability of yields in the rice-wheat zones would be beneficial for stabilizing wheat production for the country.

Agronomic Research Issues

Crop establishment and land preparation

The most critical factor in determining yield for wheat after rice is plant stand. This is a complex factor influenced by soil type, quality of land preparation, tillage implements, crop residues, and time. The crop management used for a transplanted puddled rice crop is not favorable for the following wheat crop. In many cases it results in a soil structure that is very difficult to convert into a suitable seedbed for wheat cultivation without considerable inputs of money and time for land preparation. On some heavier textured soils it is not possible to prepare a good seedbed even with these inputs, and the resulting poor yields deter farmers from investing a lot of resources for wheat production.

Table 1. Total wheat area and estimated percentage of area of wheat grown after rice in six of the major wheat producing countries of the region

Country	Total wheat area (1000 ha)	% wheat after rice	Area of wheat after rice (1000 ha)
China	29,468	30	8,978
India	24,395	26	6,392
Pakistan	7,322	20	1,464
Bangladesh	526	85	447
Nepal	472	80	378
Burma	135	10	14
Total	62,328	28	17,672

Source: 1984 data in CIMMYT World Wheat Facts and Trends (9).
Author-estimates based on official country statistics for rice and wheat

Any land preparation where traditional, tall rice varieties are grown will result in crop residue problems that prevent the use of seed drills for planting. Farmers are forced to broadcast their wheat seed, resulting in generally poorer plant stands, although this can be compensated for by increasing the seed rate.

The other important factor is time of planting. Delay can occur either because of the time needed for land preparation or the delay in the harvest of the rice crop. In Pakistan, research has shown that between 40 to 50 kg of grain (1% loss per day delay) can be lost per hectare per day if wheat planting is delayed beyond November 20th (Figure 1). Similar data are available from other countries in the region.

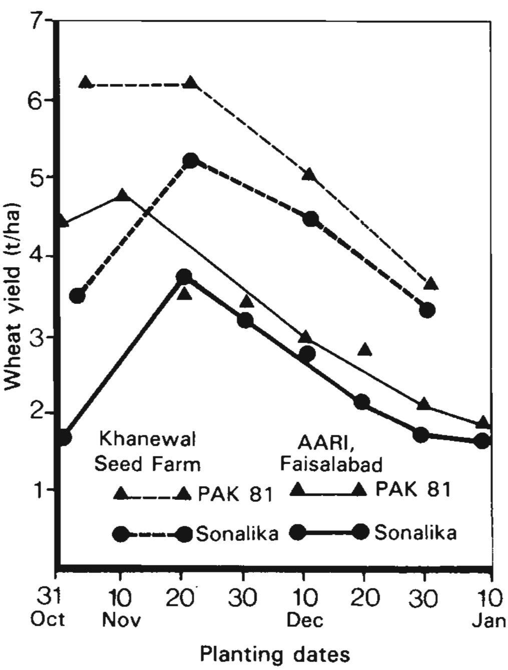

Figure 1. Effect of seeding date on the yield of PAK 81 and Sonalika wheat at two locations in Punjab, average from 1981 to 1984.

In some rice growing areas excess moisture is present at rice harvest and wheat cannot be planted until the water table drops. In these situations, either wheat should not be grown or practices to minimize turnaround time should be used.

There are two possible research thrusts for the problem of crop establishment and land preparation:

1. Develop more efficient implements for quick turnaround

2. Develop a technology based on minimal or zero tillage.

In the first thrust, the use of a soil-turning primary tillage plow followed by a secondary rotary hoe or rotavator removes the problem of the rice crop residues and, if soils are not too heavy or wet, results in a good seedbed for wheat. Research is needed to determine the effect of the depth of primary tillage on the plow pan formed during puddled rice cultivation. Would the added benefits of better rooting in wheat and subsequent higher wheat yields offset the problem of greater water percolation in the next rice crop and possibly lower rice yields? What would be needed to reform the plow pan for the next rice crop and what would it cost?

Obviously this thrust would only be feasible for the more mechanized countries of the region. Costs obtained from some pilot projects in Pakistan show that the above system (one moldboard followed by one rotavator operation) is equal in cost to the traditional system of repeated passes of the spring tined cultivator. The benefits are a better seedbed that can be drilled, resulting in a better plant stand and earlier planting.

The second thrust, zero tillage, is probably more practical for resource poor farmers, and several countries have reported success with this system — Australia (3), India (10), Philippines (8), and Pakistan (21). A more thorough review of this system is presented by Majid et al., in these Proceedings.

The following are issues for zero tillage that require verification or further research in the region:

- Development of a suitable drill. In Pakistan, we are using a multicrop seeder that utilizes an inverted-T opener developed in New Zealand and adapted to either a tractor-pulled drill or a single or double row drill that can be pulled by animals or two-wheel tractors (8).

- Study on the effect of zero tillage for wheat on the stem borer population in the next rice crop. One reason for plowing rice stubble is to kill the stem borer larvae that hibernate in the base of the rice stubble. The benefits derived from direct drilling of wheat, such as lower production costs and earlier planting, must be compared with the cost required to control stem borer in the next rice crop. This research also needs to look at the effect of different stem borer species.

- Long-term studies to determine the effects of zero tillage on soil properties (chemical, physical, and biological), and pest and weed changes. Because of the plow pan caused by puddling soils for rice, the depth of soil for wheat root growth is restricted. Zero tillage should be compared with occasional deeper tillage to quantify any declines in yields over time.

Fertilizer issues

Many fertilizer recommendations for wheat in rice-wheat areas are based on experiments where wheat follows fallow and where experimental designs do not allow a proper economic analysis of the data. What is needed is the collection of good response curve data for wheat following rice grown in situations representative of the major rice-wheat areas. Additional site data should include benchmark data on soil chemical properties (available P, K, organic matter, pH, etc.), soil physical properties, planting date, land preparation methods, previous use of fertilizer and manures, previous rice crop type, rice harvest date, number and source of irrigations, weed problems, wheat variety and any other useful data needed to interpret results.

Some results from Pakistan are shown in Figure 2, where the yield of wheat after rice is lower than after maize or sugarcane. Wheat responded almost linearly up to 140 kg N/ha with little response to phosphorus and no response to potash.

Because of the restricted rooting zone, caused by the plow pan on puddled rice soils (32), there is a good chance that nutrient deficiencies (both micro and macro) will occur in this cropping pattern over time. This problem can be overcome by applying nutrients or by deeper tillage, depending on research findings.

Research, especially from India, has looked at the residual carryover of fertility from wheat to rice and vice versa. Saggar et al. (28) in a 5-year wheat-rice rotation, and Soni and Mukherjee (31) in rice-wheat studies showed that it was better to apply phosphorus to the wheat crop than the rice crop. Bhardwaj and Prasad (4) showed that zinc applied to rice had a residual carryover to wheat in the first and second crop, but none by the third and fourth crop. Singh and Sharma (29) showed that nitrogen applied to wheat had no residual effect on the next rice crop, but 180 kg N/ha applied to rice did have some residual effect on the succeeding wheat crop. More research is needed on this issue, especially since efficiency in fertilizer use will become an important future research issue.

Fertilizer studies are needed for the zero tillage system. Should all the fertilizer be applied at planting, be split, or applied at the first irrigation? How do you apply fertilizer in zero tillage? Evidence from Pakistan and Australia (3) indicates that delaying fertilizer application, including phosphorus, until the first irrigation is better than applying fertilizer at planting. Data are also needed on the benefits of fertilizer placement (possible if drills are used) compared to broadcasting and incorporation.

Weeds

Weeds are major yield limiting factors in the wheat-rice cropping patterns of the subcontinent. Gill and Brar (12) showed that from 1976 to 1982 a continuous rice-wheat rotation using herbicides encouraged the growth of *Phalaris minor*. Byerlee et al. (7) reported that 28% of the wheat fields in the rice-wheat area of the Punjab had an economic level of *Phalaris* infestation to warrant weed control measures. Volunteer rice was also reported as a strong weed competitor in wheat in more tropical environments (29). Research is needed to quantify the weed species present in rice-wheat rotations and assess the yield losses caused by the dominant weeds.

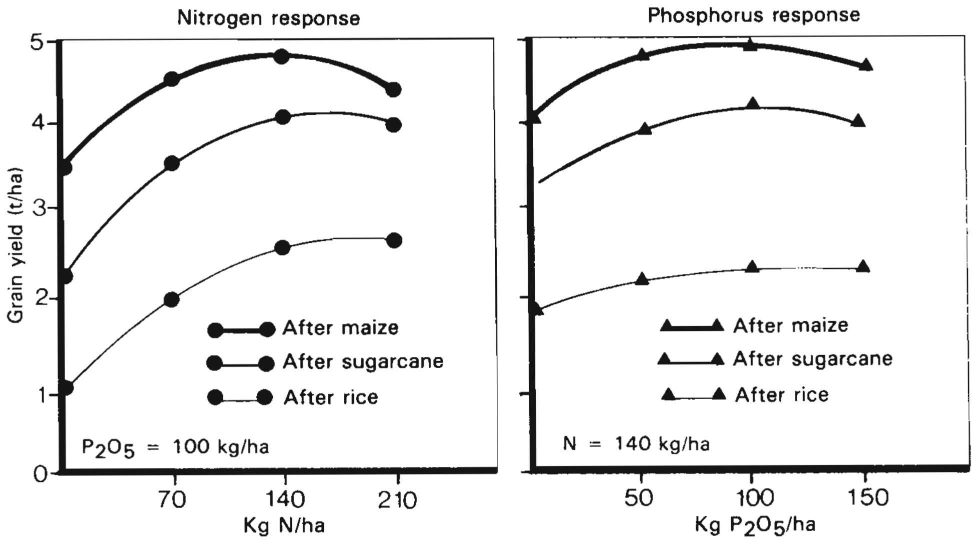

Figure 2. Fertilizer response curves for wheat in three different cropping patterns.

Long-term studies are needed to analyze the changes and buildup of weed species with different cultural practices and weed control strategies in this rotation. This should be done for traditional land preparation and zero tillage methods. Interestingly, in the rice-wheat pattern in Pakistan, few weeds are present in rice fields at harvest, and those weeds that do exist are summer weeds that do not survive the cool winter temperatures. The relatively clean fields following rice harvest allow zero tillage planting of wheat without the need for herbicides. The winter weeds germinate when temperatures drop to critical levels and are a major constraint to higher wheat production, especially the grassy weeds. However, in zero tillage, winter weed populations are lower than in traditional tillage because of less soil disturbance.

There are plenty of data available concerning suitable herbicides for controlling the weeds in this rotation. Data on economic thresholds, however, are needed to help develop recommendations on weed control.

In some countries of the region, sprayers are not readily available. As long as herbicides are applied uniformly, broadcasting of soil active herbicides is feasible. On 40% of the farms of the Indian Punjab, weeds in wheat are controlled by herbicides, with many farmers broadcasting substituted urea herbicides. Use of carriers such as brick dust, soil, sand, or urea to assist more uniform application is a possible research topic. Timing of herbicide application in relation to the first irrigation and crop and weed growth stages is an important question to be answered to increase weed control efficiency.

Other methods of weed control in this system, including crop rotation (using an alternate fodder crop to wheat) and pre-irrigation or delayed planting to allow the first flush of weeds to be killed by cultivation, need to be quantified economically.

Irrigation

In much of the rice-wheat cropped land of South and Southeast Asia, some irrigation water is available. The issue is how efficiently it can be used; if only one irrigation is available, when should it be applied.

An issue in this rotation is the timing of the first irrigation. Because of the restricted rooting zone caused by the plow pan and slow percolation of water, waterlogging frequently occurs after an irrigation. Since young wheat seedlings are sensitive to waterlogging, early irrigation often results in yellowing of plants and reduction in plant stands.

Most irrigation recommendations are based on data from a fallow-wheat rotation where no plow pan constraint exists. Work is needed to measure the consumptive use of water in the rice-wheat rotation with and without the presence of the plow pan.

Alternate cropping pattern

In Pakistan and India, vegetable oil production is only a fraction of the countries' needs. The balance is imported at great expense. Research is needed on developing cropping patterns to help alleviate this deficit. For example, it may be more economic to grow sunflower or soybean after late harvested rice than wheat. These patterns need to be evaluated over time with regard to the same potential problems as in wheat, such as stand establishment, fertilizer, pests, diseases, weeds, and irrigation. Economics and stability of production would then determine farmer acceptance.

Byerlee et al. (6) showed that in fields where rice-wheat had been planted continuously for 3 or more years, there was a large and significant decline in yields. Even when weeds were included in the regression as an independent variable there was still an effect of -400 kg/ha due to continuous cropping of wheat. Rotation with berseem was a major alternative to continuous cropping, and its large positive effect could be due to factors such as residual fertility, improved soil structure, and perhaps control of root diseases or nematodes. Data from fertilizer trials conducted in farmers' fields by soil fertility surveys and soil testing institutes during the past 15 years, which were analyzed by the National Fertilizer Development Centre, Islamabad (Case deBie, personal communication), confirm this finding. In order to ensure stable production, long-term studies are needed to explain these declines in yield over time and to develop cropping patterns that minimize these problems.

One of the major reasons for poor performance of wheat after rice occurs because of the puddling needed to reduce water infiltration in the rice crop. Also, in Pakistan it is becoming more expensive and difficult to get labor to do the more menial farming jobs like transplanting. Research is needed to develop a rice-wheat system that reduces the need for transplanting (direct seeding) and that could remove the need for puddling. The advantages of non-puddling to the next wheat crop must be evaluated against the increase in water use, weed problems, and yields of the next rice crop. There is also a possibility that some environments would be able to support a dry-seeded rice-wheat rotation, especially if soil properties and high water tables were favorable for this rotation. In fact, a high percentage of the wheat grown in Bangladesh follows deep water aman or aus rice, two rice crops that are planted dry without puddling.

Harvesting and threshing

Harvesting, threshing, and marketing costs account for as much as 30% of the total gross returns in wheat and rice production in Pakistan. Many farmers also concentrate on drying, threshing, and marketing of the rice crop before starting cultivation of the wheat crop, which further delays planting. Analysis of constraints and implications of large-scale mechanical harvest using reapers and combines is needed.

Pathology Research Issues

No pathogen appears to be exclusive to rice-wheat rotations, but the entrance of wheat into these areas, where high temperatures and humidities generally prevail, has resulted in greater stresses on the crop and the greater importance of diseases caused by polyphagous pathogens, such as *Helminthosporium sativum* Pam., King & Bakke, *Sclerotium rolfsii* Sac., *Fusarium* spp., and *Rhizoctonia solani*, Kuhn, some of which are only marginally important in temperate climates. Although the danger of leaf and stem rusts is no less important than in more traditional areas, genetic variability for resistance is available and is straightforwardly bred into appropriate backgrounds. However, as a general rule, resistance to wide-spectrum, opportunistic pathogens has not been easily defined or transferred in any crop species. The danger presented by these organisms is compounded by predisposition to diseases imposed by stresses often associated with rice-wheat rotation environments, which may significantly reduce yields alone. Further, the influence of rice-wheat rotations on disease incidence and severity and on the life-cycles and survival of phase pathogens has yet to be adequately assessed. Control of these pathogens will challenge pathologists, plant breeders, and agronomists alike.

Helminthosporium sativum

Taken as a whole, diseases caused by *Helminthosporium sativum* perhaps present the major pathological obstacles to wheat production in tropical environments (16, 17, 22, 25, 26, 27). The common foliar phase, spot blotch, perhaps because it is so obvious, has precipitated the most concern, with epidemics that have resulted in up to 100% crop loss (17, 22, 25). However, the pathogen may also cause pre- and post-emergence damping off, root rots, and head blights. Crop loss assessments are not readily conducted for the latter types of attack and the total loss may be much more alarming than that due to leaf blotch alone. The pathogen is opportunistic and disease tends to be more severe under stressed plant growth conditions caused by leaf rust (L. Butler, unpublished observation) or other environmental factors. The pathogen can be seedborne and loss of seed viability and/or seedling blights may occur as a result of heavy infections. These interactions and indirect effects are insufficiently understood and should be studied.

Although variation for levels of susceptibility or tolerance is clearly observed among wheat varieties (22, 25), simple inherited resistance independent of physiological races of the pathogen (17, 22, 25) or ameliorating environmental factors and plant growth stage does not appear to be available. Resistance instead may be composed of minor genes or additive factors that will be only slowly accumulated, if at all, in adapted plant backgrounds. Alien genes for resistance from species of *Elymus* and *Agropyron* may offer opportunities, but the problems of incorporating this resistance into an appropriate background make this a long-term possibility. Moreover, since the pathogen has an extremely wide host range, which includes rice (23), such single-gene resistance may soon break down in the face of high inoculum pressure. We believe the identification of resistance and the accumulation of these factors, to as high a degree as possible, in conventional backgrounds aided by "shuttle" breeding programs offer the best strategy for the near term.

Fungicides, such as dithiocarbamates, may offer a degree of economic control as seed treatments against damping off (15, 17) (which may be due to a combination of *H. sativum*, *Fusarium* spp., *R. solani*, and *S. rolfsii*), but how safely or effectively they can be used by small farmers to whom they may be expensive and/or unavailable and in environments where they may be toxic to seed is uncertain. In Bangladesh, for example, the government seed producing agency is prohibited from applying fungicides to certified seed because of the fear that foodstuffs may be contaminated or that the seed may be eaten. More research on the effectiveness and phytotoxicity of seed treatments (over time) in warmer, more humid environments is needed.

Fungicides such as triadimefon and fentinacetate-maneb (25) and Tilt 250 (17) have been reported to provide effective control of spot blotch. However, the feasibility of such control may be restricted to economically protected situations. A combination of genetic resistance and chemicals may provide the appropriate control where spot blotch has been determined to cause severe economic losses. Identification of varieties with measurable levels of resistance to the pathogen should be allowed first priority, if this can be accomplished by breeding programs. Crop loss assessments should be undertaken to determine points in terms of time and loss at which chemical control becomes an economically viable supplement.

Sclerotium rolfsii

Known primarily as the causal agent of "southern blight," a severe disease of tomatoes and peanuts in various tropical countries and the South of the USA (2), *Sclerotium rolfsii* has emerged as a major pathogen of wheat in more tropical areas. Although the pathogen is entirely soilborne, it is very nearly omnivorous, attacking numerous dicot and monocot species (16). The pathogen may attack the roots and crown of the wheat plant at any stage of development including the pre-emerged seedling. The activity of the pathogen is probably most obvious and devastating in the crop at the pre-tillering seedling stage, when large patches of yellowing and wilting plants may be observed.

Although high soil moisture initially favors *S. rolfsii* invasion (16, 27), dry soil at crown root initiation may cause greater subsequent losses by discouraging the root formation that might aid the recovery of an infected plant if cool temperatures, which discourage growth of the pathogen, prevail. Disease incidence may vary greatly from one year to another depending upon climatic and cropping circumstances particularly in subtropical cropping environments as in Bangladesh, but losses of up to 30% are not uncommon in many tropical areas (27). The variability of disease incidence, however, even under controlled, known-inoculum potential experiments, has made crop loss and resistance assessments difficult and tentative, and better techniques to gain this type of information are needed.

Differences of susceptibility have been reported (16), but less variability for resistance seems to exist than for *H. sativum*. Nevertheless, sources of relative tolerance should be identified — ideally by screening in "disease gardens" established on reasonably large areas in the field over a number of years.

A number of seed treatments including some common dithiocarbamates have been widely reported to offer protection to the young seedling (15, 17) and systemics (15, 16) may effectively reduce incidence in the developing crop through the critical crown initiation stage as well. The safety of their use, particularly systemics, is again at question, and their long-term practicality should be fully assessed before commitment to their ubiquitous application.

Agronomic techniques have often been cited as ameliorating measures. However, deep plowing — after nitrogen application — of crop residues, clean cultivation, etc., are probably impractical in an unmechanized, small farm environment. Reduced nitrogen encourages the disease on tomatoes (1) and allows the speculation that the most vigorous wheat plants will resist invasion. The form of nitrogen itself needs to be tested as a factor particularly in reference to antagonists. Disease is always more severe at temperatures between 25 and 35° C given adequate moisture (2). Planting at times when seasonal temperatures are at their lowest may be relevant where flexibility for sowing date exists.

Although no cultural practice will eradicate the disease, some may significantly reduce incidence. A strategy in which these are used in combination with seed treatment of more tolerant varieties probably offers the best approach. More research on the cultural control measures of this disease and their interaction is required.

***Fusarium* spp.**

The various species of *Fusarium* that could cause disease in wheat are widely distributed (27), with wide host-ranges, and some may be both root and foliar pathogens. *F. graminearum* Schwab. (*Gibberella zeae* [Schwab] Petch) may be the most important in more tropical areas (19, 20) and is capable of causing head blights (scab), damping-off, and root rots. Incidence and severity of disease may vary dramatically from one year to the next depending on environmental variables, making crop loss assessments very difficult. Losses due to scab, more easily observed and measured, are more generally known; while 100% is possible, losses ranging up to 40% are probably more likely where the disease is chronic (19).

Resistance in various crop species to root rots caused by *Fusarium* spp. is often not clear and, as with the above diseases, defined in terms of relative susceptibility. However, variability for tolerance has yet to be fully assessed for wheat and should receive attention. The development of resistance to scab has received most attention in China (19) and Brazil (20). Effective degrees of resistance have been demonstrated in adapted plant backgrounds in China (19). Obtaining and disseminating this resistance for incorporation in varieties adapted to other areas is of immediate concern.

Seed treatments, such as those mentioned previously, offer varying degrees of protection to the seedling and must be assessed under the terms referred to above. Applications of fungicide to the developing head may offer protection, but timing would be critical and probably not practical in low yield environments.

Environmental changes have profound effects on the incidence and severity of fusarium diseases, and those changes that increase crop vigor and/or promote the proliferation of antagonists may reduce severity of root rots significantly (33). Research is needed to assess the efficacy of various cultural practices in combination with seed treatments to reduce disease incidence.

Rhizoctonia solani

Rhizoctonia solani, a root and culm pathogen of wheat, has perhaps the broadest host-range of any pathogen, and most economic crops appear to be susceptible to some degree (33). The organism's capacity to survive in soil is legendary and is due, in part, to its ability to compete successfully as a saprophyte. Losses due exclusively to this pathogen have not been assessed in the rice-wheat rotation, and assessment may be impossible due to the interaction with other root invading organisms. As with other root pathogens mentioned herein, the organism is profoundly affected by changes in the environment and tends to be more severe in crops lacking vigor (33).

Genetic variability for resistance may be nonexistent. Seed treatments should offer some control (17) but should be assessed under the terms referred to above. Under conditions of economic damage, amelioration by cultural methods such as shallow planting and fertilizer applications should be investigated.

Nematodes
Systematic surveys of nematode populations in wheat crops in more tropical areas have not been conducted. Perhaps as a result, losses resulting from infestations have been assigned to other pathogens. *Meloidogyne* spp. are often noted as a result of the production of root galls, however, free-living nematodes such as *Pratylenchus* spp. are usually not discovered without purposeful investigation. *P. minyus* in combination with *R. solani* causes a serious root and stem disease in Canada and the USA (33). Surveys and population assessments should be conducted.

Breeding Issues

Besides disease resistance, several other characters need genetic improvement in order for wheat to fit into a rotation with rice.

Heat tolerance
Under high temperatures wheat, triticale, and barley complete their cycle much faster than under temperate conditions (11); all crop stages have a short duration. Consequently, leaf and spike insertion and development, tillering, leaf maintenance, meiosis, and grain filling are all critical phases. Plants lacking heat tolerance typically have reduced height, generally with only 3 or 4 active leaves at the flowering stage, which are often erect and small, one or two head bearing tillers, small heads, and poorly filled grain.

Optimum agronomic practices help to overcome these deficiencies, but there is also genetic variability available for many characters that are affected by heat. Further improvements can be made by accumulating these factors into one variety. There is also room for relevant basic research on heat tolerance to help clarify the morphological and physiological characters that contribute most to heat tolerance. Subsequent screening for variability and estimates of heritability would lead to appropriate breeding methods.

From personal experience, we suggest that such research should be accomplished in hot climates for characters such as leaf area and leaf maintenance, head size, number of tillers, ratio between vegetative and reproductive phase, complete or partial absence of daylight sensitivity and vernalization requirements, and root development. A number of observations suggest that selection for head size and/or grains per head is more promising than increasing the number of heads per area unit

(18), but it is unknown whether this is broadly applicable in hot climates. In addition, if some of the identified plant hormones or other factors (30, 32) could be used as a reliable screening method for heat tolerance in single plants, the problem of selecting among poorly developed plants in plots lacking uniformity could be decreased.

Earliness

Earliness is a necessity where crop rotations are very narrow, where it provides a disease escape mechanism, and where irrigation water becomes scarce late in the dry season. It is not necessarily required as a heat escape mechanism toward the end of the cropping cycle. It has been shown that there are varieties that are later in maturity but still fill the grain well with increasing temperatures. Such varieties are Kanchan in Bangladesh, Trigo 3 in the Philippines, and Pak 81 in Pakistan. Earliness is related to daylength insensitivity.

There is an undesirable type of extreme earliness under hot conditions that leads to small heads within a very short time after minimal or no tillering. An environmental factor is involved in this phenomenon, but it is poorly understood. However, there is still abundant variability for true earliness, which can be incorporated into otherwise desirable genetic backgrounds. The use of slightly daylength-sensitive lines could be useful to prevent early heading. Lines requiring vernalization, although delayed in flowering, appear less suitable (23).

Plant height

Hot climates result in shorter wheat plants per se. In addition, it is often necessary to overcome weed competition, especially volunteer rice, which is often the most serious problem to young wheat plants. It has also been reported that *Helminthosporium sativum* development is slower in taller varieties, probably due to microenvironment changes (5). As there are few genes involved in height, this task will be easy to accomplish.

Tolerance to adverse soil conditions

Acidic, salty, and waterlogged conditions appear in rice paddies quite often. For all three conditions there are genetic limits in wheat for tolerance to these stresses, but current varieties are far from exploiting the available variability.

In recent years, the fastest progress has been made in developing aluminum tolerant varieties that also have a good yield potential. (This is dealt with in another paper of this conference.) Varieties developed in the Southern Cone of South America, however, need additional breeding to adapt to the conditions of Southeast Asia, where rice-wheat rotations are prominent.

Although rice is not known as an especially salt-tolerant species, the impact of salt is often alleviated by standing water during the rice season, but its effects can be fully seen on wheat. Wheat cannot tolerate high concentrations, but in soils showing an electrical conductivity of about 25 dS/m^2 there is substantial differentiation between varieties (14). Tolerant varieties can reduce yield losses, but cannot make up for poorly engineered irrigation systems. For example, there are areas where salty water from deep wells has made fields unsuitable for cotton that are now growing wheat. Sooner or later, the wheat will not tolerate a continuous increase in salt content either.

Waterlogging is enhanced in many rice paddies due to the plow pan, which does not allow drainage. Agronomic practices such as proper leveling, careful irrigation, or sowing on beds are especially important in heavy soils. But, genetic tolerance can substantially contribute to reliable yields. Genetic variability seems available but has not been exploited (J.S. Lales and S. Siddique, personal communication), except possibly in China.

Drought tolerance
Although it may seem contradictory to the previous point, drought tolerance is often required in the same field where waterlogging is found. This can be due to problems associated with irrigation water availability, water holding capacity above the plow pan, or soil type. Progress for this character has been achieved and is discussed in a separate paper of this conference.

Conclusion

Research must shift from the traditional isolated, discipline-oriented approach to an integrated, interdisciplinary and multi-commodity approach if we are going to solve the problems of the intensive rice-wheat cropping patterns of South and Southeast Asia. There is a need for a balance of practical applied on-farm research to identify researchable issues and basic on-station research to solve problems that require more control and quantitative data. Social scientists, extension workers, and farmers should work with the agronomists, breeders, and pathologists in an interdisciplinary team. It is no longer sufficient to develop technology for single commodity crops at the research station without understanding the interactions that occur in the cropping system and how the technology performs under the many different environments encountered in farmers' fields. With a good, integrated on-farm research program backed up by a sound on-station program the chances of farmer adoption of technology and the resultant increase in productivity are dramatically improved.

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6

Constraints to Wheat Cultivation in Nonirrigated Areas

Fertilizer Requirements and Management Issues for Nonacid Soils in Nonirrigated Areas

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Abstract

Fertilizer use on wheat has always been low in Argentina, due to a number of economic reasons. With the introduction of high yielding semi-dwarf varieties in the 1970s, fertilization has become much more feasible. This paper shows the response of wheat to N and P in the Pampa Humeda and analyzes the soil and climatic parameters that condition yield and response to fertilizer.

Moisture availability affects both yield and response, as does length of fallow period and the previous crop. Soil analysis for nitrogen does not give a good correlation for nitrogen response, but soil analysis for P is highly correlated to P response.

This report brings together the results of research carried out in Argentina by the National Institute of Agricultural Technology (INTA) in the Pampa Humeda.

In this region, wheat is one of the most important crops. On the average for the 5 years from 1980 to 1985, 6.3 million ha were planted annually to wheat. The average yield for the same period was about 1.8 t/ha, resulting in an average annual production of 11.5 million t. There are many reasons for annual variations in wheat production, such as climatic conditions, diseases, etc. However, there has been a positive yield increment trend of 75 kg/ha per year due to the introduction of new production techniques.

Even though the trend is positive, the consumption of fertilizers is low. There are several reasons for the low fertilizer use, principally:

- Lack of sufficient fertilizer response data
- Unfavorable input/output price relationships
- Uncertainty of crop prices

The introduction of high-yielding, short-season wheat varieties in the 1970s made fertilization more feasible. As a result, fertilizer use has increased.

The cost of fertilizer to the average Argentine farmer has been generally too high relative to the market price of wheat grain. Cirio et al. (3) reported that about 8 to 10 kg of wheat were necessary to pay for 1 kg N. However, since 1984, when the National Fertilization Program was introduced, the wheat/nitrogen relationship has been reduced to 5 to 6 kg of wheat per kilogram of nitrogen.

Another reason for the low fertilizer use is that most of the soils in this region still produce crops profitably without fertilization, except where cropping has occurred for many years without a legume rotation. In the past, it has been common to have pastures in the rotation, generally a mixture of grasses and legumes. However, the uncertainty of beef prices has increased the land dedicated to crop production. The shift of production systems from those that include legume rotation to continuous cropping of cereals has caused concern about soil nutrition management strategies.

Characteristics of the Wheat Production Area

The wheat production area under study is shown in Figure 1. It is a flat area (slopes vary between 0 to 2%). The soils are derived from loess deposits and belong to the order of Mollisols. The predominant suborders are Udolls, Albolls, and Aquolls.

The soils in the northeast are classified as Argiudolls with a well developed clay horizon, which varies in depth over the area. In the southwest part of the region, the soils are coarse-textured and classified as Hapludolls, in which the typical profile is an A-AC-C sequence.

As a rule, the soil clay content of the B horizon varies from 20% in the west to almost 50% in the east. A similar variation is observed in the soil organic content. These variations are positively correlated with the average annual rainfall. Unfortunately, a gradual degradation of the originally high organic matter content (5 to 6%) has been observed, primarily due to the intensive soil cultivation. The soil pH ranges from 5.5 to 6.5.

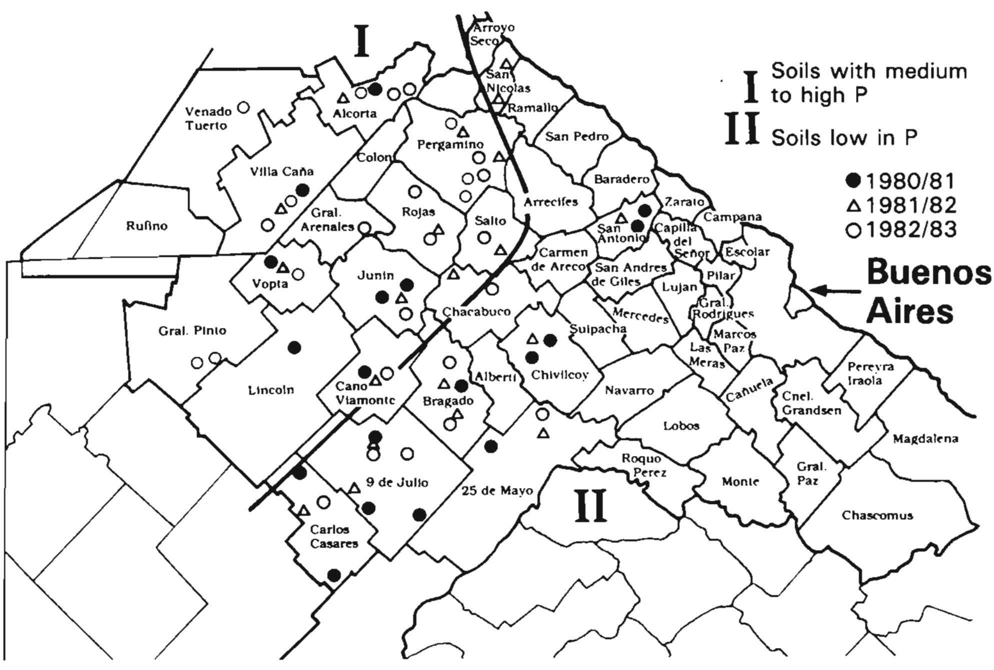

Figure 1. Location of experiments.

The average annual rainfall for the region is around 1000 mm in the northeast and gradually diminishes to 600 mm in the southwest. During the wheat growing season, the precipitation varies from 450 mm in the east to 250 mm in the west, but considerable variations are recorded among years. Annual rainfall is concentrated in autumn, spring, and summer. Wheat is commonly sown in the dry winter period, which occurs during the months of June and July.

The annual mean temperature is around 14°C in the southern part of the region and 16.8°C in the northern part of the area, with temperatures of -4 to -6°C in wintertime (June and July) and a maximum of 35 to 38°C in the summer (December).

Methodology

Since 1960, the Argentine government, through INTA, has conducted several cooperative projects with the United Nations Food and Agriculture Organization, CIMMYT, and other agricultural research institutions. From 1980 to 1984 a cooperative program between CIMMYT and INTA investigated the relationships between soil fertility, management, climate, and crop production in a group of experiments conducted in farmers' fields. The main objective was to assess fertilizer response in wheat.

The experimental design was varied between years and within different parts of the area. In 1980 a randomized complete block design with three replications was used. There were five treatments of N alone and some additional P treatments. In 1981 through 1984, a factorial experiment in an incomplete arrangement, 2^5, with two replications was also used. The nitrogen doses were 0, 30, 60, 90, and 120 kg/ha, while the doses of phosphorus (P_2O_5) were 0, 20, 40, 60, and 80 kg/ha.

Plots were 7 m wide and either 20 or 30 m long, depending on the experimental site and/or the machinery used. Phosphorus was applied as triple superphosphate (0-46-0) and nitrogen as urea. Both nutrients were broadcast on the soil surface before planting and incorporated with a disk harrow.

Each site was characterized by a certain number of soil, climatic, and management parameters (Table 1). Since the trials were surrounded by the farmer's wheat crop, the weed and pest controls were done by the farmer. Information regarding previous crops and management of the field was collected at each site.

Available P was determined with the method described by Bray and Kurtz (1).

Total N was measured by the normal macro-Kjeldahl technique (2), while nitrates (NO_3-) were analyzed by the disulfonic phenol method.

Exchangeable K was extracted with 1 N ammonium acetate solution and measured by a flame photometer (8). Values ranged between 1.5 and 3 meq/100 g soil.

Soil pH was measured by using a glass electrode in a soil water suspension with a soil to water ratio of 1:25.

Effects of Soil Parameters on Wheat Yields

The soil was found to be deficient in nitrogen throughout the area. In the southeast, 57% of the experiments showed significant crop response to N fertilizer application (4). A highly significant crop response was reported in 75% of the 65 experiments carried out in the north-central part of Buenos Aires province (9). Similar results (52% and 85%, respectively) were reported for the southern parts of Cordoba and Santa Fe provinces, and the northern part of Santa Fe (6, 7).

There was strong variation in the relationship between soil NO_3-content and crop response, and the reliability of the results seemed to be related to the amount of rainfall.

Better correlation coefficients were found in the areas with lower precipitation at planting time.

Other parameters such as soil organic matter and total N content were used to predict crop response to N application, but the correlation coefficient was also low.

No significant effect was found on wheat yield with pH values ranging from 5.5 to 6.8. A 5.9 pH average value was reported over 65 experiments carried out in the northern part of Buenos Aires Province (9). No negative effect on either wheat grain yield and/or crop response to fertilization was observed.

Table 1. The average value, range, and standard deviation of various site parameters (N = 65)

Parameter	Average value	Range	SD
pH	5.9	5.2-6.2	0.2
Organic matter (%)	3.13	2.0-4.7	0.61
Total N (%)	0.139	0.082-0.196	0.027
NO_3 (0-20 cm) (ppm)	52	15-136	25.4
Soil P Bray 1 (ppm)	12.4	3.4-36.0	6.8
Depth of A horizon (cm)	27.9	21-34	3.3
Available H_2O to 1.5 m (mm)	221	107-357	52
Total rainfall (mm)	250	111-373	67
Rainfall sowing to tillering (mm)	55	0-206	48
Rainfall tillering to flowering (mm)	102	4-239	51
Rainfall flowering to maturity (mm)	93	16-208	47
Years of continuous agriculture	11.9	0-50	8.8
Length of fallow (days)	60	10-270	44

Moisture availability was one of the most important factors (Table 2). The water content of the soil surface layer (0 to 20 cm depth) was significantly related to wheat grain yield. For each mm of water, an increase of 30.9 kg/ha was registered. In addition, both high yield and crop response were associated with adequate winter-spring rainfall; for each 10 mm of precipitation above the average (86 mm during tillering), the yield was increased about 210 kg/ha.

The length of the fallow period, which varies from a few days to 2 to 3 months, depends on the region and the previous crop. Gambaudo and Vivas (6) reported that the longer the fallow period, the higher the wheat yield and the lower the crop response to N fertilizer (Figure 2).

The previous crop influenced the wheat yield (9). In one study (9), the wheat yield following soybeans or any other legume crop was about 485 kg/ha higher than following maize or any other crop. In another study (7), wheat yielded 514 kg/ha more following soybeans than following a nonlegume crop.

Table 2. Economic optimum doses of nitrogen (kg/ha) under different soil nitrate contents, different rainfall conditions, and different price cost ratios

Wheat/nitrogen price/cost relationship	Rainfall (mm) tillering-visible first node	Soil nitrates ppm (0-30 cm)					
		20	35	50	65	80	95
		N Recommended					
		kg/ha					
3:1	50	82	64	46	29	11	–
	100	97	79	61	43	26	8
	150	112	94	76	59	41	24
6:1	50	54	36	18	1	0	0
	100	69	51	33	16	0	0
	150	84	66	48	31	13	0
9:1	50	26	8	0	0	0	0
	100	41	23	5	0	0	0
	150	56	38	20	3	0	0

Source: Novello et al. (7)

Evaluation of Wheat Response to Fertilization

Methodologies in field experiments have drastically changed over the last 20 years. Before the 1960s, the effect of one experimental variable at different levels was generally studied by keeping all other factors at a constant level. However, recently in fertilizer experiments, each experiment is analyzed individually using a quadratic equation. After a total correlation between all the parameters is evaluated, a stepwise regression method (5) is used in the model building process, which includes the soil, climatic, and management factors that affect the response of wheat yields to fertilization at different sites. Through this type of model, it is possible to diagnose the fertilizer requirements and estimate the economical doses.

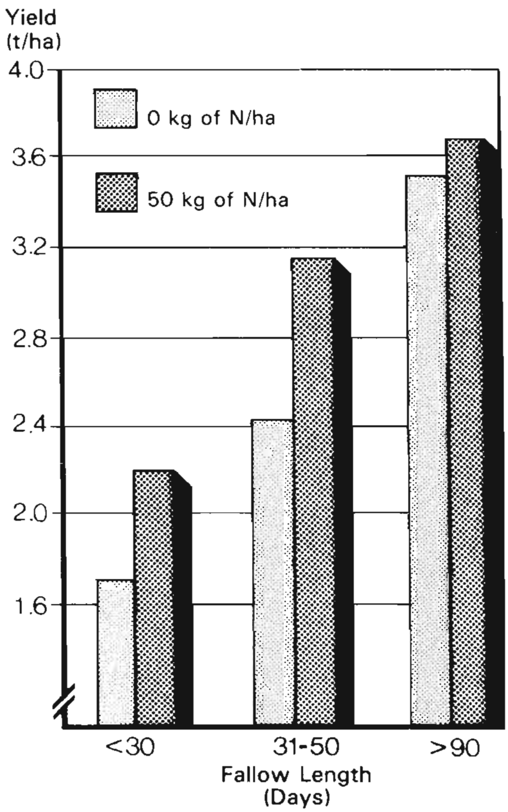

Figure 2. Relationship between fallow length and grain yield.

Source: Gambaudo and Vivas (6)

Novello et al. (7), using this methodology, reported that wheat yield was explained in a $R^2 = 56.4\%$ model as follows:

$$Y = 388.35 + 12.77\ N - 0.054\ N^2 + 30.99\ W + 4.22\ R + 10.28\ NO_3^- + 0.127\ N{*}NO_3^- + 4.251\ D{*}NO_3^-$$

Where:

N = applied nitrogen (kg/ha)

N^2 = quadratic applied nitrogen $(kg/ha)^2$

W = soil water content at planting, in mm (0 to 20 cm depth)

R = rainfall in mm (tillering-first node visible)

NO_3^- = soil nitrates in ppm (0 to 30 cm depth)

D = dummy variable (corn = 0, soybean = 1)

Based on this methodology, Table 2 compares three levels of rainfall: 50, 100, and 150 mm; six soil nitrate levels from 20 to 95 ppm, and three wheat/nitrogen price-cost relationships, 3:1, 6:1 and 9:1.

Similar results were reported by Senigagliesi et al. (9). In addition, they reported that there are moderate responses when N is applied alone and the response is highly dependent on soil moisture content. In contrast, the crop response to phosphorus fertilization, when applied alone, was very small. However, a very strong N*P interaction yield response was reported and a properly balanced application of these two elements was extremely efficient. Figure 3 shows the relationship between available soil P content at planting and crop response to fertilizer application. It can be concluded that soil analysis is a useful tool in predicting crop response to phosphorus fertilization. In addition, the soils can be divided into different classes with regard to available soil P content:

very deficient	=	soils with less than 7 ppm P
deficient	=	soils with more than 7 and less than 15 ppm P
adequate	=	soils with more than 15 ppm P

Conclusion

The INTA studies have shown that fertilizer application to the wheat crop, if done properly, can be a very profitable enterprise. In Argentina soil analysis is a useful tool in predicting phosphorus fertilizer requirements. However, it is not sufficient to determine a nitrogen recommendation. Years of continuous cropping, previous crop, and length of the fallow period, are some of the management factors that should be taken into account at planting time for the N fertilizer diagnosis.

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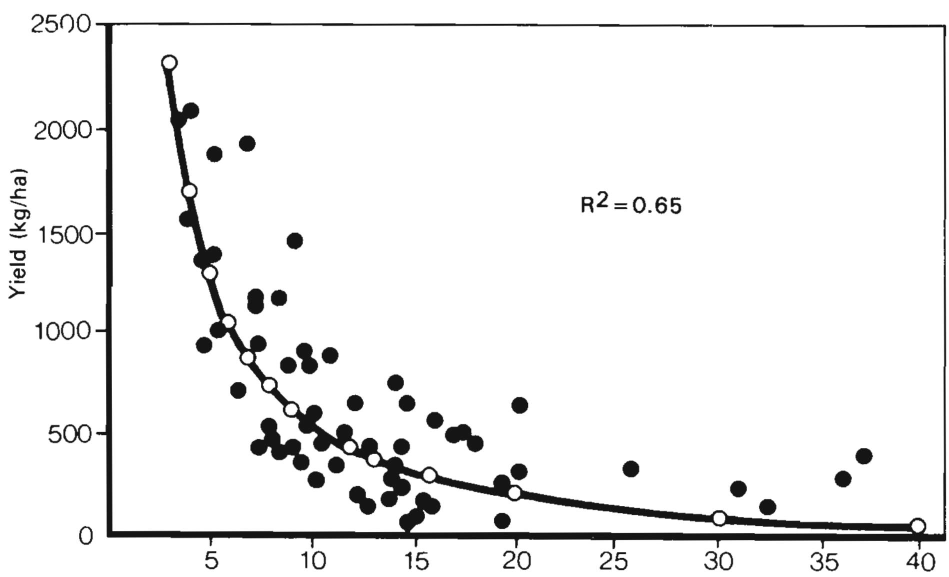

Figure 3. Relation between soil P (Bray 1) and response to applied P.

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Fertilizer Requirements and Management Issues for Acid Soils in Nonirrigated Areas

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Abstract

The 17 million ha of potential wheat growing area in Brazil can be divided into three climatic regions — southern, south central, and central. The main problems associated with wheat production are related to soil conservation/management, soil fertility and acidity, and diseases and insects. The natural properties of the Oxisols and Ultisols that predominate in these regions are discussed, as well as their response to tillage practices and fertilization. Conservation tillage, while not widely adopted as yet in Brazil, shows potential for reducing soil degradation.

Historical Background

According to historical records, wheat was first brought to Brazil by the Portuguese navigator Martin Alfonso de Sousa. Manuscripts belonging to the library of Évora indicate that even before 1584, wheat was grown in São Paulo. According to Sebastião Ferreira Soares, wheat was introduced in Rio Grande do Sul by the Açorians, with the growing region concentrated around Porto Alegre, Rio Pardo, and Rio Grande.

Although wheat has been grown at one time or another in several states (Pernambuco, Alagoas, Bahia, Goiás, Rio de Janeiro, and São Paulo), it is now grown principally in Paraná, Santa Catarina, and Rio Grande do Sul States. The first statistics about wheat production in the Planalto Médio (Passo Fundo), Rio Grande do Sul State, go back to the 1862-1863 period. Wheat was grown on traditional pasture areas in Rio Grande do Sul and the southern part of Paraná, and mechanization of farms evolved rapidly.

Rapid development of wheat production in Brazil has been a long-standing objective of the Brazilian Federal government. Factors contributing to this policy have been: 1) a periodic food supply deficit in the nation's large urban centers; 2) favorable potential in the external market; and 3) an awareness that expanding the agricultural area into new lands would not in itself guarantee both an adequate domestic food supply and agricultural products for export in international markets.

In the early 1960s, soybean production experienced rapid growth based on the structure created for wheat production. The factor that made the Brazilian farming system (grain storage, banking, and extension service) feasible was the strength given to the farm cooperative system. Today all of the wheat produced is bought by the government through the Bank of Brazil.

Since the mid-1960s, Brazil has been a major producer of soybeans for the world market. The overall importance of this export is indicated by the fact that in 1977 soybean sales accounted for 30% of the agricultural export revenue of the country. In conjunction with the growth in production, Brazil has rapidly developed a large and modern domestic soybean processing industry.

Significant wheat cultivation began in the far southern part of the country, in Rio Grande do Sul, later spreading north through Santa Catarina, Paraná, and São Paulo. Not long ago it was believed that this subtropical region would be the only area suitable for the production of wheat as well as soybeans on a commercial scale. However, today the production area of these crops has been extended to the states of Mato Grosso do Sul, Minas Gerais and Goiás, comprising an immense area of the Brazilian "Cerrado."

Present estimates are that 17 million ha of cropland can be planted to wheat. Taking into account all climatic peculiarities, Brazil can be divided into three main wheat growing regions. The southern wheat growing region (4 million ha of potential use) comprises Rio Grande do Sul and Santa Catarina, as well as south-central Paraná. In this region there is a uniform pattern of rainfall distribution throughout the year, with somewhat higher amounts being received during the winter and spring periods. During these seasons, solar radiation is low and the relative humidity is high. During the winter, temperatures fall and frosts may occur. To avoid frost damage, winter crops are normally seeded between May and July, so that flowering occurs after the beginning of September.

The south central wheat growing region (6 million ha of potential use) comprises the north and west of Paraná, the southern portion of Mato Grosso do Sul and the southwestern portion of São Paulo. Characteristically, this region is less cold and the winters are dry, which allows seeding to take place during the fall and at the beginning of the winter season, with no risks of frost damage. Some of the soils have high exchangeable aluminum, which is toxic to wheat, but there is also a large area that is free of aluminum toxicity; thus it is possible to grow genetic material that has originated mainly in Mexico.

The central wheat growing region (5 million ha of potential use—1.5 million ha irrigated) comprises the high-altitude regions (over 600 m) of the Federal District and Mato Grosso do Sul, Minas Gerais, and Goiás states, plus the south of Bahia and northern part of São Paulo. The weather is characterized by a dry winter (wheat is grown under irrigation) with limited low temperatures and little risk of frost. In this region, it is possible to grow wheat (upland) that is seeded during the summer and harvested in the autumn. Low soil fertility and aluminum toxicity prevail in most of the soils of this region. With the removal of these impediments, cultivars susceptible to toxic aluminum can be grown under irrigation.

Climate

The southern part of Brazil has well defined growing seasons that allow double cropping in Rio Grande do Sul, Santa Catarina, Paraná, and São Paulo. Under irrigation it is possible to extend the double cropping area to Mato Grosso do Sul, Minas Gerais, Mato Grosso, and Goiás. In the southern region, winter crops are seeded from May to July and harvested from October to November. Summer crops are seeded from September to December and are harvested from March to April.

The annual precipitation in Rio Grande do Sul is slightly over 1700 mm and is well distributed throughout the year (Table 1). The mean monthly precipitation is approximately 150 mm. The rainfall distribution pattern is not the principal cause of soil losses by erosion; the main factor is the high intensity of the rainfall (Figure 1). Forty percent of the erosivity index is concentrated in the months of October, November, December, and January. October and November are months in which the farmer has to till the fields or when summer crops are being established. Under conventional tillage the soil is bare, with virtually no protection against raindrop energy. In addition, summer crops (black beans, maize, and soybeans) use wide row spacing, take a long time to fully cover the ground surface, and require a more intensively prepared seedbed. Under conventional tillage, in which the farmer tills the soil for seedbed preparation once or twice and then incorporates herbicides by discing, soil losses will obviously occur due to the high erosion index during these months (October, November, and December).

The annual precipitation in Paraná State is between 1200 and 1900 mm, with the southern region receiving the larger amount. Rainfall is high during the summer months and averages less than 100 mm per month in the winter, when drought of up to 6 weeks may occur. August is usually the driest month of the year. Frost seldom occurs north of latitude 24°S, while in the south and southeast regions it is common during the winter.

Table 1. Normal rainfall (1950-1979) and monthly rainfall values from 1985 for weather data from the weather station of the CNPT/EMBRAPA, Passo Fundo, Rio Grande do Sul (2)

Parameters		Jan.	Feb.	Mar.	Apr.	May.	Jun.
	1985	73	150	112	171	184	110
Precipitation	Normal	155	150	130	120	100	138
(mm)	D.P.	72	72	46	82	60	92
	C.V. (%)	46.5	48.1	35.5	68.3	59.9	66.6
	1985	22.6	21.7	20.8	17.9	14.6	13.1
Mean	Normal	22.2	21.9	20.6	17.0	14.6	12.9
temperature	D.P.	0.66	0.92	1.16	1.49	1.48	1.37
(°C)	C.V. (%)	3.0	4.2	5.7	8.7	12.8	10.6
	1985	62	78	77	76	71	75
Relative	Normal	70	72	73	74	74	77
humidity	D.P.	7	6	3	5	5	4
(%)	C.V. (%)	9.5	7.7	4.1	6.7	6.9	5.6
	1985	306.5	172.4	205.1	162.9	204.1	161.5
Solar radiation	Normal	230.0	211.3	211.4	193.8	183.0	153.7
(hours)	D.P.	45.6	21.7	25.3	38.4	25.1	26.3
	C.V. (%)	19.8	15.0	12.0	19.8	13.7	17.1

In the Cerrado region (central Brazil) the total annual rainfall ranges from 1400 to 1800 mm. The average for the last 10 years is 1540 mm. Usually the rainy season starts in October, a month in which the rainfall intensity is high (460 mm in 22 days), and extends into April. The dry season coincides with the coldest months of the year. The temperature varies from 21.0 to 27.2°C. During the rainy season, normally only short periods (1 to 3 weeks) of drought occur (6).

Problems

The main constraints for wheat production in Brazil are related to soil conservation/management, soil fertility and acidity, diseases, and insects. Soil conservation and fertility will be treated separately. The main diseases attacking the roots, stems, leaves, and heads are listed in Table 2. The relative importance of each varies from region to region, year to year, and according to the weather conditions during the growing season.

Diseases

Generally speaking, the largest wheat production losses are due to diseases. Breeding programs have to take into account the genetic variability of the causal agents of diseases, which makes it difficult to obtain promising new material. The severity of this problem becomes evident if we consider that there are 26 and 20 different races of leaf and stem rusts in Brazil, respectively. Therefore, suitable germplasm has to be resistant to all races of the causal agent that prevail in the growing region.

Leaves are mainly infected by leaf rust (*Puccinia recondita*), tan spot (*Pyrenophora tritici-repentis*), leaf blotch (*Septoria tritici*), glume blotch (*S. nodorum*), and powdery mildew (*Erysiphe graminis* f.sp. *tritici*). All the above cause reductions in yield by reducing the leaf photosynthetic area. Stem rust (*Puccinia graminis*) may infect leaves and spikes; the spikes are also infected by glume blotch, tan spot, powdery mildew, head blight (*Fusarium* spp.), and

Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Mean	Annual Total
130	205	151	39	56	63	120	1444
134	173	197	183	119	164	147	1763
60	104	100	95	71	74	–	–
45.1	60.2	50.7	51.8	59.0	44.0	–	–
12.6	14.1	15.3	18.8	22.5	23.4	18.1	–
12.8	13.8	15.5	17.4	19.3	21.2	17.4	–
1.94	1.35	1.27	1.42	1.10	1.11	–	–
15.2	9.7	8.2	8.1	5.7	5.2	–	–
73	79	75	61	53	55	70	–
74	72	72	71	66	66	72	–
3	5	5	5	7	6	–	–
4.4	6.5	7.0	7.4	9.9	9.1	–	–
193.1	99.2	141.5	223.0	276.0	275.6	201.7	2420.9
171.5	169.4	153.5	201.5	230.4	257.0	197.2	2366.5
37.8	34.6	37.9	35.6	30.5	33.9	–	–
22.0	20.4	24.7	17.7	13.3	13.2	–	–

loose smut (*Ustilago tritici*). Barley yellow dwarf virus is transmitted to wheat by several species of aphids and the soilborne wheat mosaic virus is transmitted by the fungus *Polimixia graminis*. Wheat roots are mainly infected by common root rot (*Helminthosporium* spp.) and take-all (*Gaeumannomyces graminis* f.sp. *tritici*). Control of these diseases includes resistant cultivars, crop rotation, and chemical control.

Insects

Aphids and caterpillars are the main groups of insects that can damage wheat in southern Brazil. Aphids were first introduced in this country during the 1960s, probably from Europe. They multiplied at an enormous rate, so that farmers soon had to spray three or four times during the growing season. With the assistance of the University of California and the United Nations Food and Agriculture Organization (FAO), the National Wheat Research Center started a program on biological control of aphids in 1977. Fourteen species of micro-heminopters, which are parasites of the aphids, were introduced. The results of this biological control program can be measured by the large reduction in the aphid population. During the last 3 years, only 3% of the wheat fields had to be sprayed with insecticides in Rio Grande do Sul. This is in contrast to previous periods in which virtually the whole area was sprayed several times during the season. Presently, wheat cultivars resistant to some species of aphids are being developed at the National Wheat Research Center. Caterpillars, which occur sparsely, are still controlled by insecticide spraying.

Aluminum toxicity

Aluminum toxicity is an important growth limiting factor for plants in many Brazilian soils and restricts the root development of most crops (21). The damaging effects of excess aluminum on plant growth are among the most important attributable to soil acidity. Hence, considerable research has been devoted to describing and elucidating the physiological aspects of aluminum toxicity. The most striking effect is the stunting and thickening of the whole root system at high aluminum concentrations (8).

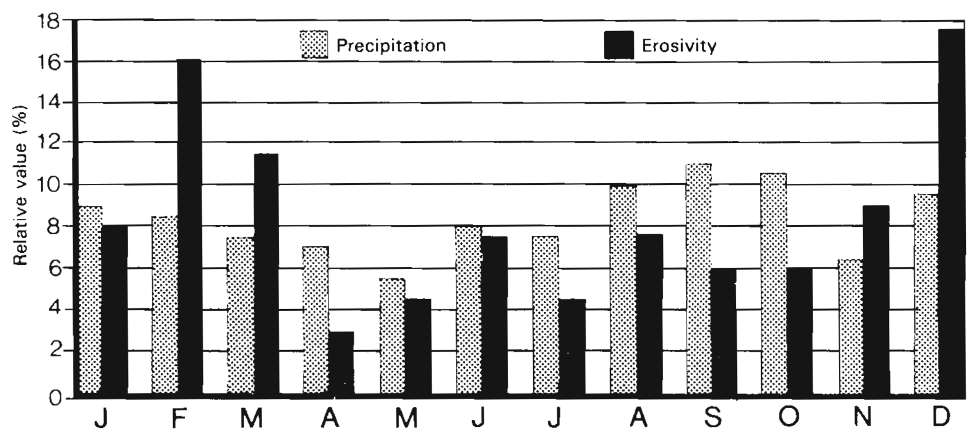

Figure 1. Mean annual precipitation and erosivity distribution for Passo Fundo - Rio Grande do Sul - Brazil.

However, plant species and even cultivars differ widely in their tolerance to excess soluble or exchangeable aluminum. In some plants, aluminum tolerance is associated with accumulation of aluminum in the tops, rather than exclusion from the tops and/or roots. This differential tolerance among cultivars of the same plant species is of interest because it suggests the possibility of breeding for greater tolerance to toxic aluminum (9). Cultivars that are different in aluminum tolerance are valuable tools in gaining a better understanding of the morphological, physiological, and biochemical nature of aluminum toxicity. This plant material may be useful as a biological indicator to test for potential aluminum toxicity in various acid soils (9).

A better understanding of wheat cultivar differences may provide significant insight into plant adaptation to low levels of fertilization. Hence, a complementary or supplementary approach to the problem of acid soils in Brazil is to select genotypes tolerant to aluminum toxicity and/or soil acidity. This approach does not imply the elimination of fertilizing and liming, but it could result in higher fertilizer and lime efficiencies (9). Fortunately, several Brazilian-bred genotypes are tolerant to aluminum toxicity, which allows the crop to be grown in areas that have never been cropped before. Some of this aluminum-tolerant material also shows higher phosphorus extraction efficiency (1).

Brazilian Soils

Brazil is a very large country, and thus has a great variety of soils that differ widely in their chemical, mineralogical, and physical properties. The most common are Oxisols and Ultisols. In the southern states (Rio Grande do Sul, Santa Catarina, Paraná, and Sáo Paulo) more than 60% of the soils belong to the Oxisol type. In the Cerrado area of central Brazil (which covers more than 20% of the country), they account for more than 50%. They are highly weathered and the crystalline clay fraction is dominated

Table 2. Main diseases causing wheat yield losses in Brazil and methods of control

Disease	Method of Control: Genetic	Chemical	Cultural Practices
Stem rust	0	0	X
Leaf rust	0	0	X
Powdery mildew	0	0	X
Glume blotch	0	0	X
Leaf blotch	0	0	X
Head blight	0	0	X
Tan spot	0	0	X
Common root rot	X	X	0
Take all	X	X	0
Barley yellow dwarf virus	0	X	X
Soilborne wheat mosaic virus	0	X	X
Loose smut	0	0	X

0 - Effective control
X - No control

by kaolinite and/or gibbsite, with only minor amounts of the more active 2:1 clays (12). Most, if not all, of them contain substantial quantities of amorphous materials rich in iron and aluminum. Aluminum saturation ranges from 50 to 90%.

Fertilizer response

Normally, the Oxisols are less responsive to lime than are the Ultisols at a comparable soil pH and percentage of aluminum saturation. These soils have a high lime requirement, in many instances close to 10 t/ha. The large response to liming on these soils generally has been attributed to the removal of exchangeable aluminum or aluminum from the soil solution. The native supply of available phosphorus is generally quite low and relatively high amounts of fertilizer phosphorus are required for optimum crop yields (10). When soluble phosphorus fertilizers are applied, only a small portion of that added can be extracted with dilute acid solutions or salt solutions. This decrease in solubility of fertilizer phosphorus is generally referred to as phosphorus retention or "fixation." The magnitude of this effect is dependent upon the chemical properties of the soils (7). Understanding the factors affecting phosphorus fixation is beneficial in developing sound phosphorus fertilization programs.

Most Brazilian soils are naturally well supplied with potassium. Potassium in the soil solution is in equilibrium with the exchangeable form. It is difficult to distinguish one from the other, since equilibrium occurs rapidly and varies according to prevailing conditions (22). The amount of exchangeable potassium in soils depends on the clay content, on the intensity of mineral decomposition, and on the quantity of fertilizers used. The soil solution and the exchangeable potassium are directly available to plants. It is well known that in any kind of soil, the exchangeable potassium content varies widely from one place to another (3). The potassium fertilizer most commonly used is potassium chloride, usually containing about 50% potassium.

Physical properties

From the physical standpoint, soils that have potential for crop production, in general, possess excellent structure and high infiltration rates and are well drained. According to Sanchez (21), "the excellent structure of these soils is caused by primary particles being aggregated by iron oxides in very stable sand-sized granules." Their high stability is associated with high clay content and cementing or coating of amorphous iron and aluminum oxides. The organic matter content is also directly associated with the aggregate stability.

Cultivation of Brazilian soils deteriorates soil structure, and improvement of soil tilth becomes difficult. Tilth is generally defined as the physical condition of the soil in its relation to plant growth. These soil physical conditions include ready infiltration of rainfall, sufficient moisture, adequate aeration, and favorable soil temperatures. This means that tilth is related to the size distribution of the soil aggregates. Ideal soil tilth is manifested in the friable range of soil consistency. It is a dynamic soil condition and tends to deteriorate under the usual cropping and tillage operations.

Tillage

Tillage can produce good tilth by loosening and granulating the soil. By breaking up the soil mass, infiltration of rainfall and aeration are increased and soil strength is decreased. It is important to point out that the range of friable consistency in which tilth reaches an optimum is the same range in which the soil can be tilled with the least output of power and with its best effects upon granulation. The damaging effects of intense cultivation on the size distribution of water-soluble aggregates have been evaluated on Oxisols and Ultisols of Brazil (Table 3). Cultivation reduced the percentage of aggregates larger than 2 mm by about half in both soils. A uniform increase of other aggregate sizes in the Oxisol and a drastic increase of the aggregates smaller than 0.21 mm in the Ultisol were observed. This is what usually happens. The smaller aggregates clog the pores between the larger aggregates and decrease infiltration.

The soils of the south, central, and west-central regions of Brazil are mainly Oxisols and Ultisols originated from basalt. Their chemical, physical, and topographical characteristics sustain the high annual agricultural production of the country.

The intensive use of agricultural machinery beginning in the 1960s, and the promising soybean market associated with subsidized credit, led to an expansion of our agricultural frontiers. In these regions, the farmers have moved from a diversified cropping system into an intensive cropping system based on wheat and soybeans only.

With the aim of reducing production costs and lowering erosion risks, the no-tillage system was investigated as an alternative to conventional (plowing + disking) tillage systems. However, due to some deficiencies, the no-tillage system has not been widely adopted and tillage systems carried out chiefly with diskings have prevailed. The exaggerated use of shallow diskings at the same depth has induced the deterioration of the plow layer, generating two distinct sublayers: a well pulverized (structureless) layer at the surface and a slightly harder one below. These alterations reduce the water infiltration rate and restrict root development, resulting in surface runoff and losses in crop yields. This aspect, along with the lack of crop residues, the high-intensity rainfalls at the time summer crops are being established, and the use of terracing as the only means to control soil erosion, are the main factors contributing to the soil degradation process and soil erosion in those regions.

Table 3. Effect of intense cultivation in a Brazilian Oxisol and Ultisol on wet-sieved aggregate size distribution without pretreatment (% distribution of water-stable aggregate)

	Terra Roxa Legítima (Oxisol)		Massapé Soil (Ultisol)	
Aggregate size (mm)	Forest	Under cultivation	Pasture	Under cultivation
>2	84.2	48.2	80.8	36.0
2-1	1.1	13.2	7.2	11.1
1-0.5	0.5	13.0	3.9	6.6
0.5-0.21	0.5	15.1	4.2	12.5
<0.21	13.7	10.5	3.9	33.8

The Erosion Process

Precipitation

Wind erosion in Brazil is restricted to the sea coast and to a small area with sandy soils. Precipitation, with its characteristics of erosivity, intensity, and distribution, is one of the main agents responsible for the erosion process. Erosivity, expressed in kinetic energy per unit of area, represents the erosion power of the rainfall. It is a function of the size, shape, and falling speed of the raindrop, being related to the rain intensity. The higher the rainfall intensity, the larger the raindrop and, consequently, the higher the erosivity index. The impact of the raindrop on a bare soil surface breaks the aggregates and a surface crust is formed, which has low permeability, reducing water infiltration and enhancing surface runoff. Surface crusting sometimes reduces germination of large seeds, e.g., soybeans.

In the above regions, intense precipitation coincides with the period in which tillage operations are performed or summer crops are being established. It is during this time that 80% of soil losses occur. In Rio Grande do Sul, the primary tillage systems are based on cultivators, disc plows, and heavy discs. The primary tillage operation never reaches a depth of 20 cm, and it is usually followed by two or more light leveling diskings. In a tillage comparison of a wheat-soybean cropping sequence, soil losses through erosion reached 12.8 t/ha per year under conventional tillage when the straw was burned. Under the same system, when straw was plowed down, losses dropped to 4 t/ha per year. Under zero-tillage, losses were 1.1 ton/ha per year. With the same tillage systems, the nutrient losses were 38.4, 12.8, and 3.2 kg/ha of phosphate and 55, 18.2, and 4.5 kg/ha of potassium, respectively.

Mean estimates of soil erosion losses in Rio Grande do Sul are 41.8 t/ha per year, which represent 242.4 million t/year. With this total annual loss, 484,800 t of limestone, 660,700 t of nitrogen, and 3600 tons of P_2O_5 plus 46,100 tons of K_2O are needed to replace the nutrients lost.

Degradation categories

In 1970, Rio Grande do Sul was divided into three categories of soil degradation (Table 4). Category 1 (30% of the soil of the state) related to soils with yield potential ranging from 75 to 100%. Category 2 (also 30% of the state) referred to soils with a yield potential from 50 to 75%. Category 3 (40%) included soils that have a yield potential from 25 to 50%. The weighed mean yield potential of the state in 1970 was 59%.

From 1970 to 1975, due to the intensive use of limestone and fertilizer, the three categories represented 70, 20, and 10% of the soils, respectively. The mean yield potential increased to 77% in 1975. During the period from 1975 to 1985, the subsidy for limestone and fertilizer was reduced and the proportion of soils in each category changed to 60, 23, and 17%, respectively. The mean yield potential decreased to 73%. If this soil degradation trend continues for another 10 years, the mean yield potential in 1995 will drop to 64%, which is only 5% higher than in 1970 (5).

Effects of tillage

Oxisols and Ultisols also prevail (65.4% of area) in Sáo Paulo State, and the average soil loss by erosion is higher than 20 t/ha per year. The Brazilian experience shows that any soil tillage practice will alter considerably the native physical characteristics. The magnitude of this effect is a function of the intensity by which the soil is tilled. The aggregates of an Oxisol were evaluated under different management systems. Water-stable aggregates larger than 4.76 mm were 96% of a natural forest soil. Native pasture soil showed 72% of aggregates of this size. The soil under conventional tillage for 19 years, in which the crop residues were always burned, showed only 3% of these aggregates. The soil under the conventional tillage system above, in which the crop residues were always plowed down, showed 11% of aggregates having this size. When zero tillage was introduced for 4 years, after 20 years of conventional tillage, the percentage increased to 35%.

The water infiltration rate is also affected when an Oxisol (red Latosol) is submitted to different tillage systems. Under natural forest, the infiltration rate was 136 mm/hr. After 7 years of tilling the field with oxen, the infiltration rate dropped to 31.3 mm/hr. Under conventional tillage for 20 years, the infiltration rate dropped so drastically that barely any water moved through the soil (0.2 mm/hr). When no-tillage was practiced for 4 years after 20 years of conventional tillage, the infiltration rate increased from 0.2 mm/hr to 7.5 mm/hr. From the above, one can see that to restore a soil physical characteristic once it has deteriorated takes many years of a sound tillage system.

There are other soil characteristics that are altered under any tillage system. This can be illustrated by comparing two fields from one farm in Mato Grosso do Sul, in which the soil has been tilled by disking only (Table 5). In the 3-year-old field, 6 cm at the surface were completely structureless. This surface pulverization exposes the soil to the erosive action of rainfall, breaks down the aggregates, and reduces

Table 4. Evolution of soil degradation categories in Rio Grande do Sul State

Year	Category	Area of the state (%)	Soil potential in expressing high yield: Mean amplitude (%)	Soil potential in expressing high yield: Weighed mean (%)
1970	1	30	75-100	
	2	30	50-75	59
	3	40	25-50	
1975	1	70	75-100	
	2	20	50-75	77
	3	10	25-50	
1985	1	60	75-100	
	2	23	50-75	73
	3	17	25-50	
1995	1	40	75-100	
	2	30	50-75	64
	3	30	25-50	

the organic matter content, leaving the soil more susceptible to erosion. The field with 7 years of diskings also had surface pulverization, and showed an increased soil density, which may alter the air diffusion inside the soil profile, causing restriction in the root development of different crops. In addition, the development of the pan layer also restricts vertical water movement, which during a dry spell will not reach roots that are concentrated inside the top (loose) soil layer. During the rainy season, the low infiltration rate of the pan layer induces the structureless top soil to saturate completely and to slide downhill, causing erosion.

Besides altering the soil physical characteristics, the use of diskings also causes an uneven fertilizer distribution pattern in the soil profile (Table 6). During a heavy rainstorm the farmer may lose all fertilizer located in the top layer, while under short dry periods the crop may suffer water deficiency because the roots are confined in a thin structureless soil layer.

Soil Management

Soil management comprises all practices involved in a production system, i.e., soil tillage, crop species, seeding time, cultural practices, and harvesting. An adequate soil management system takes into consideration the three factors: soil, climate, and crop. The present state of soil degradation and its capability-of-use classification are the main soil concerns. Intensity, erosivity, and distribution of precipitation are the major climate aspects considered (Figure 1). Seedbed preparation depends somewhat on the crop. Winter cereals do not have the same need for an intensively prepared seedbed as do soybeans, for example. An adequate soil management system under Brazilian conditions must involve practices that a) retain the rainfall where it hits the soil surface, b) increase the water infiltration rate, c) decrease the surface runoff, d) increase water storage capacity, and e) provide good physical and chemical conditions, so that any crop can be grown.

Tillage systems

The main objective of any soil tillage system is to increase production at low costs. In any case, the farmer has to see a cost-effective profit from this system. It is very clear at present that the tendency is changing from costly conventional tillage to modern conservation tillage systems, which are more cost-effective.

Table 5. Physical characteristics of soil in two fields under tillage system involving only disking in Ponta Pora, Mato Grosso do Sul

Soil depth (cm)	7 years		3 years	
	Soil density (g/cm^3)	Established aggregates (%)	Soil density (g/cm^3)	Established aggregates (%)
0-6	*	*	*	*
6-14	1.43	48	1.20	78
14-23	1.40	58	1.19	79
23-30	1.25	56	1.18	78

* Structureless soil

Degradation of the nation's cropland will continue unless conservation tillage systems are adopted. These systems can result in optimum yields, and they leave crop residue on the surface to help improve tilth and to protect the soil from erosion. Few innovations in agricultural technology offer as many potential advantages as conservation tillage crop production, although more research is needed to solve problems associated with the system. One has to be aware that as scientists develop the technology, farmers must be able to adapt it to field conditions.

Conservation tillage is "any tillage system that reduces loss of soil or water relative to conventional tillage; often a form of noninversion tillage that retains protective crop residues on the surface." Conventional tillage, on the other hand, is "the combined primary and secondary tillage operations performed in preparing a seedbed." Notice that the term "conservation tillage" has a broad definition, but requires the reduction of soil or water losses compared to conventional tillage. Successful conservation tillage reduces soil and water losses by leaving appreciable crop residue on the surface, or by leaving the surface rough, porous, and cloddy, or a combination of the two. The effectiveness of any tillage system for controlling erosion ultimately depends upon the amount of crop residue left on the soil surface (13).

Thorough tilling of soil was once regarded as a necessary practice on most soils. The soil was stirred or manipulated to prepare a suitable seedbed. Additional stirring of the soil controlled weed growth and promoted desirable physical conditions to encourage air and water movement and plant root growth. Thorough tillage also provided an opportunity to incorporate plant residue, fertilizer, and other crop production material into the soil (4). Using a field cultivator for secondary tillage leaves more residue than using disks (14). For each 10% increase in groundcover, erosion is reduced about 40%. The greatest reduction in erosion comes between 0 and 20% cover.

Effects of conservation tillage

No-tillage is generally the most effective means of erosion control, mainly because more crop residue is left on the soil surface. The longer a field remains in no-till, the more effective erosion control becomes. This is due to the improvement of soil structure with larger size aggregates; it is also more water

Table 6. Soil fertility distribution in an Oxisol profile submitted to diskings only for a period of 7 years in Ponta Pora, Mato Grosso do Sul

Depth (cm)	pH in H_2O (1:1)	Al (me/100 g)	Ca + Mg (me/100 g)	P (ppm)	K (ppm)	O.M. (%)
0-2	6.0	0.00	8.10	12.5	+200	5.4
2-4	5.8	0.05	9.05	82.0	+200	5.3
4-6	5.8	0.00	8.60	11.5	171	5.3
6-10	5.4	0.30	6.00	5.0	142	5.1
10-15	5.0	1.25	3.90	5.0	98	5.1
15-20	4.9	1.90	1.95	1.0	60	4.5
20-25	4.8	2.15	1.30	1.0	40	3.7
25-30	4.7	2.05	1.15	1.0	28	3.4

stable (23). Crop yields produced with the first conservation tillage systems were disappointing. Often crop stands were severely reduced, resulting in low yields. Unfortunately in Brazil on some heavy clay soils, even with the knowledge of tillage system requirements now available, crop yields under conservation tillage may not equal yields under conventional tillage. In cases in which crop yields are lower with a conservation tillage system, in spite of proper management, the limiting factor may well be the soil itself.

Many site-specific tillage studies in Brazil have shown significant increases in crop yields on some soils when conservation tillage was used (Table 7). On other soils, a significant reduction in crop yields occurred. On still other soils, the selective placement of crop residue, along with the cropping sequence, determined whether crop yields increased or decreased in relation to conventional tillage yields. Evidences are that selective tolerance levels do exist, among different soils, for conservation tillage systems (4). Although there have been significant improvements in knowledge of how conservation tillage systems function, only limited information is available to identify the soil behavior.

Adopting a new tillage system

Conservation tillage is a complex technology. The number, timing, and sequence of management decisions are much more critical than with conventional tillage. From the operator's perspective the decision to move into conservation tillage is neither simple nor trivial (11). Individuals, when deciding whether to adopt a new technology, go through a series of stages (5). First either they become aware of some problems and begin to search for technology to solve them; or they become aware of a technology and begin to realize its problem-solving potential. This can be called the awareness stage. Second, they gather the necessary information to evaluate the technology in terms of their needs. This may be referred to as the evaluation stage. If the information is adequate and if the evaluation is positive, they will probably try the technology on a small-scale basis. This is usually called the trial stage. If this stage produces enough beneficial results, then they may possibly move toward full-scale adoption. During this adoption stage individuals may either modify the technology or adapt their systems to increase overall efficiency. One must be aware that the decision to adopt

Table 7. Effect of different soil tillage systems on wheat yields of cultivar IAC 5-Maringá on a dark red Latosol in Ponta Grossa, Paraná, 1973

Soil tillage systems	Yield (kg/ha) and (%)			
	Experiment "A"		Experiment "B"	
Conventional[a]	1580	100	2825	100
Conservation tillage[b]	1640	104	2963	105
Direct drilling	1760	111	2825	100

[a] Disk plowed + disking (light)
[b] Light disking

Adapted from Pereira (16)

conservation tillage also follows these stages and that is why it takes a long time to adopt any system of conservation tillage.

The major obstacle during the adoption stage involves the adaptation of the technology to the operation or the adaptation of the operation to the new technology (15). Conservation tillage is a system that must continually be adapted to the changing environment in which it is used. Additional obstacles may arise in this adaptation process. The managerial decisions that worked in a dry year may not work in a wet one. Farmers who followed recommendations by changing to conservation tillage expect a follow-up from research. How adopters evaluate conservation tillage can be an obstacle or can be an inducement to their neighbors. Ultimately what matters to farmers is net return, and not only yield.

Soil Fertility Recommendations

Southern region: Rio Grande do Sul and Santa Catarina states

All fertilizer and limestone recommendations are based on soil analysis (20).

Soil acidity neutralization—The liming requirement method used by the Brazilian network of 13 Soil Analysis Laboratories is called the SMP buffer test. It measures potential soil acidity, which, when associated with organic matter content and water pH values, produces an accurate lime recommendation for the variety of soils of both Rio Grande do Sul and Santa Catarina. The amount of limestone indicated by this procedure will bring the soil pH to a value close to 6.0. The full lime requirement is recommended when wheat is grown in rotation with other crops that are not hosts for the root rot diseases. Only 1/2 the lime requirement is recommended to farmers that do not adopt crop rotations. Limestone has to be evenly broadcast and incorporated 20 cm deep in the soil. If the lime requirement is higher than 5 t/ha, the neutralization has to be done in split operations. The mean effectiveness of the present recommendations is for 5 years. After this period, a new analysis will indicate if limestone is needed. Limestone is not advised for fields with take-all fungus.

Fertilizer—The fertilizer recommendations for wheat are based on soil analysis and on the crop response to N, P, and K fertilization. The recommendations are designed to supply soil deficiencies as well as establish a nutrient balance for the crop demand (19).

Corrective fertilization is based on soil analysis and on soil type (clay content) and has the purpose of improving soil P and K status to a level that can support almost every crop. This recommendation is good for 4 or 5 years, after that a heavier per-crop fertilization should be used or, if possible, a second corrective fertilization should be used.

Maintenance or per-crop fertilization is recommended to supply the nutrients required by the crop while maintaining soil nutrient contents at an adequate level. Applications of 15 kg/ha N and 70 or 40 kg/ha of P_2O_5 and 50, 20, or 15 kg/ha of K_2O (depending upon soil tests) are recommended, to be applied at seeding time.

The use of nitrogen in topdressing 30 to 45 days after seedling emergence, at rates of 40 or 25 kg/ha according to soil organic matter content (<2.5 or 2.5-5.0%, respectively) is recommended.

A variety of factors have to be taken into consideration when deciding to use topdressed nitrogen: the stage of the plant cycle; the genotype (cultivar lodging resistance); soil (pH, texture); crop rotation/sequence or winter fallow; use of technology (fungicide, insecticide); weather conditions (prolonged rainfall during the highest N requirement by plants); and the soil management system (conventional tillage, conservation/minimum tillage or zero tillage).

South central region: Paraná State

Soil acidity neutralization. Limestone is recommended when aluminum saturation in the soil is greater than 10%. Aluminum saturation is calculated as below:

$$\%\ \text{Al saturation} = \frac{Al^{3+}}{Al^{3+} + Ca^{2+} + Mg^{2+} + K^{+}} \times 100$$

Lime requirement (t/ha) is calculated by the equation:

$$LR = Al^{3+} \times 2$$

Fertilizer—For tall wheat cultivars, 30 kg N/ha are recommended; for short material, 50 kg N/ha. N fertilization can be split in two operations: with the seed and topdressed. With high soil organic matter content, N fertilization may be reduced or even canceled.

For soils with very low P content (<4 ppm) 90 kg P_2O_5/ha is recommended for a gradual correction of soil P status. For soils with a P content between 4 to 9 ppm, the recommended rate is a function of the cost of the P_2O_5 unit/cost of the wheat unit:

$$\text{kg } P_2O_5/\text{ha recommended} = 94.5 \times \log(51.75\ W/T) - 67.2$$

where W = wheat price and T = P_2O_5 price. For soils with a P content greater than 9 ppm, the P fertilization recommendation is 8 to 30 kg P_2O_5/ha.

The potassium recommendations are 60, 45, and 30 kg/ha for soil K levels of 0-0.10, 0.11 to 0.30, and 0.30 (Mehlich-1 procedure), respectively.

South central region: São Paulo State

Soil acidity neutralization—Different procedures are used to establish lime requirements in different wheat production regions. Limestone is recommended when base saturation is below 50%. Lime requirement is calculated to reach 60% of base saturation, and if 4 t/ha (maximum rate) is not sufficient then Al-tolerant cultivars should be used (18).

$$\text{Lime requirement (t/ha)} = \frac{T(V_2 \times V_1)}{100} \times f$$

where:

T = Cation exchange capacity
V_2 = Desired % of base saturation
V_1 = Present % of base saturation
f = 100/Prnt, usual value is 1.5 for common limestone.

Fertilizer—All fertilizer recommendations are based on soil analysis as indicated in Table 8. Seed-placed sulfur (10 kg/ha) is recommended. For early and short-strawed wheat cultivars under irrigation, 40 kg N/ha topdressed 30 days after emergence are recommended.

South-central region: Mato Grosso do Sul State

The maintenance fertilizer recommendation is based on soil analysis and is designed to be seed-placed, preferably using soluble sources (Tables 9 and 10).

Topdressed N fertilization is optional and the rate is up to 35 kg N/ha. Liquid N as urea can be used as foliar fertilizer at concentrations of not higher than 10%. Foliar fertilization of micronutrients is not recommended. Use of boron is encouraged for correction of male sterility (1.0 kg/ha).

Central region: Mato Grosso, Goiás, Minas Gerais, and Bahia

Acidity neutralization—The lime requirement is calculated as follows:

$$LR\ (t/ha) = [2 \times Al^{3+}] + [2 - (Ca^{2+} + Mg^{2+})]$$

A re-application of lime is recommended either when aluminum saturation is greater than 20% or if $Ca^{2+} + Mg^{2+}$ is smaller than 2 me/100 g of soil (17).

Corrective fertilization—This fertilization is based on soil analysis and on soil texture and is aimed to improve soil P and K status. Two different ways are recommended:

1) Fertility correction (P and K) in one operation according to Tables 11 and 12; and

2) Gradual correction according to Table 13 (nonirrigated) and Table 14 (irrigated). This gradual P and K corrective fertilization is based on annual applications heavier than the maintenance fertilization.

Maintenance fertilization—Under irrigation, 80 kg P_2O_5/ha and 40 kg K_2O/ha are recommended, while on nonirrigated wheat fields, 60 kg P_2O_5/ha and 30 kg K_2O/ha are recommended. Nitrogen applications (20 kg/ha) are recommended at seeding, and 20 or 40 kg/ha topdressed at tillering for nonirrigated and irrigated wheat, respectively. Sulfur (20 kg/ha) is also recommended.

Table 8. Nitrogen, phosphorus, and potassium fertilizer recommendations for São Paulo

Soil P[a]	Soil exchangeable K[a], meq/100 cm^3		
	0 - 0.07	0.08 - 0.15	>0.15
μg/cm^3	kg/ha of N - P_2O_5[b] - K_2O		
0 - 6	20 - 90 - 40	20 - 90 - 30	20 - 90 - 20
7 - 15	20 - 60 - 40	20 - 60 - 30	20 - 60 - 20
>15	20 - 40 - 40	20 - 40 - 30	20 - 40 - 20

[a] Extracted by the resine method
[b] Soluble in water and in ammonium citrate

Table 9. Interpretation for soil phosphorus and potassium for Mato Grosso do Sul State

Nutrient[a]	Sandy soils Content (ppm)	Sandy soils Interpretation	Clay soils and clay-loam soils Content (ppm)	Clay soils and clay-loam soils Interpretation
P	0-10.0	Low	0-6.0	Low
	10.1-20.0	Medium	6.1-12.0	Medium
	>20	Adequate	>12	Adequate
K	0-30	Low	0-30	Low
	31-60	Medium	31-60	Medium
	>60	Adequate	>60	Adequate

[a] Mehlich-1 procedure

Table 10. Maintenance fertilizer recommendations for wheat in Mato Grosso do Sul, forest and prairie soils

Soil content		Nutrients recommended (kg/ha) Seed-placed					Top-dress
			P_2O_5		K_2O		
Phosphorus	Potassium	N	Forest	Prairie	Forest	Prairie	N
	Low	5-15	60	75	45	45	0-35
Low	Medium	5-15	60	75	30	30	0-35
	Adequate	5-15	60	75	0	15	0-35
	Low	5-15	45	60	45	45	0-35
Medium	Medium	5-15	45	60	30	30	0-35
	Adequate	5-15	45	60	0	15	0-35
	Low	5-15	30	30	45	45	0-35
Adequate	Medium	5-15	30	30	30	30	0-35
	Adequate	5-15	30	30	0	15	0-35

Table 11. Corrective soil P fertilization recommendation - central region

Texture groups[a] Soil P ppm (Mehlich) 1 and 2	Soil P ppm (Mehlich) 3	kg P_2O_5/ha[b] recommended 1 and 2	kg P_2O_5/ha[b] recommended 3
0-5	0-9	240	150
5.1-10	9.1-18	120	75
>10	>18	0	0

[a] Soil texture groups 1 and 2 have a clay content higher than 20%, group 3 has a clay content below 20%

[b] Soluble in ammonium citrate + water

Table 12. Corrective soil K fertilization recommendation - central region, for soils with more than 20% clay

Soil K (Mehlich) (ppm)	Recommended rate kg K_2O/ha
0-25	100
26-50	50
>50	0

For texture group 3 soils (sandy, clay 20%) no K is recommended. For soil K higher than the critical level (50 ppm), use only maintenance.

Table 13. Phosphorus and potassium gradual corrective fertilization for nonirrigated soils

Soil P (Mehlich) (ppm)	Soil K (Mehlich) ppm 0-25 P_2O_5	0-25 K_2O	26-50 P_2O_5	26-50 K_2O	>50 P_2O_5	>50 K_2O
	kg/ha					
0-5	100	50	100	40	100	30
5.1-10	80	50	80	40	80	30
>10	60	50	60	40	60	30

Table 14. Gradual corrective phosphorus and potassium fertilization for irrigated soils

Soil P (Mehlich) ppm	Soil K (Mehlich) ppm 0-25 P_2O_5	0-25 K_2O	26-50 P_2O_5	26-50 K_2O	>50 P_2O_5	>50 K_2O
	kg/ha					
0-5	120	60	120	50	120	40
5.1-10	100	60	100	50	100	40
>10	80	60	80	50	80	40

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Screening Techniques and Sources of Resistance to Fusarium Head Blight

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Abstract

Fusarium head blight of wheat (FHB) causes great losses in wheat grain yield and animal production in the Yangtze River region of China. More than 300 FHB-resistant wheat sources have been selected. About 40 of them have been used in wheat breeding.

The predominant species identified from 2450 samples of isolates from 21 provinces of China was Fusarium graminearum. *A significant difference was found in virulence of isolates. But no pathogenic specificity of isolates of* F. graminearum *was found. There were no significant differences in pathogenicity between ascospores and conidia or between 1 to 2 and 100 spores per 5 μL suspension.*

Inoculation methods, in vitro and in vivo, have been compared. It is suggested that the selection of FHB-resistance should be based on primary selection in large screening trials of wheat germplasm using the traditional field method. The selected advanced materials should be screened again using the inoculation injection technique and etiolated coleoptile bioassay in order to confirm their FHB resistance.

Fusarium head blight of wheat (FHB), caused by *Fusarium* spp. is a serious problem in many countries with temperate climates including Japan, parts of North America, and eastern Europe (16). The disease can also be found in more than 20 provinces in China. The wheat-growing areas of China where FHB occurs encompass more than 6.7 million ha (5). The most affected areas are the provinces along the Yangtze River. Many crops, including wheat, barley, rice, cotton, maize, sorghum, rapeseed, legumes, vegetables, and green manure crops can be infected by *Fusarium* spp. After infection, the fungus causes root rot, stem ear damage and seed decay.

The greatest problem, however, is head blight of wheat. Since 1952, FHB of wheat has been epidemic 16 times in the Yangtze River region. Generally, the yield loss was 10 to 20%. However, in years of severe epidemics, the incidence of diseased heads reached 50 to 100% and the yield loss was between 20 and 40%. More than 1 million tons of wheat can be lost in a bad year. In addition, grain contaminated by fusarium mycotoxins (eg. deoxynivaleno, zeralenone), is toxic to domestic animals, thus causing losses in animal production (4, 15, 20).

It has been known for at least 50 years that resistance to FHB is based on at least two factors: resistance to initial infection and resistance to disease spread in the plant (12). While these generalizations are supported by empirical observations (10), little is understood about the genetic basis of any resistance mechanisms. The fact that FHB remains such a serious worldwide concern in terms of lack of resistant germplasm and the confusion concerning the epidemiology of the disease argues that the biochemistry involved must be understood for economic solutions to be achieved.

Recent studies have demonstrated that the secondary metabolites of *Fusarium graminearum* affect and are affected by plant cells. Acetylated secondary metabolites of *F. graminearum* are deacetylated by plant enzymes. For example, deoxynivalenol can be formed by wheat and maize cells from 3- or 15-acetyldeoxynivalenol produced by the fungus (8, 21). Various studies have demonstrated that some wheat and corn varieties have enzymes that degrade deoxynivalenol in vivo (8, 9, 10, 11, 13). These facts led Miller et al. (9) to propose that a third type of resistance existed in wheat and maize based on plant biochemistry associated with the metabolism of fungal toxins.

Studies made in China for 20 years show that FHB has become a serious problem due to at least three factors: 1) susceptible varieties of wheat planted in large areas; 2) sufficient inoculum present during the flowering stage of wheat; 3) weather (rainy and warm) favorable to the production and dispersal of spores of the fungus. Continuous moisture over 3 days and a daily mean temperature above 15°C during the wheat flowering stage play important roles in disease initiation and epidemic spread (12, 14). Therefore, the severity of FHB in the field varies with years. Due to this variability of infection under uncontrolled field conditions, it is necessary to develop more precise and consistent methods for screening FHB-resistant cultivars for use in wheat breeding.

Sources of FHB-Resistant Wheat

Since 1976, more than 10,000 wheat varieties and lines have been studied in the Plant Protection Institute of the Jiangsu Academy of Agricultural Sciences, Nanjing, Peoples Republic of China. Wheat sources from China and abroad were screened in the field by artificial inoculation under environmental conditions suitable for disease occurrence. Although 321 FHB-resistant wheat sources were selected (2), only about 40 of them, including Su mai #3, Wang shui-bai, Zheng 7495, and Xin zhong-chang have been used in breeding programs (Table 1) (7, 22). The higher yielding and disease resistant wheat varieties or lines, Ning 7840, Ning 8017, Ning 8026, Su8113, Su7906, and others, were developed from thousands of crossing progenies in Jiangsu province and have been used in wheat breeding by other provinces in China and in other countries.

According to the Jiangsu cooperative wheat variety comparative test, these varieties produce more than Yang mai #3, which is planted widely in the Yangtze River Valley (22). In particular, the cultivars belonging to the 'Ning' system—Ning 7840, Ning 8026, and others—are resistant to the three rusts, powdery mildew, and FHB (18). In addition, Ning 8026 has 14% protein (Table 2). The planting area of this variety is being extended.

Table 1. Some fusarium head blight-resistant wheat lines used in breeding

Name	Parentage	Disease resistance FHB	Rust	Powdery mildew	Origin
Su mai # 1	Funo/Taiwan mai	R	S	S	Jiangsu[b]
Su mai # 2	Funo/Taiwan mai	R	S	S	Jiangsu
Su mai # 3	Funo/Taiwan mai	R	S	S	Jiangsu
Wang shui-bai		HR	S	S	Jiangsu
Zheng 7495	Fu sui-huang/You yi mai	MR	S	S	Jiangsu
Fan shan mai		MR	S	S	Fujian[b]
Xin zhong-chang		MR	S	S	Japan
Yan gang fang-zhu		R	S	S	Japan
Frontana		R[a]			Brazil

R = resistant; HR = highly resistant; MR = moderately resistant; S = susceptible
[a] Resistant to initial infection, not to disease spread inside the tissue
[b] China

Table 2. The improved fusarium head blight-resistant wheat sources

Name	Parentage	FHB	Yield[a] (t/ha)
Ning 7840	Aurora/Anhui # 11//Su mai # 3	HR	4-5
Ning 8017	Aurora/Su mai # 3//Yang mai # 2	MR	4-6
Ning 8026[b]	Aurora/Su mai # 3//Yang mai # 2	MR	4-6
Ning 82109	Yang mai # 3/Ning mai # 3/Su mai #1 //Su mai # 3/Aurora	MR	
Ning 8405	263/Fan Xiu # 5//Ning mai # 4/Ning 7084 /Yang mai # 3	MR	5.25
Ning 8428	75-6711/Luo fu ling//Ning 7840	MS-MR	high yield potential

MR = moderately resistant; MS = moderately susceptible

[a] According to regional cooperative wheat variety comparative test
[b] Has 14% protein

Screening Techniques

Inoculum

According to the research by various groups in China, 18 species of *Fusarium* have been identified from 2450 samples from 21 provinces or cities (Table 3) (1). Fourteen species of *Fusarium* were found from 476 isolates in Jiangsu Province (6). Among them, *F. graminearum* was the predominant species, representing 94.5% and 91.6% of total samples, respectively.

The virulence of 102 isolates of *F. graminearum* collected from 33 counties in Jiangsu province was determined on nine representative wheat cultivars by injecting a spore suspension into a single floret of an excised wheat spike in vitro (19). Differences were found in virulence of isolates and in the resistance response of the wheat cultivars that were apparently significant. However, when the virulence of isolates was averaged county by county, there was no significant difference between regional collections. These results indicate that no pathogenic specificity of isolates of *F. graminearum* was found. Our experience has shown that it is generally best to use the most virulent isolate available (as tested locally) for resistance testing. This strain should be stored in a lyophilized state to ensure that virulence is retained on a year-to-year basis (never on agar media). If such an isolate is unavailable, a mixture of several strains should be used.

Types and concentrations of inoculum

The virulence experiments were focused on the types and concentrations of inoculum (*F. graminearum*) that would be used in screening wheat varieties (18). The FHB susceptible cultivar Ning mai # 3 was used. Spores were injected (5 μL) as suspensions containing 1-2, 10, 50, or 100 ascospores or conidia into a single floret in the middle of the spike (10 replications). The inoculated spikes were incubated in a moisture chamber at room temperature (25°C). The percentage of diseased spikelets was calculated 8 days after inoculation.

The results showed that the difference in incubation time of the disease for the two kinds of spores was less than one day. In both cases, the percentage of diseased spikelets was about 94%. There was a trend toward a shorter incubation stage of the disease with higher spore concentrations, with a 1.7-day difference in incubation period between the highest and lowest concentrations of spores used. There were no significant differences in pathogenicity between ascospores and conidia or between 1 to 2 and 100 spores per 5 μL suspension. Therefore, conidial suspensions containing 100-200 spores/mL were used.

Inoculation Methods and Evaluation of FHB Resistance

Two types of FHB resistance, resistance to initial infection (type 1) and resistance to spread of hyphae inside plant tissue (type 2) , have been described by Schroeder and Christensen (12). The resistance to initial infection was highest in Su mai # 3, Ning 7840, 2108, and 6718-7-2-2-13-4 (Table 4). Infection ratings of the varieties inoculated indicated differential resistance to spread of the fungus in the plant as well. For example, the resistance to fungal spread by Su mai # 3, 12G-12-4, Ning 7840, and Wang shui bai was much higher than for the others.

Table 3. The species of wheat fusarium head blight in China

	In 21 provinces of China (%)[a]	In Jiangsu (%)
Fusarium graminearum Schwabe	+ (94.5)	+ (91.6)
F. culmorum (W.G. Smith) Sacc.	+	+ (0.42)
F. camptoceras W. & R.	+	+ (0.63)
F. moniliforme Sheld.	+	+ (1.47)
F. subglutinans (W. & R.) Nelson, Tousson & Marasas)	—	+ (0.21)
F. longipes W. & R.	+	—
F. equiseti (Corda) Sacc.	+	+ (0.21)
F. compactum Gordon	+	—
F. sambucinum Fuckel (W&R)	+	—
F. graminum Corda (W&R)	+	+ (0.21)
F. avenaceum (Fr.) Sacc.	+	+ (1.05)
F. tricinctum (Corda) Sacc.	+	—
F. acuminatum Ell. et Ev.	+	—
F. nivale (Fr.) Ces	+	+ (0.21)
F. sporotrichioides Sherb.	+	+ (0.42)
F. chlamydosporum (W&R)	+	—
F. semitectum Berk. & Rav	+	+ (1.36)
F. oxysporum Schlecht. emend. Synd. & Hans	+	+ (0.21)
F. solani (Mart.) Appel & Wollenw.	—	+ (0.63)
Unknown	—	+ (1.47)
Total no. of isolates	2450	476

[a] + indicates presence

In addition, the field data from 1976 to 1981 indicated there was a wide variability in the "infection-resistance" of wheat cultivars to *F. graminearum*. The resistance to disease spread in the plant for the same varieties was relatively constant (Table 5).

The inoculation and evaluation methods most appropriate to the study of type 2 resistance were examined (18). The representative cultivars — Su mai # 3 and Wang shui-bai (R), Wan lian 2 (MR), Ai gan zao and Shu ye # 1 (S) — were planted in a greenhouse. When the plants were at heading, the spikes were cut below the top stem node and placed in water containing 100 mg/L streptomycin. Approximately 10 to 20 conidia in a 5-μL suspension were injected into a single floret in the middle of the excised spike (20 to 26 replications per cultivar). The inoculated spikes were placed in a moisture chamber at 25°C for 2 to 3 days. When brownish chlorotic water-soaked spots appeared on the glume of the

Table 4. Comparison of fusarium head blight-resistant types of wheat varieties in Nanjing, China

Name of variety	Flowering stage	Incidence of diseased heads (%)	Infection rating[a] (average value)
Shu ye # 1	April 23-24	95	3.9
Zhen 33	"	99.5	3.8
12G-12-4	"	80	1.6
Su mai # 3	"	40	1.2
Ai gan zao	April 25-26	100	3.4
Fu hong ke 13	"	85	3.9
Jing hua hong ke	"	85	3.9
6718-7-2-2-13-4	"	45	2.1
2108	"	40	2.1
Ning 7840 (16 lines)	"	5-55	1-1.6
Wang shui bai	"	—	1.3

[a] Infection rating was evaluated in four levels. Each was assigned points: 1-the disease was restricted to the inoculated spikelet and there were no symptoms on the axis; 2-the axis was invaded, but the other spikelets were not; 3-the axis and a second spikelet adjacent to inoculated spikelet were invaded; 4-the axis and more than one additional spikelet were invaded and/or whole head appeared to be wilting

inoculated floret, the moisture was removed and the temperature was adjusted downward to 20°C. The number of diseased spikelets was assessed daily, recorded, and subjected to statistical analysis by a multiple comparison procedure 8 to 9 days after inoculation.

There were significant differences among the varieties. The fungal growth on diseased spikelets of resistant varieties Su mai #3 and Wang shui-bai was much lower than on the susceptible varieties Shu ye # 1 and Ai Gan zao and even than on the moderately resistant variety Wan lian #2 (Table 6).

FHB-resistance could be identified from the symptoms of inoculated spikes. On highly resistant varieties, the symptoms were restricted to the inoculated spikelet. In susceptible varieties, severe symptoms spread to the axis or whole spike and caused head wilt. The appearance of moderately resistant varieties was intermediate; the disease developed along the axis and the spikelets adjacent to the inoculated floret. Forty-four HR, R, and MR single-plants were selected in 1981 from 305 cross-progenies (Aurora/Su mai # 3//Yang mai #2) by using this method.

In the field, the same inoculation method was used as described above in vitro. Thirty-seven wheat varieties and two sowing times (Nov. 1 and Nov. 20) were tested in 2 years (1979 and 1980). Spikes (20 to 25) were inoculated from each cultivar. The degree of infection was recorded 20 days after inoculation according to

Table 5. Comparison of fusarium head blight resistance stability of wheat cultivars in the field

Name of cultivar	Rate of diseased heads (%)[a]						Infection rating[b]			
	1976	1977	1978	1979	1980	1981	1976	1979	1980	1981
Wang shui-bai	4.0	64.0	0.5	40.0	0	0	1-2	1.3	1.3	1.1
Su mai # 3	18.0	98.0	0.5	40.0	0	0	2	1.2	1.7	1.2
Xiang mai #1	4.0	86.0	1.0	52.4	5.0	0	2-3	2.5	2.9	2.3
Wan lian # 2	18.0	90.0	1.5	55.0	5.0	0	2-3	2.3	2.5	2.2
Fan shen mai	—	76.0	—	35.0	5.0	0	3	2.7	2.4	2.2
Vanessa 2022	4.0	80.0	1.0	55.0	10.0	0	4	3.9	3.4	3.2
Frontana	6.0	84.0	0.5	40.0	30.0	0	4	3.7	3.7	3.3
Ai gan zao	54.0	100	5.0	100	10.0	5.0	4	3.4	3.6	3.3

[a] Inoculation by spreading diseased grains on the surface of soil or spraying conidia suspension on spikes

[b] See Table 4; inoculation by injecting 50 μL of conidial suspension (10 spores) on a single floret of a spike; 1-1.9 = R-HR; 2.0-2.9 = MR; 3.0-4.0 = S

results (Table 7) indicated that differences with respect to FHB resistance were significant only between varieties and not between sowing times or between years. However, when the plants were inoculated by spreading diseased grains or by spraying spore suspensions, differences were also significant between sowing times and years. Therefore, the FHB resistance of varieties is most reliably determined by needle inoculation.

The correlation between the effects of in vitro and in vivo inoculum injections was tested on 181 wheat lines in 1981. The disease infection rating of wheat lines in vitro generally was slightly higher than those of same lines in vivo. The correlation of laboratory and field results was 92%.

Table 6. Daily increase in the number of diseased spikelets on an inoculated head of different wheat varieties

Name of variety	Average daily increase in number of diseased spikelets
Su mai # 3	0.39 a
Wang shui-bai	0.52 a
Wan lian # 2	1.52 b
Ai ganzao	2.04 c
Shu ye # 1	2.44 c

Values followed by the same letter are not significantly different at $p < 0.01$ level

Table 7. F value of different screening techniques between varieties, sowing times, and years

	Injecting spore suspension/Infection rating	Spreading diseased grains or spraying/ Arcsin (diseased spike rate) 0.5	Spore suspension/Disease Index
1979			
Between varieties	48.17**	4.55**	6.45
Between sowing times	0.076	15.87**	10.80**
1980			
Between varieties	17.69**	3.59**	2.79**
Between sowing times	1.62	5.27**	4.34*
1981			
Between varieties	11.17**	2.60**	1.60
Between years	0.63	180.62**	67.59**

* Differences significant at $P < 0.05$
** Differences significant at $P < 0.01$

Etiolated Wheat Coleoptile Bioassay

The bioassay used for the study of the interaction between wheat coleoptile and mycotoxins was described by Cutler and Jarvis (3). These experiments focused on the response of different wheat varieties to *F. graminearum* metabolites (17). Coleoptiles (4-mm segments) were cut from 4-day-old etiolated wheat seedlings. Ten coleoptile segments were added to test tubes containing 2 mL of phosphate-citrite buffer solution (pH 5.6) and 2% sucrose plus the metabolite to be tested. Each mycotoxin was tested at 10^{-3}, 10^{-4}, 10^{-5}, and 10^{-6} M for effects on growth. The coleoptile sections were incubated with gentle shaking for 18 to 20 hours in the dark at 25°C. Each segment was measured by placing it on an overhead projector to project an enlarged image (X3).

F. graminearum metabolites (in decreasing order of toxicity to etiolated coleoptile tissue of 21 wheat cultivars) were deoxynivalenol (DON), 3-acetyldeoxynivalenol (3-ADON), culmorin (CUL), dihydroxycalnectrin (DHCAL), butenolide (BUT), and sambucinol (SOL).

The sensitivity of etiolated coleoptile tissue of wheat cultivars to these metabolites differed among cultivars (Table 8). The response of seven representative winter wheat varieties from China to DON was consistent with the FHB resistance of these

Table 8. Comparison of sensitivity of etiolated coleoptiles of some wheat cultivars to mycotoxins

Cultivar	Disease resistance in the field	Sensitive concentration (M)[a] in vitro[b]					
		DON	BUT	CUL	DHCAL	3-ADON	SOL
Wang shui-bai	HR	10^{-4}	—[c]	—	—		
Su mai # 3	R	10^{-5}	10^{-3}	10^{-4}	10^{-4}		
Yan gang fangzhu	R	10^{-5}	—	10^{-3}	10^{-3}		
Xin zhong-chang	MR	10^{-6}	10^{-4}	10^{-3}	10^{-4}		
Fan shan mai	MS-MR	10^{-6}	—	10^{-3}	10^{-3}		
Ning mai # 6	S	10^{-6}	10^{-6}	10^{-3}	10^{-4}		
Ai gan zao	S	10^{-6}	10^{-5}	10^{-5}	10^{-3}		
Frontana (Winnipeg)	MS-MR	10^{-6}	10^{-4}	10^{-3}	10^{-3}	10^{-3}	—
Casavant	S	10^{-6}	10^{-6}	10^{-4}	10^{-5}	10^{-6}	10^{-3}
Concorde	S	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-5}

a Minimum concentration at which toxic effects are observed
b The data are significantly different ($P < 0.05$) relative to control according to Duncan's multiple range test
c "—" No effects at tested concentrations

varieties in the field. The difference in sensitivity concentration of six mycotoxins on 21 wheat varieties varied over 3 orders of magnitude (17). For example, deoxynivalenol was active at 10^{-4} M on the very resistant variety Wang shui bai, but down to 10^{-6} M on susceptible varieties. The results in the etiolated wheat coleoptile bioassay can be used to determine FHB-resistance in wheat germplasm in conjunction with field tests (17).

Discussion

Screening techniques for FHB-resistance should be improved in order to rapidly select reliable resistant sources. Some methods have been attempted and are briefly discussed below.

- Inoculation by spreading inoculated grains on the surface of the soil or spraying spore suspensions on flowering spikes is simple and convenient, and approaches the natural situation. However, infection processes are variable depending on environmental conditions. This is the most common method used, but is not reliable and is suitable only for mass screening.

- Inoculation by injecting a spore suspension into a single floret on plants in the field or on the excised spikes in vitro is more labor intensive than the above method, but is more precise. This method can be used in resistance selection of key materials and single plants of advanced cross-progenies.

- The etiolated coleoptile bioassay is a simple, rapid, sensitive method to determine the biological activity of metabolites produced by *F. graminearum*, and the response of wheat varieties to such compounds is consistent with data obtained from field trials. Further studies are under way to evaluate the broader utility of this approach. Toxins of microbial pathogens can inhibit plant growth and damage plant tissues and cells. Based on this principle, the techniques of plant biotechnology can be used in the identification of the genetic basis for biochemical events involved in disease resistance.

Preliminary selection for FHB-resistant materials in large-scale screening trials should utilize the traditional method of spreading inoculated grains. Selected advanced materials should be screened again using the needle inoculation technique and coleoptile bioassays in order to confirm their FHB resistance.

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Wheat Root Rots in Tropical Environments—Potential Impact and Control

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Abstract
All of the problems that pathologists and breeders will be confronted with in developing root rot-resistant cultivars for tropical environments are not well defined at this point. Such a task will be a very challenging endeavor. This presentation emphasizes: 1) importance of a healthy wheat root system; 2) host and pathogen environmental interactions; 3) difficulties of root rot problem recognition; 4) potential soilborne pathogen problems; and 5) soilborne disease control approaches. Pathologists and breeders will be responsible for recognition of a pathogen's importance, and the development and implementation of short-term cultural and chemical controls with the long-term objective of developing resistant cultivars.

Soilborne diseases are associated with inhibition and/or dysfunction of a plant root system. One early perspective on soilborne disease was summarized in 1913 (1): "When a valuable fertilizer is present and the roots are dead by disease, the wheat plant cannot make use of it. If the roots are healthy, they can make use of it." This is an important concept regardless of the area of wheat production.

If producers follow soil fertility, weed, and insect control recommendations, and use good soil management and preparation practices, they should expect to economically increase their biomass production potential. However, if soilborne pathogens are present and root rot damage occurs, the benefits of these practices will be reduced in proportion to the severity of the root rot epidemic. Roots debilitated by root rot cannot take advantage of these optimum environmental conditions. The term "debilitated" is important because soilborne pathogens damage plants throughout their life cycle, from planting through maturity. In fact, most soilborne pathogens are persistent "nibblers" of the root system, and retard root development over a long period of time. Only rarely, e.g., as seedling pre- and post-emergence damping-off, do root pathogens cause outright plant mortality over a relatively short period of time. For this reason, we may not always be fully aware of the yield suppression that root pathogens cause.

The root system of a plant is comparable to the foundation of a building or a factory; obviously neither will be a productive unit for long if the foundation is inadequate or fails.

Thus, let us keep in mind two things relative to root health:

1) A dead or damaged plant root system does not allow for the expression of a plant's maximum genetic potential for productivity.

2) Poor root development can result not only from the effects of root rot pathogens, but from less than optimum agronomic inputs, inappropriate planting dates, inadequate seedbed preparation, and an inadequate fertility program.

In any case, the result of an unhealthy root system will be reduced capacity for wheat to produce an economic return for the producer. Again, these considerations are applicable regardless of the production environment. However, we will be concerned with some of the problems that might be encountered when growing wheat in tropical environments.

Expected Tropical Environment Concerns

A summary, modified from Klatt (16) of the environmental situations associated with growing wheat in tropical areas, is presented in Table 1.

In this table, the environments are differentiated in terms of expected temperature and relative humidity differences. Their probable effects on the occurrence of foliar and soilborne disease problems are shown in terms of their probability of occurrence and anticipated importance.

In both environments (Table 1), resistance to foliar diseases, such as the rusts and other common airborne pathogens, will need to be utilized in the normal scheme of cultivar development.

In environment II, resistance to various soilborne disease pathogens will be important. Also, under these environmental extremes, more problems associated with "nontraditional" soilborne pathogens such as *Sclerotium rolfsii* will likely be encountered. In tropical environments, there should be optimum conditions for the survival and development of soilborne pathogens, and less than optimum conditions for the host's growth and development.

However, in environment I, the probability for low to high levels of root disease potential has been included. *Fusarium* spp. and *Helminthosporium* (Syn = *Bipolaris*) are causal agents of diseases associated with "traditional" stress-activated root rot problems. Because of their ubiquitous presence, these pathogens probably will be present and potentially damaging in both environments. This is especially true in environment I if the host is subjected to periods of drought stress as a result of the high temperatures and limited rainfall.

Expected Host and Pathogen Concerns

Assumptions with regard to anticipated host and pathogen characteristics associated with growing wheat in tropical environments are shown in Table 2.

Initially, wheat cultivars will be poorly adapted for growth in tropical environments for various agronomic as well as pest related reasons. Reasonably, these cultivars should

Table 1. Expected environmental concerns associated with growing wheat in tropical environments

Environment	Temperature	Relative humidity	Expected disease problems and probability of importance: Foliar	Soilborne
I	warm	low	low	low-high
II	warm	high	high	high

be expected to have adequate levels of resistance to most of the common foliar diseases because of the germplasm from which they will be derived. Because of the environmental stress, unadapted cultivars would be expected to be more subject to attack by soilborne pathogens than if they were grown within their normal area of adaptation. This is because a weakened or stressed host is usually more susceptible to attack by soilborne pathogens than an unstressed host of equal susceptibility.

Most of the pathogens to be encountered in these environments would be endemic, and thus are well adapted for survival in tropical environments. Also, these pathogens would most likely possess wide host range capabilities, and may be capable of attacking other crops in rotation with wheat. For example, soybean-wheat rotations may result in the buildup of *Sclerotium rolfsii*, which can attack both hosts. Another association may be the buildup of *H. sativum* in wheat-rice rotations where host range studies show that this pathogen can potentially attack rice as well as wheat (17, 27).

Table 2. Anticipated host and pathogen characteristics

Host:
- initially poorly adapted for growth and development
- possessing adequate levels of resistance to common foliar pathogens such as leaf rust, stem rust, and septoria leaf blotch
- susceptible to attack by various traditional and nontraditional root rot pathogens

Pathogen:
- endemic
- adapted for survival as a result of well developed saprhophytic and facultative traits
- wide host range capabilities

Physical components (pH, texture, etc.) of the soil can affect crop productivity, and can interact with soilborne pathogens. Such views have been presented (21), and will not be discussed here.

Soilborne Pathogen Problems

Root pathogens can limit wheat production in tropical environments (8, 30). Recognition of a soilborne pathogen's role, and therefore its relative importance in reducing wheat yields in tropical areas, will always be a problem because of the more highly visible foliar pathogen symptomology. Root rot pathogens are more subtle in effecting wheat yield reductions than foliar pathogens.

Because of their soilborne environment, elucidation of the presence of root rot pathogens requires more sophisticated techniques and procedures than the simple visual observations needed to detect the presence of foliar pathogens.

Measuring root rot disease effects

Various techniques are available for elucidating soilborne disease effects (37). Regardless of the technique employed, we are primarily interested in answering the following questions:

- Do we have a significant root rot problem in an area?
- What type of losses are being encountered?

- Which pathogens are involved?

Various approaches can be taken in answering these questions about suspected root rot disease problems. Here, we will be concerned with some indirect and direct approaches that can be used. These approaches are presented as examples, and are not meant to imply that these are the only methods available. There are limitations to each approach, and no one approach is sufficient to answer all of the above questions.

Indirect approaches—The recognition of the importance of soilborne diseases really came about with the development of soil fumigation techniques (37). These techniques and, more recently, selective fungicides can be quite useful for indirectly characterizing soilborne disease problems in an area.

Two advantages to soil fumigation are: 1) it provides information about the importance of soilborne disease pathogens in an area, and 2) it provides an estimate of yield potential for a given environment in the absence of the biological components of the soil. Disadvantages to soil fumigation include: 1) possible overestimation of the contribution of soilborne pathogens to yield suppression because it also controls weeds, nematodes, and other pests, and 2) it is not an economical control measure for soilborne pathogens of wheat.

Four advantages to selective fungicides are: 1) the effects are specific using Ridomil, Imazalil, and other types of fungicides with well defined spectra of activity, 2) they can be used in the form of seed treatment, granular broadcast, or in-furrow treatment, 3) they may inexpensively provide an indicator as to the types of pathogens present in a soil environment because of the specificity of their action, and 4) they may provide preliminary data for economic chemical control for some pathogens. Disadvantages include possible underestimation of total effects of the soilborne pathogens in an area because of the narrow spectrum of activity and such fungicides may lead to an increase in damage caused by pathogens outside the spectrum of activity.

Direct approaches—Most soilborne disease problems can be observed in terms of seedling disease and mature plant effects (36, 38).

Seedling disease problems are manifested as stand establishment problems, and are usually quite evident soon after planting. The severity of seedling damage as pre- and post-emergence damping-off can lead to reductions in stand to the extent that replanting is necessary. However, seedling damage may be more subtle, resulting in weakened plants that never fully recover. Other problems such as nutrient deficiency can be confused with root rot damage. However, stands weakened and yellowed as a result of root rot pathogens will not respond to post-planting applications of nitrogen as one would expect if only nitrogen deficiency were involved. Thus, the lack of response to fertilization provides a further clue that root disease problems may be involved.

Comparison of the root systems of diseased plants and healthy plants should provide clues as to the reasons for the symptoms. The observation should also be made here that true nutrient deficiency symptoms usually occur uniformly over a field, assuming that there are no drastic changes in soil type within an area. On the other hand, soilborne disease problems appear as irregular and patchy areas throughout a field because of the unlikely occurrence of uniform inoculum distribution throughout a field.

The major mature plant effects caused by soilborne pathogens would be variable plant height, premature death of individual scattered tillers, and/or quite large irregular areas of dead plants throughout a field. Direct examination of such plants will usually provide clues as to the causal agent.

Once we have defined the symptomology associated with a given root disease problem, our diagnosis should be confirmed by isolating the causal agent. This would provide us with isolates for use in pathogenicity testing and/or cultivar screening. There are various techniques and methodologies available for this type of work (6, 15). Two approaches to this problem will be briefly presented.

The first approach involves the direct isolation from host tissue of pathogens such as *Fusarium* spp., *Helminthosporium* spp., *Rhizoctonia* spp., and *Sclerotium rolfsii*, which have less fastidious growth requirements. This can be done using a nonselective medium such as Potato Dextrose Agar or various types of selective media. For example, selective media have been developed for isolating *Fusarium* spp. (28) and *Helminthosporium* spp. (32) directly from host tissue.

The second approach involves the indirect isolation from diseased host tissue using a baiting technique for more fastidious pathogens that are less aggressive than competitive saprophytes. For example, *Pythium* can be isolated from field collected and washed roots by using roots of young wheat seedlings as a selective medium. Wheat seeds are planted directly into a balled up root mass, covered with sterile soil, and allowed to grow for 6 to 7 days. The seedling roots are then removed, washed thoroughly, and placed directly onto cornmeal agar (1/5X). If *Pythium* is present, colonies of 20 to 50 mm in diameter will be present within 24 to 48 hours. This pathogen may be completely overlooked if a direct isolation method is used because of its inability to compete successfully with pathogens such as *Helminthosporium* and *Fusarium*. We have found that this technique also allows for the selection of pathogenic strains of *Pythium*.

The next step involves testing the isolated strains of a given pathogen to determine if they are pathogenic. These isolates can be used later for various field and greenhouse screening trials. Gilchrist (12) has outlined a procedure that should be adaptable for screening for resistance to most pathogens.

Potential Soilborne Disease Problems in Tropical Areas

It is obvious that we will be unable to make all the right assumptions at this point for identifying all of the potential soilborne pathogen problems in tropical environments. However, from the limited literature, we can be certain that some of the common pathogens such as *Helminthosporium*, *Fusarium*, and *Pythium* that are important in temperate climates, are also likely to be important in tropical environments. Soilborne disease problems in tropical areas may be more important because of the environmental stresses associated with wheat growing outside of its area of adaptation. Because of its well documented occurrence in the tropics (8, 30), *Sclerotium rolfsii* will be used as an example of a nontraditional soilborne pathogen problem. This is not to imply that it will be the only problem, but it will give us a baseline from which to start.

Helminthosporium (Identification references: 19, 20, 31)
Organism—Helminthosporium sativum P.K. & B. (syn. *Bipolaris sorokiniana* Sacc. in Sorok.) has been identified as important in tropical areas (30).

Field symptomology—For *helminthosporium*, the most characteristic symptomology would be brown to black colored lesions on the subcrown internode. These lesions tend to increase in severity as the growing season progresses. Changes in lesion severity can be monitored throughout the growing season as long as the subcrowns maintain their integrity. *Helminthosporium* can also cause whitehead symptoms as the plants approach maturity, like fusarium and take-all. In tropical areas, there may be further potential for progression into a foliar blight phase (36), where it can cause distinct dark to black lesions on the leaves. The foliar phase of development may be a more common occurrence in humid areas than in more temperate climates.

Survival—This pathogen can survive as free conidia in the soil and in association with infested crop residue. If wheat is being grown in rotation with rice, it needs to be determined if one crop is producing inoculum for the next. Host studies (17, 27) indicate that *H. sativum* isolates can attack quite a wide host range of plants including rice seedlings. Thus, the possibility exists for rice and wheat to produce inoculum for each other.

Fusarium (Identification references: 2, 10, 26, 38)
Organism—Fusarium culmorum (W.G. Smith) Sacc., *F. graminearum* Schwabe, and *F. moniliforme* Sheldon have been identified as species associated with root rots on wheat in tropical areas (30).

Field symptomology—As wheat nears maturity, one may observe the development of scattered whiteheaded areas consisting of from one to several tillers to quite large irregular patchy areas involving many plants. The lower internodes of plants with whitehead symptoms will be dark to light brown in color if *Fusarium* is involved. In temperate climates, the development of whiteheads is very closely correlated with drought stress. The greater the drought stress near maturity the greater the potential for development of whitehead symptoms in root rot prone areas (36).

Survival—This pathogen typically survives in host residue as mycelium and as chlamydospores in the soil.

Note—Both *fusarium* and *helminthosporium* would be expected to occur in tropical areas because of their broad host range and temperature adaptations. Both would be expected to interfere with stand establishment as pre- and post-emergence damping-off, especially if they occur in conjunction with high soil temperatures (25-30°C) at planting. Wet soil conditions should tend to favor damage caused by *helminthosporium*. Drier soil conditions should favor the development of *fusarium*, especially as the plants approach maturity in conjunction with drought stress.

Pythium (Identification references: 25, 29, 34, 35)
Organism—Pythium spp. No specific list of species will be given here because there are several that normally occur on wheat (36). One

should be cautious about assessing *Pythium's* importance in tropical environments for several reasons. Host range studies (23) point out that given species can have relatively broad host ranges in attacking both soybeans and wheat to some degree. Also, this pathogen is important in the temperate climate of Oklahoma, and was readily found in the El Batan nurseries in Mexico in 1986, using the baiting technique described previously (Singleton, unpublished data). *Pythium* may prove to be very important in tropical areas as a seedling blight pathogen, and throughout the crop season as a constant "nibbler" on the root system.

Field symptomology—Pythium damage in the field can result in stunting and yellowing of plants, which can be quite obvious, although almost indistinguishable from nitrogen deficiency problems (36). Upon direct examination of the roots, however, if *Pythium* is involved, we should find stunted roots with watery, brown to reddish lesions. One can look for oospores in the root tissue by staining the tissue with lacto fuchsin (0.1 g Acid Fuchsin/100 ml lactic acid; [4]).

Survival—Pythium primarily survives as oospores in soil and in plant tissue.

***Take-All* (Identification reference: 36)**
Organism—Gaeumannomyces graminis var. *tritici* (Sacc.) Arx & Oliv. (syn. *Ophiobolus graminis* Sacc.; common name, take-all). The importance of take-all in tropical environments cannot be assessed at this time (8). In greenhouse studies, Henry (14) found that take-all damage was suppressed as soil temperatures increased up to 27°C (13, 14). Thus with high soil temperatures in tropical areas, this pathogen may be suppressed and not important.

Field symptomology—Damage in temperate areas is primarily associated with the occurrence of irregular patchy areas of prematurely dead plants (whiteheads) similar to that caused by *fusarium* for example. Examination of the lower internodes will reveal the presence of a deep black charcoal-like discoloration of the roots and lower internodes of the wheat plants that is distinctly different from the symptomology caused by *fusarium*. Microscopically, a superficial black network of mycelium will be present on infected root surfaces.

Survival—Take-all survives primarily as mycelium in the root crown or other colonized host tissue.

***Rhizoctonia* (Identification reference: 36)**
Organism—Rhizoctonia solani Kuhn. This pathogen has very broad host range capabilities.

Field symptomology—Rhizoctonia can cause seedling blight damage and/or mature plant damage similar to that caused by *helminthosporium* and *fusarium*. As a mature plant problem, it causes eyespot-like lesions on lower culms, which can result in weakening of the stem and subsequent lodging.

Survival—This pathogen can survive in soil and host debris as mycelium and sclerotia.

Sclerotium
Organism—Sclerotium rolfsii. This organism has very wide host range capabilities, and has been found to seriously affect production in some tropical areas (8, 30).

Field symptomology—This pathogen will typically produce a white mycelial growth on the surface of plants and soil under the plant canopy (30). Also associated with this growth, dark brown to white sclerotial bodies resembling mustard seeds are usually produced.

Survival—This pathogen survives as sclerotial bodies in soil and plant debris, and as mycelium in infested host tissue.

Soilborne Disease Control in Tropical Environments

Control of soilborne diseases of wheat in tropical environments is going to be an interesting challenge for pathologists, breeders, and other plant scientists. Pathologists will be confronted with many of the soilborne pathogen problems found in temperate climates. Also, several nontraditional pathogens such as *S. rolfsii* and minor pathogens like *Rhizoctonia* may rise to prominence as causal agents of soilborne diseases of wheat in tropical areas. Initially, the wheat cultivars are going to be unadapted and at a disadvantage because of environmental stresses. Conversely, soilborne pathogens will have an advantage over the host as a result of their indigenous adaptation.

A listing of all the soilborne pathogens that will be encountered cannot be provided in this treatment. Based on the available literature, probable soilborne pathogen candidates have been presented. Obviously for the same reason, precise control recommendations for all soilborne pathogens cannot be given, but various principles or approaches for control will be presented. Some sources for control recommendations and principles for soilborne disease control can be found in references 5, 7, 11, 18, and 36. Most disease control measures encompass the following basic principles: exclusion, eradication, and protection (33). Once a soilborne pathogen has been found in an area, it is really too late to take advantage of either exclusion or eradication as control measures.

Exclusion and eradication
Exclusion and eradication as control measures can be useful in preventing the introduction of seedborne pathogens into a virgin area. Good seed monitoring and sanitation programs will go a long way toward preventing such introductions. Also, these principles could be useful on a local basis (field to field). For example, a farmer has two fields, and one is infested with *S. rolfsii*. Since *S. rolfsii* can survive in host debris and soil, we know that even minute amounts of soil or plant debris should not be exchanged between these fields. The pathogen cannot be eradicated from the infested field, but it can be excluded from the uninfested areas.

Similarly, the gathering and feeding of infested plant material to livestock may be a common practice. However, the subsequent use of the manure for a field may not be a desirable practice. It has been found that *Sclerotinia* sclerotia from infested peanut hay fed to ruminants were still viable and pathogenic (24). Possibly an intermediate composting step may provide a solution because this would allow time for the breakdown of soilborne pathogen propagules and infested plant debris. Thus, these aspects of crop production should also be considered when developing soilborne disease control programs.

Protection
Protection measures must consider that soilborne pathogens are: 1) endemic and environmentally adapted for survival, 2) have broad host range capabilities, and 3) survive as resistant propagules in soil and as mycelium in crop debris.

We cannot have much of an influence on the endemic and adapted characteristics of a soilborne pathogen. However, we must recognize that a pathogen is present, and develop control measures to deal with it. For example, there are some possibilities for control of pathogens with specific environmental requirements for survival. Take-all is favored by alkaline soils that are deficient in nitrogen and phosphorus (36). As a result, it may be possible to decrease the soil pH and increase the soil fertility, thus effectively putting the pathogen at a disadvantage to the host.

The broad host range capabilities of soilborne pathogens must be dealt with in terms of host resistance. Also, the possibility for diversification in developing and using rotation systems that include nonhosts should be explored. Unfortunately, this may seem to be an unlikely possibility with the group of pathogens that we have covered. However, in cases where a pathogen has a narrow host range, advantage must be taken of such a weakness in a pathogen's life cycle.

Most soilborne pathogens have some well adapted means of survival in the soil as propagules and/or in association with plant debris. Thus, most soilborne disease control practices will utilize various cultural, chemical, and host resistance in an integrated package with other agronomic practices. The expected result will be a program that will allow the producer to economically produce a wheat crop.

Cultural control

Cultural control includes tillage, soil fertility, green manure crops, crop rotation, and sanitation practices. With these approaches our main objective is to reduce pathogen inoculum levels and their effects to such an extent that the producer can attain an economic return. Tillage methods would include burying infested host residues to hasten decomposition of pathogen propagules and infested plant debris, thus exposing a pathogen to direct competition with other soil saprophytes. Obviously, these practices will be more effective against the more fastidious pathogens like *G. graminis* var. *tritici*, and less effective against pathogens such as *S. rolfsii*. Where it is possible, crop rotation schemes should be employed to avoid situations where a previous crop will produce inoculum for the next.

Chemical control

With the development of chemicals with systemic capabilities in addition to protectant action, there has been an increase in the possibilities for soilborne disease control. For example, it was found that triadimenol as a seed treatment could delay the development of take-all on spring wheat for up to 53 days (22). Such results with this compound and others such as Ridomil for *Pythium* and Imazalil for *helminthosporium* control indicate the need for further work of this type. This should be viewed, however, as a short-range solution, and not the ultimate answer to a soilborne disease problem. Why? As a result of their specificity of action, there is the possibility for the development of chemically resistant strains if chemicals are used extensively. This has already become a problem with foliar pathogens with similar types of compounds. In tropical areas, chemical control may not provide an economically feasible solution to such problems because of the added input costs. Here, mention of biological control has been excluded as an adjunct to chemical control. This is because they are based on similar principles, and both are going to cost the producer money to use.

Host resistance

Without doubt, effective root rot disease resistance characters are going to be necessary in tropical environments for efficient and stable wheat production. Herein lies the greatest unknown in dealing with the traditional and nontraditional soilborne pathogens in tropical environments. Will pathologists and breeders be able to identify and utilize host resistance against these pathogens?.

The following points must be considered and resolved. The genetics of resistance to soilborne pathogens are largely an unknown (9), and the modes of inheritance are generally found to be complex, involving more than one or two genes (3). Thus, pathologists and breeders are going to be dealing with characters such as yield, where many genes may be involved. Secondly, such resistance characters may be functionally inoculum-dependent (high levels of inoculum may decrease the effectiveness of a resistance character). Thus in tropical areas, it might be reasonable to expect that soilborne pathogen inoculum levels may be much higher than normally encountered in temperate climates. As a result, functional levels of resistance in temperate areas may not be useful in tropical areas because of high inoculum levels. Other possibilities for problems with host resistance characters may include sensitivity to high temperatures and differences in pathogen biotypes.

For these reasons, the development of soilborne disease resistant cultivars in tropical environments is not going to be an easy task. However, it will be necessary if a stable level of wheat production is going to be attained in these areas. Throughout this paper, the importance of the environment as it relates to being more favorable for the soilborne pathogen than the wheat host has been stressed. When programs are initiated and areas are chosen for developing resistant cultivars, research must be conducted under environmental conditions that favor the pathogen even though rigorous if functional levels of host resistance are to be identified. Too often, the tendency is toward carrying out selections under conditions that favor the host, which may not reflect the actual worth of the cultivar.

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Bacterial Diseases of Wheat and Their Potential Importance in Tropical Regions

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Abstract

Seven species of bacteria are pathogenic to wheat. Only two of these cause economic loss. Pseudomonas syringae *pv.* syringae *can cause severe damage when temperature is moderate and conditions are wet.* Xanthomonas campestris *pv.* translucens *is distributed worldwide and causes the most serious bacterial disease of wheat. It is also anticipated to be the most important bacterial disease in tropical areas. The major means of widespread dissemination is seed. Inexpensive methods to control seedborne inoculum are needed. Water is the main means of dissemination within fields. Cultural practices that restrict movement of irrigation water from infested fields are important. More information about survival of bacteria as parasites or as epiphytes on weeds or other crops such as rice are needed to develop control strategies in tropical agricultural systems. Resistance will be a primary means of control.*

Bacterial diseases are often considered to be relatively minor in importance on wheat compared to diseases caused by fungi and viruses. However, under certain environmental conditions, bacterial diseases can cause significant yield losses. Bacterial diseases are a potential threat to wheat in tropical environments because they are favored by warm, humid conditions. The causal agents of most bacterial diseases are widespread and probably already exist in most areas where wheat is grown. Bacterial pathogens of wheat occur in three genera, *Corynebacterium, Pseudomonas, and Xanthomonas.*

Changes in nomenclature of bacterial plant pathogens since 1980 have resulted in name changes for most of the species attacking wheat. Under the former system many species names were based on the host range of the bacterium. The new system is based on various biochemical characteristics which indicate more precisely the genetic relationships of species (10). Host specificity is now indicated by the subspecific taxon pathovar. Therefore, in many instances the former species name is now the pathovar name. It is likely that additional changes in the taxonomy and nomenclature of wheat bacteria will occur as more precise data are gathered on their physiology and genetics. Synonyms are included with the current names for clarity.

There are seven species of bacteria pathogenic to wheat (Table 1). Several of these have only been briefly described because they are only found occasionally and are probably very weak pathogens. They cause disease mostly when certain stressful environmental conditions occur (5, 39). Additional information on diagnosis and control of bacterial diseases can be obtained from various references that have already condensed most of the information available about them (5, 22, 27, 31, 39, 41).

Description of Diseases

Five bacterial diseases will be discussed briefly followed by a more detailed discussion of the other two diseases.

Pink seed, caused by *Erwinia rhapontici* (Millard) Burkholder, causes the endosperm to turn pink, but otherwise the seed is not changed. Wounding is required for infection, but disease incidence is quite low. It has been found infrequently only in Canada and Europe and may be associated with gall midge injury or premature cutting of grain (29, 39). It is not economically important.

Bacillus megaterium de Bary pv. *cerealis* has been reported only once causing white to light tan streaks and blotches on wheat in the north central region of the United States. Symptoms are similar to those caused by *Pseudomonas syringae* pv. *syringae*. Symptom expression is favored by high temperatures and high light intensity during the heading to mature stage of growth. Therefore, it could be a problem in tropical areas. The bacterium is seedborne and is probably a weak parasite that occurs widely in nature (17).

Two species of the Gram-positive genus *Corynebacterium* cause minor diseases of wheat. *C. michiganse* ssp. *tesellarius* Carlson & Vidaver causes chlorotic mosaic lesions without watersoaking. The chlorotic tissue eventually turns brown, forming streaks along the midrib. The bacterium is seedborne and can

Table 1. Bacteria pathogenic to wheat and other small grains

Bacterium	Common name	Hosts
Pseudomonas syringae pv. *syringae*	Bacterial leaf blight	Wheat, barley
Pseudomonas syringae pv. *atrofaciens*	Basal glume rot	Wheat, barley, oats
Xanthomonas campestris pv. *translucens*	Black chaff, bacterial leaf streak, bacterial stripe, Xanthomonas streak	Wheat, barley, rye, oats, triticale
Corynebacterium tritici	Spike blight, tundu, yellow slime, yellow ear rot	Wheat
Corynebacterium michiganse ssp. *tesellarius*[a]	Bacterial mosaic	Wheat
Bacillus megaterium pv. *cerealis*	White blotch	Wheat
Erwinia rhapontici	Pink seed	Wheat

[a] Davis (8) and Davis et al. (9) proposed placing this species in the new genus *Clavibacter*

enter unwounded plant tissue. It has been reported only from North America, causing minor yield reductions (3, 4, 39).

A more widely reported disease is spike blight or tundu caused by *Corynebacterium tritici* (ex Hutchinson) Carlson & Vidaver. The disease is also known as yellow ear rot and yellow slime. The bacterium apparently is unable to incite disease unless it enters the plant via its vector *Anguina tritici*, the gall nematode (15, 16, 27, 38). The disease has been reported most often from India, but it has occasionally been found in China, North America, and Europe (39). The disease affects the head by producing a profusion of mucoid bacterial exudate. During dry weather the exudate hardens and can cause distortion of the leaves, peduncle, and head. Soaking affected seed in brine to eliminate the nematode galls is a simple and effective control (37).

There has been a recent proposal to place these two and several other *Corynebacterium* species in the new genus *Clavibacter* (8, 9). Therefore, it is likely that additional changes in the nomenclature and taxonomy of these pathogens will be forthcoming.

Pseudomonas syringae pv. *atrofaciens* (McCulloch) Young, Dye & Wilkie (syn. *P. atrofaciens*) causes water-soaked irregular spots on leaves and peduncles and most prominently on the lower portions of glumes (40). The affected areas quickly turn from dark green to brown. This disease may sometimes be overlooked and be diagnosed as septoria nodorum blotch or frost injury (11, 27). When severe, the disease causes shriveled grain. Losses are usually very light and are associated with extended periods of excess moisture during the grain-filling period. The bacterium occurs worldwide, but has been reported mostly from temperate areas. Apparently, resistant lines are easily selected. Improved resistance was considered to be responsible for its decline in Canada.

The two bacterial diseases that cause the greatest economic loss in most wheat growing areas of the world are also likely to be serious in tropical regions. The first of these is bacterial leaf blight caused by *Pseudomonas syringae* pv. *syringae* Van Hall. It causes an irregular white to tan leaf blotch which can result in extensive blighting of the foliage. The disease often appears rapidly near the time of heading following prolonged periods of wet weather when leaves remained watersoaked (13, 24, 34). Losses to bacterial leaf blight are probably underestimated because the pathogen is often difficult to isolate. Avirulent strains occur commonly in nature with virulent strains. It is difficult to prove pathogenicity because symptoms often do not develop in greenhouse inoculations.

The most important bacterial disease of wheat is bacterial leaf streak or stripe, also known as black chaff, caused by *Xanthomonas campestris* pv. *translucens* (Jones et al.) Dye and *X. c.* pv. *undulosa* (syn. *X. translucens*). In the older system of nomenclature, isolates of *X. translucens* primarily associated with wheat were designated subsp. *undulosa*. However, the various subspecies had a host range of one or more small grain species or grasses. Often the host ranges overlap when individual isolates are compared. Now that the species *translucens* and subspecies *undulosa* are both pathovar names, the correct designation is confusing. Most authors refer to the pathogen as *X. c.* pv. *translucens*, recognizing that individual isolates may vary in host range. From the practical point of view, it is important to understand that the inoculum source for wheat or another small grain crop may originate on that crop or another species of Gramineae.

Xanthomonas campestris pv. *translucens* produces very narrow, elongated watersoaked lesions that make the leaves translucent when held to the light. The stripe lesions produce copious amounts of yellow bacterial exudate, which hardens into coarse flakes or spheres when the leaves dry. These dense quantities of bacterial cells permit the pathogen to disseminate rapidly. The black chaff symptom is very prominent on the heads. It may be confused with physiological melanism which is also referred to as false chaff (27). Water is the main means of spread, but aphids and other insects may also carry the bacterium to healthy plants (2).

This disease may be especially important in tropical areas because it is favored by a wide range of temperatures (15 to 30°C), whereas bacterial leaf blight is favored by cooler temperatures (15 to 20°C). Bacterial stripe has been found throughout the tropical areas of the world where wheat is grown. It is found only in irrigated areas in the more arid areas. It is most severe in the cooler highland areas in the more humid regions and less common in the hotter lowlands (J.M. Prescott, personal communication).

Xanthomonas campestris pv. *translucens* is also a potentially serious problem on triticale (6, 14, 28, 42). Most strains from wheat, rye and triticale are virulent to all three crops. Cunfer and Scolari (6) compared strains of *X. c.* pv. *translucens* from triticale and wheat collected at several locations in the southeastern USA and at several CIMMYT test sites in Mexico. A strain collected from triticale in Ethiopia was also compared to the others. There were no significant differences in host range or host genotype response, indicating that there were no host-specific races among the strains compared. There have been no reports of strain difference for this bacterium from any host species. My experience has been that isolates from wheat, rye, and triticale are virulent on each of the other species. Isolates from barley tend to be more restricted to barley.

Etiology and Epidemiology

Requirements for disease

Bacteria have more stringent requirements than fungi for invasion of the host and for pathogenesis. It is necessary that plant tissue be watersoaked to provide a continuous water film for the bacterial cells to enter through natural openings (stomata, hydathodes) or wounds. Some bacterial pathogens are weak parasites, only causing disease under very specific environmental conditions and only when their population reaches critical levels (23). Following invasion of the host, wet, humid conditions which keep plant tissues at full turgor are required for bacterial multiplication. Usually the younger tissue is more likely to become infected although this is not always the case. Optimal temperatures for disease development are variable but generally bacterial diseases are favored by warmer temperatures (20 to 30°C).

Survival

Survival of inoculum occurs by several means. Bacteria pathogenic on wheat do not form spores; they survive only as vegetative cells. The polysaccharide exudate produced by some, notably *X. c.* pv. *translucens* serves to protect the cells from desiccation and ultraviolet light.

Bacterial pathogens of wheat survive poorly in soil away from crop debris. Bacterial cells free in soil probably survive only for a few days or weeks at most (2). Bacteria pathogenic to wheat survive for varying lengths of time on crop debris. Survival of *X. c.* pv. *translucens* is related directly to the rate of deterioration of the crop debris on which it resides (2, 23). In warm and humid climates, organic matter decays rapidly. Therefore as crop debris decays, the population of bacterial pathogens declines also. Even in semiarid temperate climates wheat debris does not usually persist for more than a year and pathogenic bacteria decline accordingly.

An experiment was conducted to determine the survival of *X. c.* pv. *translucens* in soil. Leefield sandy loam at pH 5.3 when collected from the field was adjusted to three higher pHs with lime. A suspension containing 10^7 colony forming units (cfu)/ml of the bacterium pathogenic to wheat and triticale was used to saturate air dry soil. The strain used was a mutant tolerant to the antibiotic rifampin to facilitate recovery. The soil samples were stored at 20 to 25°C in the laboratory. They were allowed to air dry, then rewetted to saturation during the course of the study. Periodically soil was removed from each treatment and planted on nutrient agar with 100 μg/ml of rifampin. The bacteria declined to undetectable levels within 14 days at pH 5.3 and 5.9 (Figure 1). The rate of decline was slower at pH 6.6 and 7.2, but after 14 days only 10^3 cfu/ml were detected. The experiment was repeated and *X. c.* pv. *translucens* did not survive beyond 14 days (Cunfer, unpublished).

A similar experiment using the same soils was set up to follow the survival of *X. c.* pv. *translucens* in leaf tissue. Triticale leaves with many lesions were air-dried and placed in moistened soil. Periodically leaf samples were removed and soaked in sterile saline. A portion of the bacterial suspension was plated on agar and another portion was injected into triticale leaves. In two tests, the leaf tissue decomposed within 57 days and *X. c.* pv. *translucens* could no longer be recovered from the soil (Table 2). Water suspensions injected into plants no longer induced symptoms (Cunfer, unpublished).

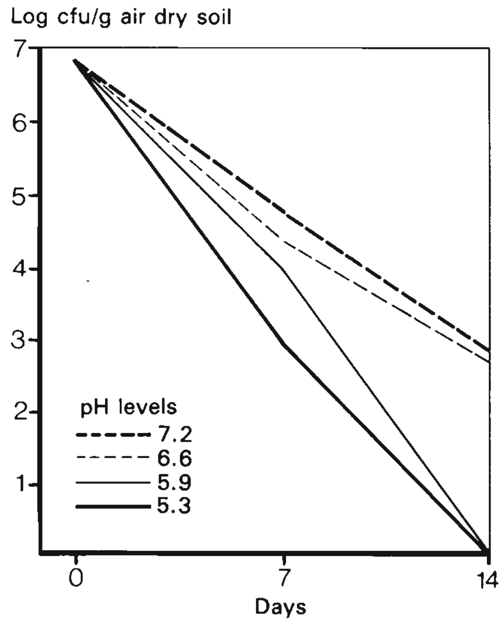

Figure 1. Survival of *Xanthomonas campestris* pv. *translucens* in soil adjusted to four pH levels.

An important means of survival that has gained recognition recently is epiphytic growth of bacterial pathogens on both host and nonhost species. Pathogen populations are maintained and may increase on leaf surfaces. This is the major means of inoculum increase for *P. s.* pv. *syringae*. Large populations build up on wheat leaves without causing disease. When mild wet conditions persist for several days, bacterial cells migrate into intercellular spaces through natural openings or wounds and multiply rapidly (13, 24, 25).

Epiphytic growth of bacteria on wheat may be important in another epidemiological aspect. *P. s.* pv. *syringae* and *X. c.* pv. *translucens* are ice-nucleating bacteria (23). This means their cells can serve as nuclei for ice crystal formation. There is evidence from growth chamber experiments that *X. c.* pv. *translucens* may cause wounds by initiating frost damage (1). This mode of invasion would only be likely to occur in highland areas where mild frosts may occasionally occur during the growing season. Infection initiated by frost damage could lead to rapid disease development, especially to the upper leaves and head if epiphytic populations are high.

Table 2. Survival of *Xanthomonas campestris* pv. *translucens* in diseased triticale leaves stored in soil at 20-25°C as determined by inoculation onto triticale and dilution plating on nutrient agar

	Days of storage			
	0	14	35	57
Inoculation	+	+	+	-
Cfu/g dry soil	10^{10}	10^{6}	10^{3}	0

+ = typical symptoms produced

Dissemination

Dissemination via seed is the most important means of widespread dispersal. In almost all cases bacterial cells are carried only externally on seeds. They may be disseminated over long distances on seed or in infested crop residue mixed with seed. Because of the difficulty in detecting bacteria on seed, especially at low populations, and the lack of identified genotype-specific races, there are few quarantine regulations specifically aimed at restricting movement of bacterial pathogens.

Because seedborne inoculum is an important means of long-range dispersal of several pathogens including *P. s.* pv. *syringae* and *X. c.* pv. *translucens*, methods to detect these bacteria are needed. One of the difficulties in studying the role of seedborne inoculum has been the lack of media selective enough to detect the low numbers of cells on seeds and to isolate them from the numerous saprophytic flora. In general, the saprophytes grow much faster in culture than the pathogens. Therefore, in routine isolations the pathogens are often overgrown by saprophytic bacteria and sometimes fungi. Several improved media for selective isolation are now available (21, 32).

Within a field, the major means of movement are by splashing rain or irrigation water (34). Overhead irrigation is most conducive for creating prolonged periods of high humidity and water-soaked conditions in leaves that favor disease development. Overhead irrigation is the primary factor in many recent outbreaks of bacterial stripe of wheat (N. W. Schaad, personal communication) and barley in the western USA (30). Furrow irrigation contributes somewhat less to the creation of optimum environmental conditions, but it can be more conducive to widespread dissemination particularly when excess water from a field with disease is subsequently used to irrigate additional fields (23). Bacteria may move from wheat or from weeds or other crop species to wheat (30).

Little is known about the role of insects in the dissemination of bacterial pathogens of wheat. Insects may be important when their populations are high and wet weather persists. It is unlikely that use of insecticides will provide a practical means to reduce spread of bacteria. Cultural practices will probably be more economical and practical.

Other cereals hosts and grassy weeds may be important inoculum reservoirs. A strain of *X. c.* pv. *translucens* from barley in India was virulent to rice. This bacterium and the bacterial stripe pathogen of rice, *X. c.* pv. *oryzicola*, are probably closely related (26). Therefore it is quite possible that *X. c.* pv. *translucens* may survive as an epiphyte or a pathogen on rice and be disseminated to wheat.

Losses to bacterial streak are infrequent and often imprecisely documented. Yield reduction can be considerable and may range up to complete loss. Losses on durum wheat from 20 to 100% were recorded in Syria (19). Yield losses up to 43% have been reported on triticale in CIMMYT trials in Mexico (14, 28, 42). Losses on triticale as great as 25% occurred in replicated field tests in Georgia, USA, when plants were inoculated prior to the heading stage of growth. When initial infection began at milk stage or later, no yield reduction occurred (Cunfer, unpublished). Improved methods for loss assessment are needed. The only assessment key currently available is from James (18).

Control

Seedborne inoculum is the most important means of dissemination of bacterial pathogens of wheat. Therefore seed certification programs whose emphasis is high seed quality should also include elimination of seedborne pathogens including bacterial pathogens. A standard protocol should include growing seed wheat on land with at least a one year rotation away from wheat. Seed wheat should be grown under nonirrigated conditions whenever possible. If the land is furrow-irrigated care should be taken to be sure incoming water has not passed through other wheat fields. Seed should not be grown under overhead irrigation.

Seed treatments have been only partially effective. Forster and Schaad (12) compared several inorganic heavy metal compounds and organic mercury treatments against *X. c.* pv. *translucens*. The only treatment completely effective was cupric acetate combined with hot water (33). This is a laborious method, but it can be effective for treating small lots of breeder's seed or seed lots being moved from one country to another. Antibiotic treatments have usually been only partly effective. They are expensive and use of products also used in medicine is unwise because of the possible development of resistance to human or animal pathogens.

Because organic matter decomposes quickly in the humid tropics, a 1-year rotation from wheat should be quite effective in reducing debris-borne inoculum. Because some bacterial pathogens such as *P. s.* pv. *syringae* can survive epiphytically, studies are needed on survival of wheat pathogens on rice or common weed species associated with the rice-wheat cropping system. This is likely to be an important inoculum source.

Resistance will be an important means of control. In order to assess resistance accurately, reliable inoculation methods are needed. An important factor is means to differentiate true susceptible reactions. *P. s.* pv. *syringae* has been the most difficult of the bacterial pathogens on wheat to test. A new procedure (36) should provide a reproducible method to evaluate lines for resistance accurately. Several months are available to test for resistance in the greenhouse and field (6, 20, 30). Because the bacteria pathogenic to wheat are easy to grow in vitro, large populations for inoculation can be increased within 24 hr or less. Inoculation methods for greenhouse tests usually involve infiltrating or injecting about 10^6 cfu/ml of the bacterium into watersoaked leaves. After a drying period plants are maintained at 10% relative humidity for 48 hr or longer. Field inoculations are more difficult, but methods to introduce the bacterium into wounds are usually part of the procedure. Hypodermic injection or scissors inoculation are effective but laborious. I have inoculated *X. c.* pv. *translucens* on wheat and triticale as well as *P. s.* pv. *coronafaciens* on oats and rye with a battery-powered grass clipper whose blades are constantly sprayed with a bacterial suspension (7). Portable "weed-eaters" have also been used successfully to introduce bacterial cells into leaf wounds. These methods can introduce the pathogen into susceptible tissue even when environmental conditions are less that optimum.

There has been very little research on the genetics of resistance to bacterial diseases of wheat. Resistance to *X. c.* pv. *translucens* has been identified (2) and resistance to *P. s.* pv. *syringae* has been found in a large number of wheats (24, 35). Because numerous strains can be found and the population of *P. s.* pv. *syringae* is so variable, genotype-specific races have not been identified.

It is likely that host range is controlled by one or a few genes. Cunfer and Scolari (6) compared numerous isolates of *X. c.* pv. *translucens* from triticale collected in the southeastern USA and Mexico that were also pathogenic to wheat. No evidence was found for designating races although significant differences in genotype susceptibility on triticale was found.

Bacterial diseases represent a significant threat to wheat production in the tropics. Accurate diagnostic methods to determine the importance of bacterial pathogens will be essential. Control will require use of resistant germplasm whenever possible, combined with appropriate cultural practices.

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Drought Tolerance in Bread Wheat — Analysis of Yield Improvement over the Years in CIMMYT Germplasm

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Abstract

An analysis concentrating on yield data from low-yielding, disease-free, drought stress environments from the International Spring Wheat Yield Nurseries (ISWYNs) and data from a comparative yield trial under full (600 mm) and reduced irrigation (300 mm) at Cd. Obregon in northwestern Mexico are given. Yield performance of the long-time checks Siete Cerros 66 and Inia 66 in drought-stressed environments is compared over the ISWYNs/years with:

- *the mean yield of all the entries included in the ISWYNs*
- *more recently released cultivars developed by CIMMYT*
- *locally developed, tall drought-tolerant cultivars.*

The results show that consistent progress in yield potential in drought-stressed environments was achieved over the last two decades with semidwarf materials that were selected under near-optimum conditions. The two check cultivars showed a high level of spacial and temporal yield stability in drought-stressed environments and gave higher yields than the tall, locally developed cultivars. More recently developed cultivars, representing the top group of high yielding, widely adapted CIMMYT wheats, performed better than the checks and older cultivars under virtually all situations including drought stress. These results indicate that high yield potential and input responsiveness can be combined in drought-tolerant materials. The findings are discussed in the context of different breeding approaches for drought-stressed situations, including CIMMYT's drought breeding approach.

Drought is a major production constraint on approximately 37% or 40 million ha of wheat area in the developing countries (10). In tropical environments, wheat, as a "cool"-season crop, will be grown predominantly under drought-stressed situations in rice-wheat rotations, generally on residually stored soil moisture, low precipitation, and supplementary irrigation, or their combinations. With a target area of 20 million ha in tropical environments, differences and improvements in water-use efficiency of the wheat cultivars grown will have a large impact on eventual production and on the feasibility of growing wheat in these nontraditional areas.

Since drought is affected by many biotic and abiotic factors, there are difficulties associated with the term "drought environment" (Table 1). The interactions between these many factors make it difficult to separate the individual effects, and create an infinite number of combinations that can be highly location-specific. The effects of heat and drought stresses can be confused with damage caused by such factors as nutritional problems and diseases. As a result, no universally acceptable definition of drought exists (9), and in the context of this paper, there can be no universally applicable analysis and investigation.

Concepts and Approaches

Based on Quizenberry (9), four types of environments can be associated with drought stress and water-use efficiency:

1) The stored moisture environment. The crop completes the entire life cycle on stored soil moisture.

2) The variable moisture environment. A rainfed drought stress environment with alternating dry and wet periods.

3) The reduced irrigation environment. Suboptimum irrigation causes drought stress. Since irrigation can be applied during critical stages of crop development, water-use efficiency can be maximized.

4) "Optimal" moisture environment. Usually optimum, but occasional drought stress can occur during short periods when evaporation greatly exceeds root uptake.

Table 1. Factors affecting drought stress

1. Water input
   - Precipitation: amount, distribution, yearly variability
   - Irrigation
   - Stored soil moisture

2. Relative humidity

3. Disease

4. Management (Agronomy): agronomic practices, fertilization, weed and pest control

5. Soil: type, depth, nutritional status

6. Temperature: mean, maximum, minimum, variation

Most plant breeders accept these classifications, but opinions differ as to whether these types of drought environments should:

- determine different appropriate breeding methodologies for varieties that are highly adapted to only one of the different moisture environments, or

- whether an integrated approach of developing multiple purpose varieties — broadly adapted varieties that are superior under both high yielding and drought stress situations — is suitable and possible.

CIMMYT follows the second plant breeding approach and frequently receives criticism because this approach excludes materials with a plant architecture normally associated with drought-stressed environments, namely tall and low tillering plant types. Major cultivars for semiarid rainfed conditions have evolved from high-yielding germplasm such as the variety Barani 83 in Pakistan. Also semidwarfs such as Veery and Flycatcher compete favorably with the adapted dryland wheats C 306 and Sujata under conserved moisture conditions in India (11). The Rht1 and Rht2 dwarfing genes, the basic sources for reduced plant height and high tillering capacity, are highly correlated with high yield potential and are present in all CIMMYT germplasm.

Results

This analysis of drought-stressed environments is based on data from the International Spring Wheat Yield Nurseries (ISWYN). Further, data from a comparative yield trial under full (600 mm) and reduced irrigation (300 mm) at Cd. Obregon in northwestern Mexico are presented.

The quality of ISWYN data from nontraditional tropical environments did not permit multilocational analysis, especially in earlier years. However, the results include commercially grown and potential varieties for the tropics such as Sonora 64, Inia 66, Jupateco 73, Pavon 76, the Veerys, Papagos 86, and Kauz. Therefore, the findings may be relevant for nontraditional wheat areas as well.

The ISWYN is a standardized international yield nursery consisting of three replications of 49 spring wheat varieties and advanced lines plus 1 local check representing the major spring wheat cultivars in developing countries. The ISWYN has been distributed by CIMMYT since 1964. In ISWYNs 1 to 20 (1964/65 to 1983/84), data from about 1300 locations were available. By assuming that drought stress seriously affected yield levels and by eliminating those locations with severe disease, this analysis has concentrated on low-yielding, disease-free locations where drought stress was reported, generally type 1 and 2 environments (1). The remaining sites underwent a screening for statistical parameters, for example, coefficients of variation, heritabilities, and genetic variances. Within mega-environments, such as the Subcontinent/Middle East/North Africa, across-site analyses with five or more ISWYN locations could be conducted only in 10 ISWYNs. Even concentrating on the best disease-free, drought-stressed sites, certain abiotic stresses such as heat stress could not be eliminated due to lack of information.

Figure 1 gives the yields of the long-time checks, Siete Cerros 66 and Inia 66, as a percent of the location mean in the drought-stressed locations of ISWYNs 4, 6, 10, and 13. The sites within one ISWYN are ranked by site means (X-axis).

In ISWYNs 4 and 6, Siete Cerros 66 and Inia 66 gave outstanding performances at all locations included in the analysis. The yields at specific sites were above average, and high yields across sites and in different years indicate a high level of spacial and temporal yield stability in drought-stressed environments — even considering that the high percentage yields and differences were associated with relatively small differences on an absolute scale.

Comparing the yield performance of these two entries over the ISWYNs/ years with the mean yield of all the 50 entries included in the trial (solid line) gives an indication of the breeding progress achieved. The mean yield of the checks decreased from an average 130% level in ISWYN 4 to an average 100% level in ISWYN 13. The drought tolerance of the average genotype in the set increased by 30% relative to these two entries.

The percent yield of the highest yielding entries under drought stress in each of the four ISWYNs is given in Figure 2. The respective highest yielding genotype outyielded Siete Cerros 66 and Inia 66 at nearly all the locations. The performance of the more recently released cultivars such as Jupateco 73 and Pavon 76 was above average at all locations, indicating a high degree of risk efficiency for these cultivars and a clear improvement over the two checks. Several other cultivars performed at approximately the same level as Jupateco 73 and Pavon 76 in the respective ISWYNs.

The performance of the semidwarf Siete Cerros 66 is compared to certain locally developed tall varieties, such as the cultivars C 306 from India, C 273 from Pakistan, and Gabo from Australia in ISWYNs 4 and 6 (Figures 3 and 4). The locally developed materials represent major cultivars for rainfed situations in their respective countries. Siete Cerros 66, which ranked second in the drought-stressed sites of ISWYN 4 and fourth in ISWYN 6, yielded better than the traditional tall cultivars in four of five locations in ISWYN 4 and four of six locations in ISWYN 6. In terms of yield stability, the broadly adapted variety Siete Cerros 66 showed high yield stability compared to the very specifically adapted tall types. At locations where the tall cultivars yielded better than Siete Cerros 66, high temperatures appeared to be a limiting factor.

The comparison between Seri 82, a cultivar of the 1980s, and Siete Cerros 66 is presented in Figure 5. High disease incidence, in general, is the reason for the large yield difference shown between Siete Cerros (1 t/ha) and Seri 82 (4.5 t/ha), since low-yielding, drought-stressed environments do not provide the potential for yield differences of any

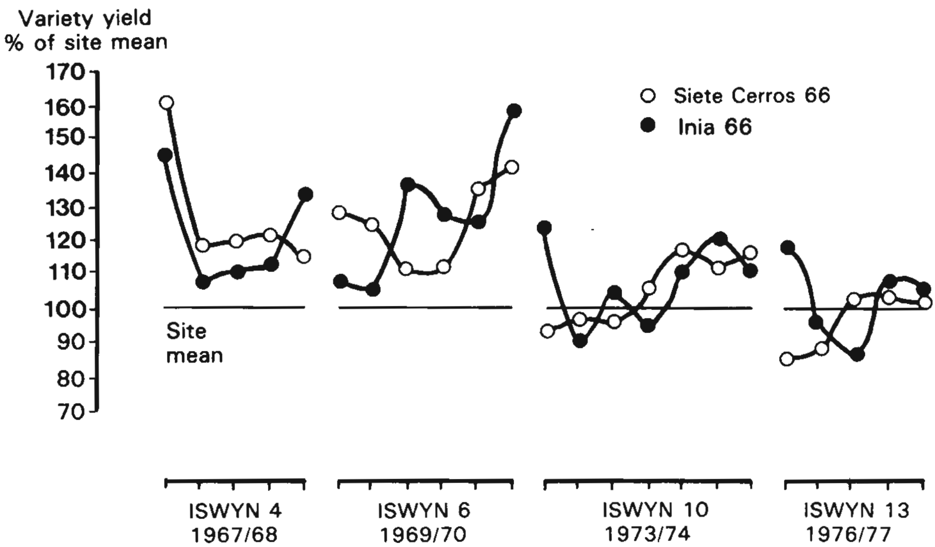

Figure 1. Yield of Siete Cerros 66 and Inia 66 in drought-stressed environments of ISWYNs 4, 6, 10, and 13.

great magnitude (2, 7, 8). The open circles in Figure 5 represent the locations where drought stress was reported, obviously most of these locations are medium to high potential sites — suggesting that drought is not necessarily associated with low site mean yields.

Concentrating on low-yielding sites where Siete Cerros 66 yielded up to 3 t/ha, Seri 82 performed equally or higher in 19 of 20 locations. The comparison with Pavon 76 gives a similar result (Figure 6), however it is less dramatic. Pavon 76 has about the same level of disease tolerance as Seri 82, therefore, the yield differences at disease-stressed, low-yielding sites are smaller. But Figure 6 indicates a clear advantage of Seri 82 over Pavon 76 at locations where Pavon 76 yielded up to 3 t/ha.

Figures 5 and 6 demonstrate that the more recently developed materials are outyielding the older check varieties in virtually all situations.

Results obtained in 1986 in comparative yield trials under full and reduced irrigation at Cd. Obregon, Sonora, have to be interpreted in the same way (Figure 7). The entries included in the experiment were released between 1962 and 1986 for the Yaqui Valley, Mexico's major wheat area. One entry is a candidate for release in 1987.

Figure 7 gives the individual yield of the cultivars under the two different moisture regimes, i.e., with approximately 600 mm and 300 mm of applied water. The cultivars were divided in three groups: those

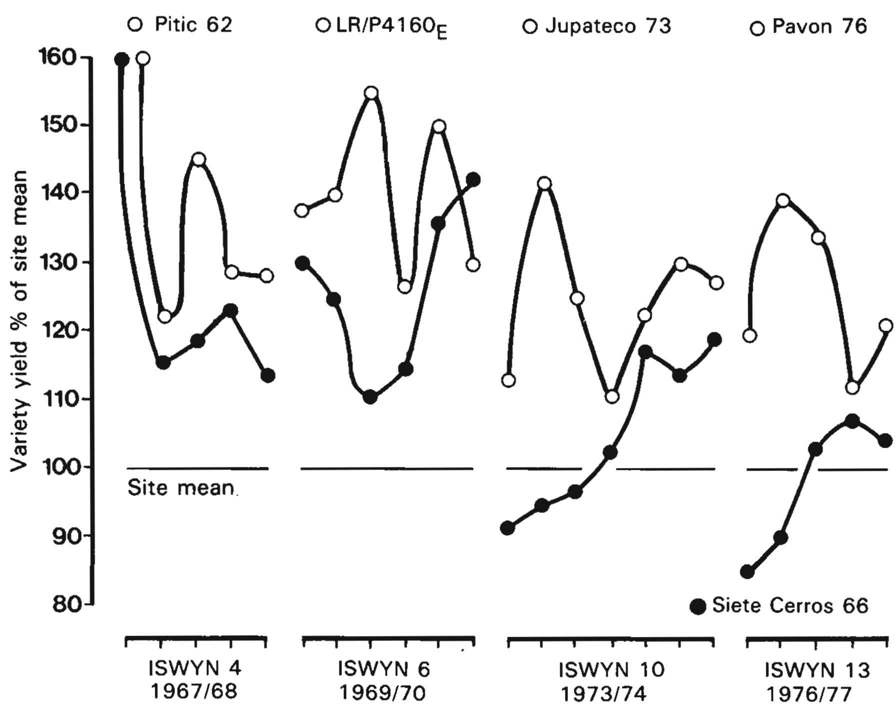

Figure 2. Yield of the respective top yielding entry compared to the yield of Siete Cerros 66 in drought-stressed environments of ISWYNs 4, 6, 10, and 13.

released from 1962-1970 (group I); 1971-1980 (group II); and after 1980 (group III). Due to average monthly temperatures up to 6°C above the long-term mean, the trial suffered from heat stress during the 1985/86 season.

The results show that progress, measured by increasing group means (line), was achieved from group II over group I and group III over group II under optimum moisture and reduced moisture regimes. The progress achieved under near optimum conditions was associated with higher yields under reduced irrigation as well. The top-yielding entries, Kauz and Ures 81, which ranked 1st and 2nd under the two different moisture situations, respectively, demonstrate that high yield potential under optimum conditions can be combined with high yield performance under reduced water supply.

Analysis of 20 years of ISWYN data (2, 7, 8) indicates that all varieties and lines identified with outstanding performance under drought stress are also widely adapted types. These materials gave superior yields across all locations, including high-yielding environments. Each of these varieties is grown on more than 1 million ha in developing countries, including major cultivars such as Siete Cerros 66 (Kalyansona, Mexipak) in the Indian Subcontinent, Jupateco 73 and its sister lines Anahuac 75 and Cocoraque 74 in Brazil, and the Veery selections that have been released in 20 countries under 27 different names. Since all these cultivars were developed under optimum water regimes, there is a strong likelihood that CIMMYT's breeding methodology utilizing shuttle breeding between diverse sites has enhanced the utility of the germplasm in a wide range of conditions.

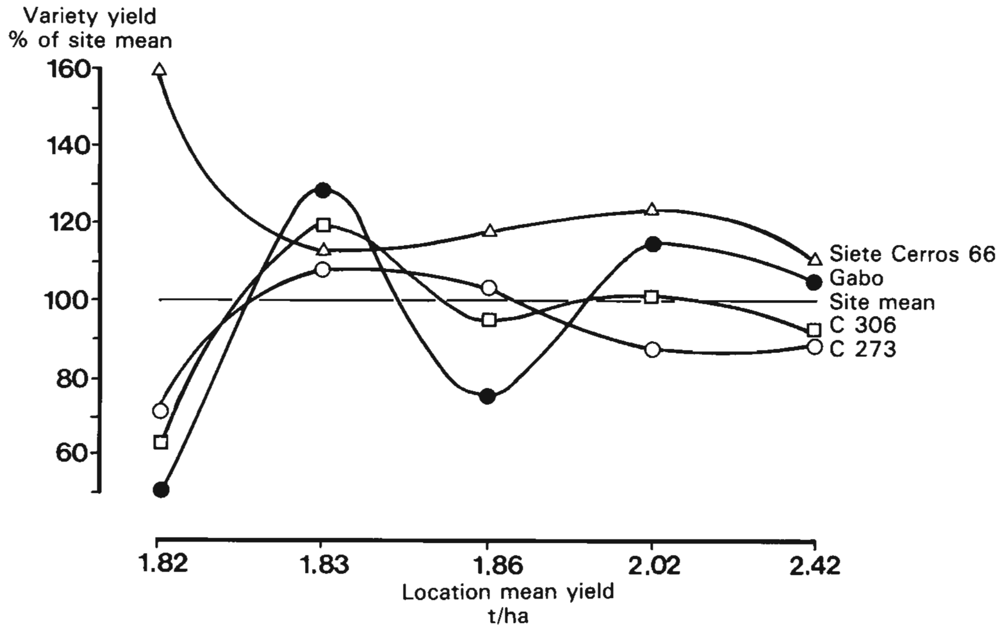

Figure 3. Yield of Siete Cerros 66 compared to the yield of C 273, C 306, and Gabo in drought-stressed environments of ISWYNs 4, 1967/68.

The occurrence of occasional periods of heat and drought stress at Cd. Obregon, a type 4 environment, plus the utilization of reduced irrigation trials, a type 3 environment, might differentiate genotypes according to water-use efficiency. In addition, testing in diverse locations facilitates the identification of genotypes that are high yielding and well adapted to various environmental conditions, including optimum, intermediate, and drought-stressed conditions, plus a wide range of biotic and abiotic stresses.

A better measure of the selection efficiency of CIMMYT's methodology is indicated by the correlation of r=0.773** between the yields of these varieties in high-yielding locations and their yields in drought-stressed locations across eight ISWYNs, including all entries, those developed by CIMMYT as well as materials developed by national programs.

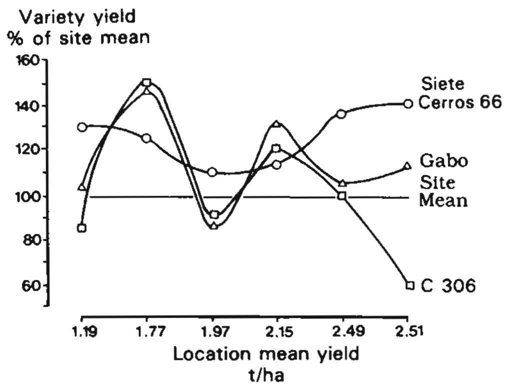

Figure 4. Yield of Siete Cerros 66 compared to the yield of C 306 and Gabo in drought-stressed environments of ISWYN 6, 1969/70.

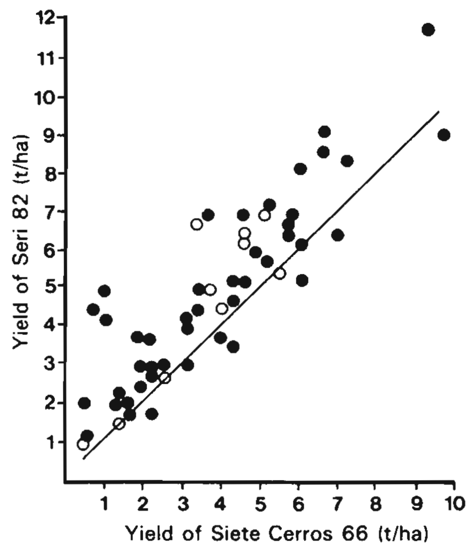

Figure 5. Yield of Seri 82 regressed over the yields of Siete Cerros 66 at 55 locations in the 20th ISWYN. The solid line has a slope of 1.0 (yield of both cultivars is equal). ○ = locations of reported drought stress.

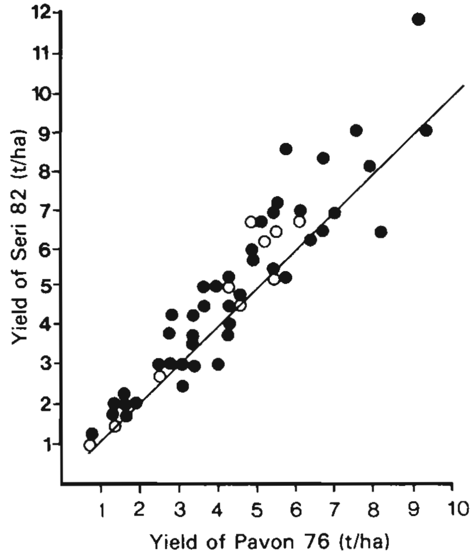

Figure 6. Yields of Seri 82 regressed over the yields of Pavon 66 at 55 locations in the 20th ISWYN. The solid regression line has a slope of 1.0 (yield of both cultivars is equal). ○ = locations of reported drought stress.

Further, the results demonstrate that progress was achieved over years in phenotypically similar, semidwarf materials that were selected under near-optimum conditions. This confirms the validity of selecting germplasm for drought-stressed conditions under optimum water situations. This method is gaining popularity in plant breeding programs in developing and developed countries, since it overcomes the problems associated with breeding under drought stress, namely, low heritabilities and low genetic variances. Genetic variances are usually high under favorable conditions and the genetic advance is greater (Tables 2 and 3). Further, under natural conditions when the amount of stored moisture or precipitation changes, the environment selection index also changes. Heritabilities and selection gains are extremely low, and so is the effectiveness of selection.

However, we do not ignore the fact that traditional drought-tolerant cultivars are generally later in flowering and maturity, taller in plant height, and lower in tillering than cultivars with high yield potential. The wheat areas where such cultivars are grown prove their suitability. In several breeding programs, selection for drought-tolerant materials is performed exclusively under drought stress, and scientists approach this objective by selecting for mediocrity or even low yield and for characters that decrease yield (3, 4, 5, 6).

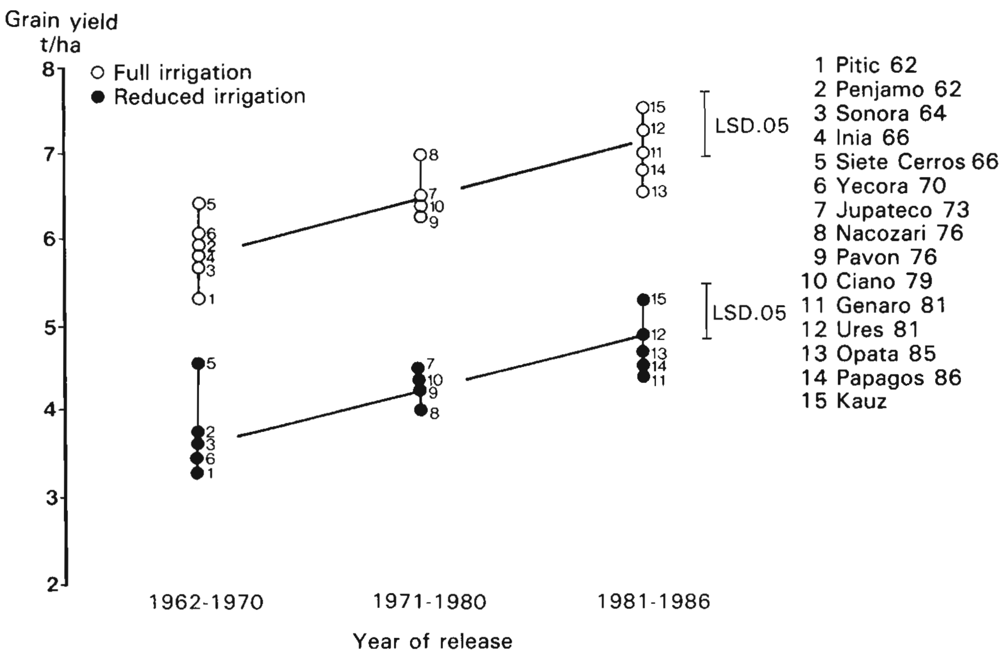

Figure 7. Yield of commercially grown semidwarf cultivars released during the period 1962 to 1986 under full and reduced irrigation at CIANO, Cd. Obregon, Sonora, Mexico.

However, there is now sufficient scientific evidence to suggest that high yield potential and input responsiveness can be combined in drought-tolerant materials. In fact, C 306 and C 273 were originally developed for the irrigated areas of the Punjab in the Subcontinent.

CIMMYT's Breeding Efforts

To take both approaches into account, CIMMYT utilizes traditional tall, drought-tolerant types in crosses with widely adapted, high-yielding germplasm. The variability in these F_2 populations allows national programs to select for the preferred plant types.

Table 2. Correlations between location means and statistical parameters in ISWYNs 1-15

Location mean: genetic variance	r = 0.48**
Location mean: error term	r = 0.50**
Location mean: CV	r = -.54**

At CIMMYT's base program in Mexico, the selection and testing procedures for breeding drought-tolerant wheats are oriented on a strategy to develop input-efficient germplasm for drought-stressed situations with high input responsiveness. Whenever environmental conditions become more favorable, increased inputs in terms of water and nutrients should be transformed into high absolute yields.

To achieve this objective, CIMMYT's Wheat Breeding Program recently redesigned and modified its selection and breeding methodology for drought (Table 4). Based on the assumption that different traits are controlled by different genes or gene systems and that they can be selected independently (9), a physiogenic approach with the combined use of optimum and drought-stressed environments may lead to materials with better drought tolerance than can be obtained from the two classical methods mentioned earlier. Germplasm emanating from this selection system will be

Table 3. Statistical parameters in high yielding, drought stressed, and disease free, low yielding locations in ISWYNs 1-15

Environment	Genotype X environment interaction (GE)	Genetic variance Abs.	Genetic variance % of GE	Heritability
High yielding	42.3	56.1	132.7	89
Drought stressed	18.2	18.8	87.0	76
Low yielding	15.4	10.6	69.0	74

distributed internationally for the first time in 1988 and several additional years of evaluation will be required to determine if this methodology is more efficient in identifying drought-tolerant wheats with responsiveness.

Conclusions

We will continue to use high-yielding, widely adapted germplasm as the basis for our breeding efforts and strive to add specific characteristics such as tolerance to drought and heat in order to better target our germplasm. This combination of high yield potential and wide adaptation guarantees maximum spatial, temporal, and system-independent yield stability.

We will continue to develop germplasm for various agroecological zones, combining resistance or tolerance to all limiting biotic and abiotic constraints. In this context, combinations of characters such as tolerance to heat, rusts, helminthosporium and fusarium, appear to be more desirable for increasing production under drought-stressed situations than a separate drought breeding program with selection of pre-defined plant types, especially in the case of tropical growing areas.

A change in selection criteria and methods in the near future is unlikely; so far there are no guidelines for selecting specific physiological traits, even though quite a number of characters have been associated with drought tolerance and water-use efficiency. However, the practical situation requires more emphasis on an interdisciplinary approach to exploit the given potential of drought-stressed environments.

For the near future, we must thoroughly evaluate the physiogenic approach. In addition, key locations for drought screening need to be identified that maximize selection gains. The next step would be the

Table 4. Breeding methodology for drought-tolerant wheats in CIMMYT

	Selection condition	Location	Selection method
F_2	Full irrigation	Obregon	Individual plants
F_3	Semi-arid rainfed	Huamantla	Modified bulk
F_4	Reduced irrigation	Obregon	Modified bulk
F_5	Well watered	Toluca	Individual plants
F_6	Full irrigation	Obregon	Bulk harvest of uniform lines
LA	Multilocation testing of advanced lines under drought at Huamantla and disease at Toluca, El Batan, and various other sites in the central highlands of Mexico		
LA-PC	Yield trial under full and reduced irrigation plus screening under disease and terminal heat stress at Cd. Obregon. Multilocation testing in the lowlands of northern Mexico		

establishment of shuttle breeding programs utilizing those key locations. Further, experimental procedures to test for drought tolerance need to be improved. In a final stage, an international drought yield nursery involving key locations should be established to quantify the drought tolerance of this improved germplasm. CIMMYT and national programs will need to play a significant role in this endeavor.

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Advances Made in Developing Wheats with Better Aluminum Toxicity Tolerance in Brazil

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Abstract

The great majority of the Brazilian soils under wheat cultivation have low pH, a high level of toxic aluminum, and low phosphorus concentration. The toxic aluminum interferes in the growth of the plants, causing a physiologic abnormality called "crestamento." All Brazilian wheat varieties released for this soil type (Latosol) are tolerant to aluminum toxicity. The soil problems and the high incidence of diseases are limiting factors for wheat production. Lime application to eliminate aluminum toxicity increases soil productivity. Several Brazilian institutions are developing aggressive breeding programs, thus greatly contributing to higher and more stable wheat productivity. Many steps characterized the evolution of the Brazilian wheats and, among these, the introduction of Mexican wheats was of relevance. In the last few years, because of new improved cultivars, grain yields as high as 5000 kg/ha have been obtained under experimental conditions in acid soils. Under field conditions, yields as high as 2500 kg/ha have been achieved in those areas where recommended technologies are applied. In limed soils under irrigation, grain yields as high as 7000 kg/ha from Mexican wheats are possible.

The history of wheat (*Triticum aestivum* L.) in Brazil begins with the country's discovery in the 16th century. The crop was introduced by the first colonizers and spread throughout the country as it was being occupied. Since then, wheat has faced favorable periods followed by periods in which it almost disappeared from Brazilian agriculture, due mainly to diseases. The consolidation of the crop occurred after 1922. In the last 10 years, wheat has occupied an average area of 2.83 million ha distributed among three major climatic regions: the southern region, with a temperate climate, comprising the states of Rio Grande do Sul and Santa Catarina and the south of Paraná (main production region); the central western region, subtropical, represented by the north and west of Paraná, the south of Mato Grosso do Sul and the southwest of São Paulo; and the central plateau (Cerrados), comprised of the states of Goiás, Minas Gerais, Bahía, Mato Grosso, and Distrito Federal. The Brazilian wheat area is located between 11 and 32° south latitude and 40 and 56° west longitude (Figure 1). The altitude varies from 50 masl in Rio Grande do Sul State to 1000 masl in the Cerrados.

In spite of advances achieved during the last few years, wheat productivity in Brazil is still low and unstable. The average yield of the past 10 years has been 955 kg/ha. Figure 2 shows the average Brazilian wheat productivity from 1963 to 1986, demonstrating a great yield variation from one year to another. There are several factors responsible for this low yield. The climatic instability of the country contributes in some years and in some regions to high incidence of fungal, viral, and bacterial diseases. Another limiting factor of utmost importance is the naturally low soil fertility, normally deficient in phosphorus, potassium, and some microelements. Soil pH values are low, between 4.0 and 5.5 on the average, with high contents of toxic aluminum and manganese. These factors occur on 70% of the area under wheat cultivation in the country, mainly where Latosols (Oxisols) predominate. It is important to emphasize that an additional 180 million ha is still available for agricultural production in Brazil, mainly in the Cerrados region, where wheat could be one of the crops grown, but with similar problem soils.

Toxic Aluminum

The presence of toxic aluminum (or exchangeable aluminum, or toxic acidity) in many of the Brazilian soils, added to the high manganese levels in some areas, produces a complex in the soil that partially inhibits the growth of many cultivated species, including wheat. Besides inhibiting the growth of the wheat plant, especially the roots, but also the above-ground parts, toxic aluminum interferes in the absorption and movement of phosphorus, calcium, magnesium, molybdenum, and other micronutrients. The high chemical affinity between calcium and phosphorus, at pH values between 4.0 and 5.0, combined with a high concentration of calcium, greatly decreases the availability of the phosphorus, resulting in a poor absorption by the plants. The free aluminum in the soil ties up the P, causing low availability to the plant. The aluminum level in Brazilian soils varies from 0 to 6 mE/100 g of soil. On the average, a low value is considered below 0.3 mE/100 g, an intermediate value between 0.3 and 1.0 mE/100 g, and a high value above 1.0 mE/100 g. The great majority of the soils are classified within the high toxic aluminum level.

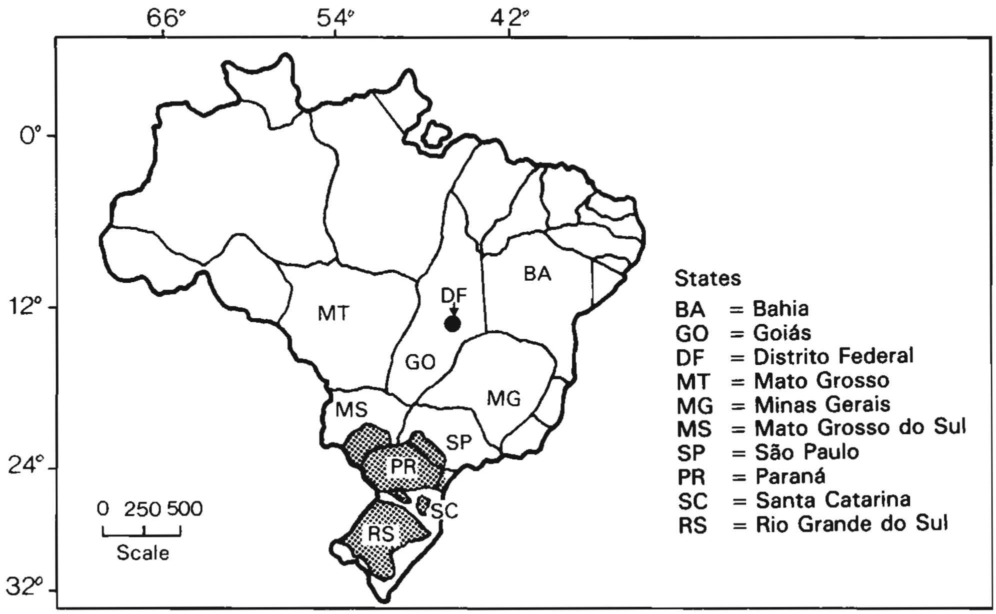

Figure 1. Brazilian wheat producing states. Shaded regions show high production areas.

Economically, enhancing root exploration in this kind of soil can only be done by correcting the pH to levels of 5.5 to 6.0 in order to eliminate the free aluminum. This is normally accomplished by incorporating limestone into the top 20 cm of the soil (liming).

Wheat plants cultivated in acid soils demonstrate very well defined symptoms. In the roots, the main effect of toxic aluminum is the cessation of growth, due to the absence of cellular division, making them short and thick with a dark color. The growth interruption of the main roots induces the development of tertiary and quaternary roots. When aluminum concentration in the soil is low, typical symptoms may be observed only in the roots. A reduced root system results in reduced absorption of nutrients and soil water, since the soil volume that the roots can explore is greatly reduced.

Besides affecting the absorption and translocation of nutrients and water, the toxic aluminum also limits the metabolism of the nutrients. Depending on the level of toxicity, aerial symptoms are characterized by reduced plant growth, yellowing of leaves, and a purplish color in both culms and leaves. Manganese, common in many Brazilian acid soils, also may cause toxicity to wheat when found in high concentrations. However, its effect is considered of lesser importance in comparison to that caused by aluminum. It has been determined that manganese tolerance is genetically independent of aluminum tolerance in wheat. Liming the soil to increase the pH to 6.0 eliminates the toxicity of both elements simultaneously.

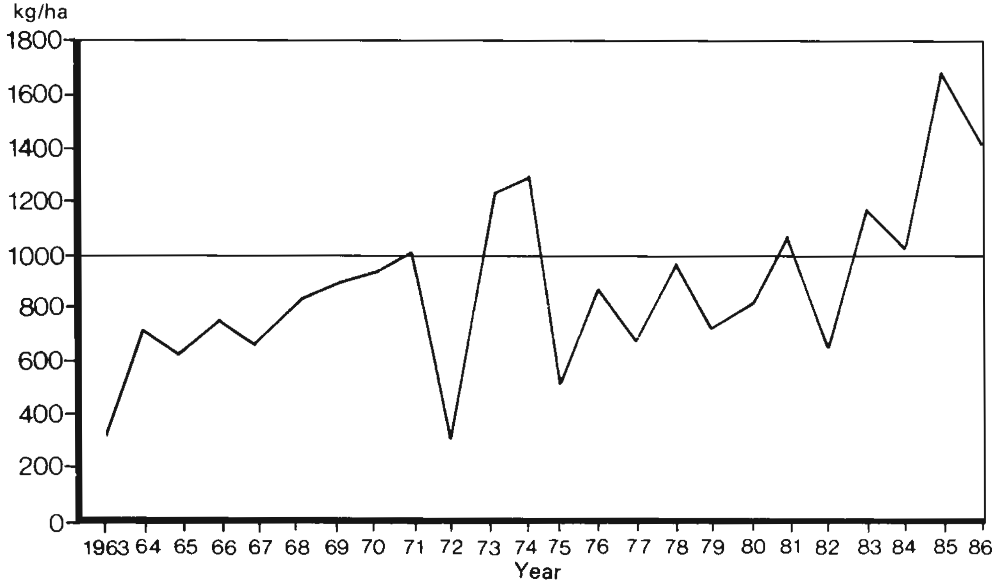

Figure 2. Average Brazilian wheat productivity from 1963 to 1986.

Genetic Varietal Improvement

Wheat varietal improvement in Brazil began in 1914 with the selection of the cultivar Polyssu in Paraná State, from materials selected under acid soil conditions in Rio Grande do Sul State. Systematic work on wheat improvement began in 1919, when the first experimental stations were founded. The basic improvement method consisted of selection of superior types from mixtures of wheats of unknown origin that were being cultivated. The pure line method was also used.

The first significant differences between wheat varieties cultivated in acid soils were detected in 1925. Due to the classical symptoms of yellowing and underdevelopment of the plants, aluminum toxicity was called "crestamento" in Brazil. In that year, hybridizations were done between resistant Alfredo Chaves' lines and the variety Polyssu, giving origin to the first Brazilian wheats with tolerance to aluminum toxicity — Fronteira, Surpresa, Minuano, Jesuita, Guarani, and Navilar. These cultivars were the base of the whole Brazilian wheat improvement program. All subsequently released cultivars were tolerant to aluminum toxicity. The above-mentioned cultivars, released in the 1930s, were characterized by a long cycle, tall stature, weak straw, low kernel weight, susceptibility to rusts, and high tolerance to crestamento. Their production potential, according to some authorities and considering the technology used at that time, was around 650 kg/ha. In experiments conducted in Rio Grande do Sul in the period 1939-42, the variety Fronteira yielded 799 kg/ha.

A new advance in Brazilian wheat production occurred in 1942 with the release of the cultivar Frontana, initiating an era of early-maturing materials, more resistant to the rusts, with shorter plants and an average productivity of 850 kg/ha. Frontana, even though cultivated for many years, had a lower tolerance to aluminum toxicity than the previously released cultivars.

Paiva, in 1942, was the first to investigate the cause of crestamento, attributing it to the high soil acidity. Araujo (1), in research conducted from 1948 to 1951, determined with precision the cause of crestamento, associating it with the presence of toxic aluminum in the soil (1).

The first indication that tolerance to toxic aluminum was a heritable characteristic that could thus be transferred through breeding came from Beckman (2). His studies, and those of others, showed that resistance was dominant and possibly controlled by a gene pair. According to Nodari (3), tolerance to crestamento seems to be differentiated by two independent loci.

In 1956 and 1957 the early varieties Preludio and Carazinho were released. These varieties had average yields of 1000 kg/ha and had better resistance to leaf rust and aluminum toxicity. Both varieties became very popular among wheat growers.

In the 1960s, a group of varieties was recommended that maintained the original rusticity and adaptation, but had better agronomic characteristics. Among them, IAS 20-Iassul became one of the most widely cultivated varieties. With these varieties the yield potential increased to 1400 kg/ha.

Starting in 1968, the increase in soybean (*Glycine max* L. Merrill) production from the wheat-soybean double cropping systems brought about two main consequences. The first was the need to lime the soil to correct the pH, the toxic acidity, and the soil fertility in order to allow efficient root exploration by the leguminous plant. Lime and fertilizer applications increased soil fertility, thus contributing to increased productivity of the wheat crop. The second consequence involved the type of wheat variety used in double-crop systems. The late-maturing varieties were abandoned, and since that time the cultivation of early maturing wheat varieties has predominated.

Liming the soil does not eliminate the need to maintain varietal tolerance to aluminum toxicity. Once lime is applied in the top 20 cm of the soil layer, the remaining soil below this layer still contains toxic levels of aluminum. When sown in limed soils, susceptible varieties develop their root system only in this superficial layer, resulting in inefficient absorption of nutrients, and increased vulnerability to water deficiency.

In the late 1960s and early 1970s, germplasm exchange was initiated between CIMMYT and some Brazilian research institutions, such as FECOTRIGO (Federation of Wheat and Soybean Cooperatives) and EMBRAPA (Brazilian Enterprise for Agriculture and Livestock Research). The main objective of this work, which was intensified in 1973, was to combine the aluminum toxicity tolerance of the Brazilian wheats with the high-yield potential of the Mexican germplasm.

The Brazilian wheat varieties, even though improved over the years, were still low-yielding, too tall, and deficient in agronomic characteristics such as spike fertility and straw strength. The material developed through the utilization of mainly Mexican germplasm, greatly contributed to increased wheat production. The average yield in experimental trials in Rio Grande do Sul during this period was 1600 kg/ha. In the last 5 years, average yield has increased to 1750 kg/ha.

In the commercial fields of Rio Grande do Sul, the largest wheat producing region during the last 35 years, the average yield has increased gradually and constantly (Table 1). Better varieties, along with more efficient agronomic practices, have contributed to more stable wheat production. On the average, the increase in productivity during this period was 25%.

Methodology

The Brazilian cultivars are, in general, tolerant to aluminum toxicity. This tolerance enables them to be successfully cultivated in areas with toxic acidity. However, when the free aluminum exceeds a certain level, no cultivar produces satisfactorily, and correction of the soil pH with liming becomes essential.

Constant germplasm introduction, on a worldwide basis, must be accompanied by vigilance in the selection process in order to maintain the tolerance level needed for Brazilian conditions.

Basically, two methods are used in Brazil to maintain this tolerance to aluminum toxicity. The first is that used by the majority of breeding programs, consisting of evaluation and field selection of resistant genotypes. The second uses a preliminary evaluation in the laboratory with a nutrient solution containing aluminum, followed by field evaluation.

The first and most widely used method is described below:

- In the crosses, at least one of the parents must be aluminum tolerant.
- The F_2 generation, or the F_3 in some cases, is space-planted in acid soils to allow selection of individual plants that are tolerant to free aluminum. The selection procedure may be in bulk, individual plants, or through individual spikes.
- F_3, F_4, F_5, and F_6 generations are sown in limed soil, either as bulks, plant rows or head rows, depending on the selection method used.
- Selected advanced lines are included in preliminary yield trials either in limed or acid soils to confirm their tolerance. Normally, the percent of those discarded due to susceptibility at this stage is very low, proving the efficiency of the method.

Field reaction is evaluated twice, at the end of the tillering stage (Stage 4 of Feekes Scale), and at the beginning of the heading stage (Stage 10.1 of Feekes Scale). With more experience, only one evaluation, at the heading stage, may be sufficient. When advanced, fixed lines are under test, at least two replications must be utilized to avoid errors caused by soil variability. When testing segregating materials (not possible to have replications), it is advisable to use larger populations (4 to 10 rows of 5 m).

Table 1. Evolution of wheat productivity in Rio Grande do Sul from 1950 to 1985

Period	Average area under cultivation (ha)	Average yield (kg/ha)	% Increase	Maximum yields (kg/ha)
1950-59	804,888	710	—	842 (1953) 918 (1955) 951 (1956)
1960-69	706,481	752	6	956 (1962) 878 (1968) 994 (1969)
1970-79	1,661,567	819	15	1119 (1973) 1079 (1974) 1210 (1978)
1980-85	1,006,324	887	25	1225 (1981) 1114 (1983) 1042 (1985)

All field evaluation is visual. Normally the aerial parts of the plant are considered, and, if necessary, the roots may also be observed. Plants are evaluated according to the scale shown in Table 2.

The second method, used in the state of São Paulo, involves a combination of field and laboratory evaluation. It consists of testing populations in the second generation (F_2) in nutrient solution containing an aluminum concentration of 6 mg/liter, at a constant temperature of 25°C. Tolerance is evaluated by the capacity of the primary roots to continue to grow in a solution without aluminum after remaining for a 48-hour period in the aluminum solution. The tolerant plants are then transplanted to the field. To confirm the laboratory selection, the tolerant material is sown in soil with toxic levels of aluminum for one generation, and then in limed soil until the end of the selection process.

Fixed material is normally tested in nutritive solution to confirm tolerance.

The CIMMYT-Brazilian Research Institutions Cooperative Program

The strong germplasm exchange between Brazilian research institutions and CIMMYT has enabled the introduction of thousands of lines and segregating populations for the various research programs of the country. Segregating populations from crosses between Brazilian and Mexican wheats are tested in Mexico in nutrient solution containing aluminum. The tolerant materials based on evaluation of the root system are selected and distributed to the various Brazilian programs to be field-tested in acid soils. Plants tolerant to aluminum toxicity, or tolerant populations, are selected and sent to Mexico to be sown in Ciudad Obregon in the same year, thus enabling two generations per year. Also, simultaneous to the

Table 2. Evaluation scale for aluminum toxicity resistance

Grade	Reaction Type	Symptoms
1	R = Resistant	Lack of toxicity symptoms.
2	MR = Moderately Resistant	Plant growth slightly reduced; normal heading; slight yellowing of leaf tips; roots slightly deformed.
3	MS = Moderately Susceptible	Reduced plant growth; thin culms; reduced tillering; small spikes; yellowing of leaves; stubby short roots.
4	S = Susceptible	Deformed plants; purplish, yellow or necrotic leaves; lack of tillering; very small spikes (3 to 4 spikelets); roots completely deformed, stunted.
5	HS = Highly Susceptible	Death of plants or plants completely rachitic, without spike formation; small necrotic leaves; root system almost absent.

Brazilian planting, the same material is sown in Toluca, Mexico. In Brazil, when plants reach the full tillering stage, they are evaluated and the results are immediately sent to CIMMYT for use during the selection in Toluca, as well as in new crosses. Until homozygosity is reached, selection is done alternately in both countries.

This process has many advantages: in Mexico selections are made mainly for agronomic type, resistance to stem rust (*Puccinia graminis* f.sp. *tritici*), leaf rust (*P. recondita*) and stripe rust (*P. striiformis*); in Brazil, tolerance to aluminum toxicity is identified, and selections are made for the naturally occurring disease complex, principally spot blotch (*Helminthosporium sativum*), leaf blotch (*Septoria tritici*), glume blotch (*S. nodorum*), and scab (*Gibberella zeae*).

Due to the adverse conditions, the great majority of the tested material is discarded for its susceptibility to aluminum toxicity and/or various diseases. However, after analyzing the hundreds of lines selected over the years, we have concluded that the final result is highly positive. It is important to emphasize, from the Brazilian point of view, that two important aspects have resulted from this alternate selection process, 1) better agronomic types (reduced height, stronger straw, and larger spike size) and 2) better levels of resistance to diseases that are important in southern Brazil, e.g., septoria, have been identified. The material obtained thus far, if not used directly, has been of great importance for the breeding program.

Recently, several cultivars obtained through this alternate selection method were recommended for cultivation in several Brazilian states (Table 3).

Many Brazilian research institutions use Ciudad Obregon to obtain an additional generation of materials from their wheat improvement programs through CIMMYT's cooperation.

Current Situation

Even though we still have a long way to go, our current status demonstrates the viability of wheat in Brazil. The new cultivars and lines are producing, in field experiments, yields higher than 4000 kg/ha and, in some cases, higher than 5000 kg/ha. Tables 4-8 show, by state and region, the yield performance of some new varieties recommended for cultivation in 1985 and the better advanced lines being tested. The data represent state or regional averages. In some locations, as shown in Figures 3-7, higher yield values have been obtained. Many of these new advanced lines and cultivars respond better to higher amounts of fertilization, thus increasing their productivity levels.

Another aspect to consider is irrigation, currently available only in certain areas of central Brazil, São Paulo, and Mato Grosso do Sul. The high-yielding Mexican varieties can be grown on the acid soils of the Cerrados that have a low aluminum level with liming and under irrigation. Under these conditions, average yields of 5000 kg/ha or above have been obtained (Table 9). In 1985, some lines yielded as high as 7220 kg/ha (Figure 8).

Even though the level of resistance or tolerance to the main diseases has been increased, it is still necessary to apply fungicides to achieve effective control of the main diseases, in order to guarantee higher yields and production stability.

The utilization of all recommended technologies has enabled many wheat growers to obtain yields higher than 2500 kg/ha in acid soils, after adequate liming and fertilization.

To further improve the productivity levels, the following objectives are being considered by the various wheat improvement programs:

- Increase the resistance or tolerance level to scab (*G. zeae*), spot blotch (*H. sativum*), yellow leaf spot (*H. tritici repentis*), leaf blotch (*S. tritici*), glume blotch (*S. nodorum*), black chaff (*Xanthomonas translucens*), bacterial leaf blight (*Pseudomonas syringae*), barley yellow dwarf virus (BYDV), leaf rust (*P. recondita*), and stem rust (*P. graminis tritici*).
- Identify cultivars with tolerance to frost, which is very common in southern Brazil.
- Identify cultivars with a greater capacity to extract phosphorus. Research has shown genetic differences among genotypes in extracting this element from the soil.
- Maintaining the aluminum toxicity tolerance level.

Table 3. Some cultivars obtained through alternate selection at Brazil and Mexico and recommended for cultivation in several Brazilian states

Name of variety	Cross and Pedigree
CEP 13-GUAIBA	PAT 19/ALONDRA"S"//GABOTO/LAGOA VERMELHA F11860 F500-900Y-312Z-0A-0Y
MG 1	IAS 64/ALDAN"S" CM 47207-16M-2Y-3F-704Y-7F-700Y
OCEPAR 8-MACUCO	IAS 64/ALDAN"S" CM47207-6M-103PR-2T-0T
OCEPAR 9-PERDIZ	IAS 58/BJY"S"//BNQ CM47971-A-4M-105PR-2T-0T
OCEPAR 10-GARCA	IAC 5/ALDAN"S" CM46961-16M-109PR-IT-0T
OCEPAR 11-JURITI	IAC 5/ALDAN"S" CM46961-16M-113PR-1T-0T
OCEPAR 12-MAITACA	PF 71124/PAT 72162 B 13707-0A-0Z-0L-0M-1L-0P
OCEPAR 13-ACAUA	IAC 5/3/IAS 20/PATO B//BB/INIA B 1442-0M-1T-2T-0T
TRIGO BR 14-THORNBIRD	IAS 63/ALONDRA"S"//GABOTO/LAGOA VERMELHA Mixture of the lines PF 79765, PF 79767, PF 79780, PF 79782, and PF 79791
TRIGO BR 16-RIO VERDE	PF 70402/ALONDRA"S"//PAT 72160/ALONDRA"S" B 19789-H-508M-1Y-10F-701Y-1F-700Y

Table 4. Yield performance of some recommended cultivars and promising lines in Rio Grande do Sul State in 1985

Material		kg/ha	% of MINUANO 82
Recommended Cultivars:			
CEP 11	PF 6968*2/HADDEN B 11950-4Z-1A-1A-0A	1927	120
CEP 14-TAPES	PEL 72380/ATR 71 B 13374-3Z-1A-6A-2A-0A	1925	120
R S 1-FENIX	PF 70100/J 15157.69	1724	105
R S 4-IBIRAIARAS	IAC 5/S 76	1671	101
TRIGO BR 8	IAS 20/TOROPI//PF 70100 F 3087-0R-3F-0R-1F-0R-0F	1671	101
TRIGO BR 14	IAS 63/ALONDRA "S"//GABOTO/LAGOA VERMELHA	1651	100
TRIGO BR 15	IAS 54*2/TOKAI 80//PF 69193 P 73387-1P-37F-1F-0F-0R-1F-0R	1677	103
Promising Lines:			
B 8537	TIFTON/COTIPORA	2212	125
CEP 8236	CEP 75203/COXILHA/3/PEL 72380/ ARTHUR 71//PAT 24/ALONDRA"S"	1930	110
CEP 8282	KAVKAZ//ANDES$_E$/MAYO 64/3/PF 70354/4/PAT 7392 B 23778-0Z-0A-12A-0A	1942	111
CEP 8283	NOBRE/CEP 7956//PEL 72380/ ARTHUR 71 B 24101-B-0A-0Z-4A-0A	2093	115
CEP 82128	PEL 72380/ARTHUR 71//CEP 75336/3/ ALONDRA"S"/PF 72707//PAT 19 B 24136-A-0A-0Z-2A-0A	2175	124
CEP 82151	PEL 72380/ARTHUR 71//CEP 75336/3/ ALONDRA"S"/PF 72707//PAT 19 B 24136-D-0A-0Z-1A-7A-0A	2052	112
CEP 83116	PEL 72380/ARTHUR 71//CEP 75336/3/ ALONDRA"S"/PF 72707//PAT 19 B 24136-D-0A-0Z-1A-8A-0A	2008	119

Table 4. (continued)

Material		kg/ha	% of MINUANO 82
Recommended Cultivars:			
CEP 83117	PEL 72380/ARTHUR 71//CEP 75336/3/ ALONDRA"S"/PF 72707//PAT 19 B 25136-D-0A-0Z-1A-9A-0A	2105	125
CEP 83141	PF 7339/3/IAS 63/ALONDRA"S"//GABOTO/ LAGOA VERMELHA CM70379-3Y-0Z-1Y-2Z-0Y	2547	117
CEP 845	BR 3/CEP 7887//CEP 7775/CEP 11 B 26294-0Z-0A-2A-0A	3044	139
CEP 847	BR 4/CEP 11 B 27059-0Z-0A-1A-0A	2709	124
CEP 8415	CEP 7668/CEP 11 B 25583-0Z-0A-0A-1A-0Y	3077	134
CEP 8417	CEP 7774/ALONDRA"S"//CEP 7596/ CEP 7776 B 26503-0Z-0A-2A-0A	2723	118
CEP 8418	CEP 7780//PF 70354/ALONDRA"S" CM70417-1M-1Y-0Z-1Y-1Z-0Y	2539	110
CEP 8435	OASIS/IAS 61 B 23828-0A-0Z-2A-3A-2A-0A	2577	120
C 8404	PF 70100/CNT 1//PF 7065	1775	120
PF 80271	RC 7201/BR 2	2006	114
PF 81107	PF 70354/ALONDRA"S"	2939	107
PF 8215	CORRE CAMINOS/ALONDRA"S"/3/ IAS 54.47/S 62//CNT 1	2119	121
PF 82341	IAS 61/INDUS//IAS 62/3/ALONDRA"S" /4/IAS 59	3198	116
PF 82345	IAS 60/INDUS//IAS 62/3/ALONDRA"S" /4/IAS 59	2027	120
PF 83144	IAC 5*2/3/CNT 7*3/LONDRINA// IAC 5/HADDEN	3385	123

Table 4. (continued)

Material		kg/ha	% of MINUANO 82
Recommended Cultivars:			
PF 83158	IAC 5*2/3/CNT 7*3/LONDRINA// IAC 5/HADDEN	2894	105
PF 83899	PF 7577/PF 78901//CNT 10/BR 5	2855	111
PF 839204	ALVAREZ 110/2* IAS 54/6/TP/4/TZPP/ SON 64//NAPO/3/CIANO/5/PF 6968	2851	107

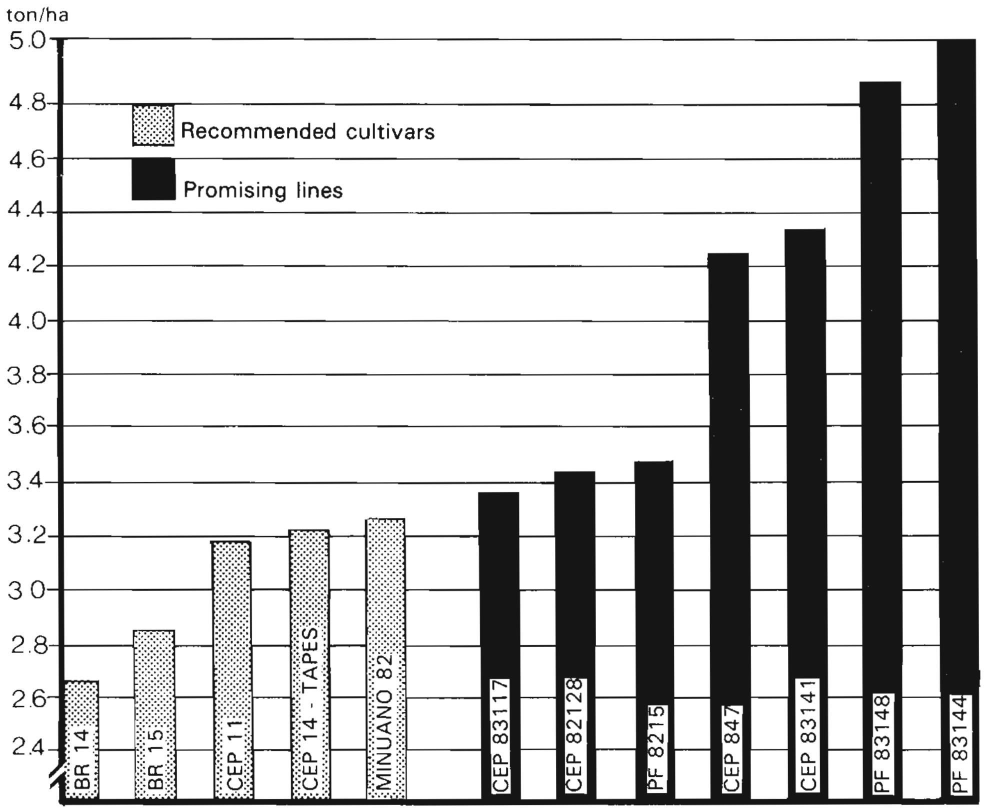

Figure 3. Maximum yield obtained in the state of Rio Grande do Sul in 1985.

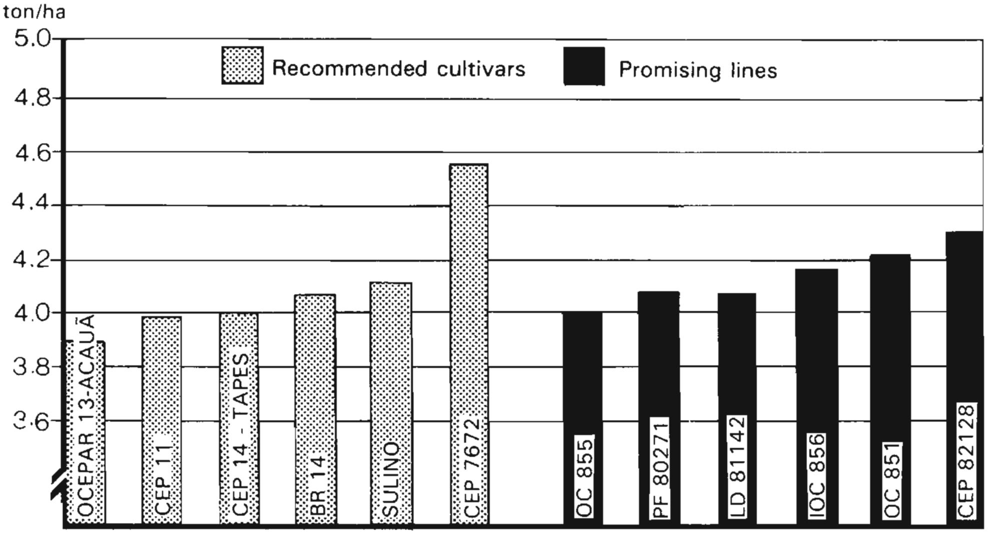

Figure 4. Maximum yields obtained in the state of Paraná in 1985.

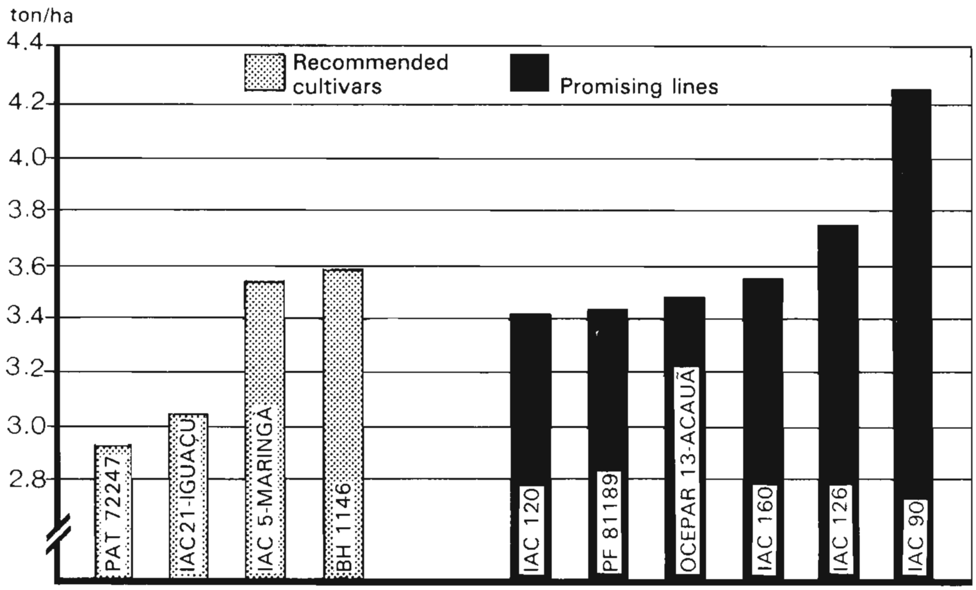

Figure 5. Maximum yields obtained in the state of São Paulo in 1985.

Table 5. Yield performance of some recommended cultivars and promising lines in Paraná State in 1985

Material		kg/ha	% of IAC 5-MARINGA
Recommended Cultivars:			
CEP 11	PF 6968*2/HADDEN B 11950-4Z-1A-1A-0A	2700	117
CEP 7672	PLATIFEN/CIANO"S"//S 67 B 7727-1C-0A-2A-0S	2555	111
CEP 7780	PF 6968*2/HADDEN B 11950-4Z-2A-2A-0A	2297	108
IAPAR 18-MARUMBI	PF 72640/PF 7326//PF 7065/ ALONDRA"S"	2220	103
OCEPAR 10-GARCA	IAC 5/ALDAN"S"	2350	111
OCEPAR 11-JURITI	IAC 5/ALDAN"S" CM46961-16M-113PR-1T-OT	2320	104
SULINO	PLATIFEN/CIANO"S"//S 67 B 7727-1C-0A-1A-0S	2650	115
TRIGO BR 19	CNT 1/CNT 10 F 6929-0R-6F-2F-0R-1F-0R-0F	2360	109
Promising Lines:			
CEP 80111	IAS 58/IAS 55//ALONDRA"S"/3/ IAC 5/4/ALONDRA"S"/IAS 58// ALONDRA"S" CM55517-B-1F-703Y-4F-0Y-0A	3080	110
CEP 82128	PEL 72380/ARTHUR 71//CEP 75336/3/ALONDRA"S"/PF 72707//PAT 19 B 24136-A-0A-0Z-2A-0A	2350	112
IDS 208-9	IDS 309/IAC 5	2490	110
IDS 237-10	BH 1146/IDS 309	2510	111
IOC 856	HORK"S"	3195	110
LD 81142	PAT 24/ALONDRA"S"	2270	109

Table 5. (continued)

Material		kg/ha	% of IAC 5-MARINGA
Promising Lines:			
LD 8254	ALONDRA//CNT 7/PF 70354/3/ PAT 24//BB/KAL	3160	105
OC 851	IAS 54/VEERY''S'/BACKA/ALONDRA'S''	2480	119
OC 853	ALONDRA''S''/PF 72707//PAT 19	3020	101
OC 854	HSJO 71/2*ERA//2*PEL 72380/ ARTHUR 71	2330	111
OC 855	CMH 74 A.754//PEL 72380/ARTHUR 71/5/IAS 20/H 567.71/3/IAS 20/ 4/PEL 72380/ARTHUR 71	2390	114
PF 7942	PF 71130/CNT 10	2938	112
PF 8016	IAS 58/MADEIRA''S''	2310	111
PF 8086	PF 72640/PF 7326//PF 7065/ ALONDRA''S''	3830	116
PF 80271	RC 7201/BR 2	2788	116
PF 81189	BH 1146*3/ALONDRA''S''	2350	112
PF 81191	BH 1146*3/ALONDRA''S''	2440	113
PF 81228	BH 1146*3/ALONDRA''S''	2320	111
PF 82225	BH 1146*6/RL 4137	2480	110
PG 8215	CNT 8/ALONDRA''S''	2903	111
PG 8256	ALONDRA''S''/PAT 7219	1980	114

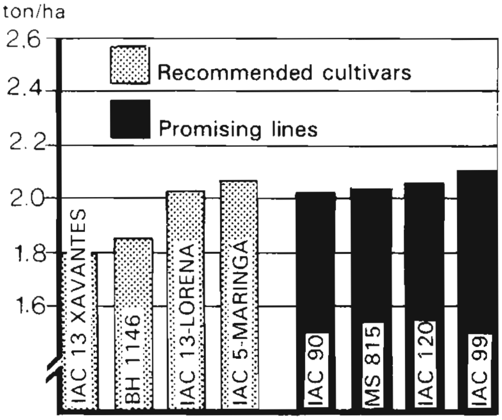

Figure 6. Maximum yields obtained in the state of Mato Grosso do Sul in 1985.

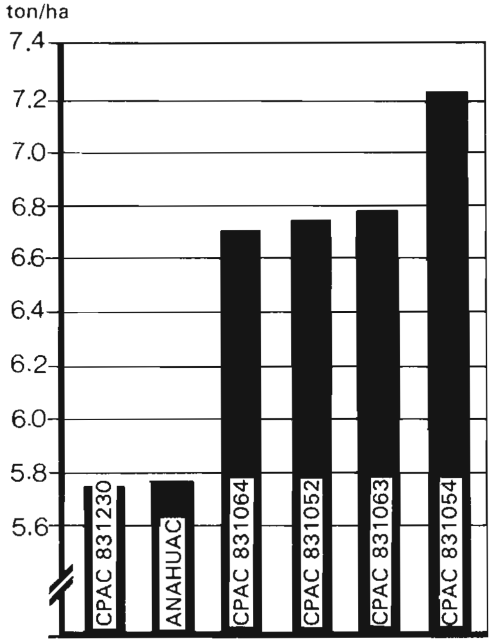

Figure 8. Maximum yields obtained in limed and irrigated soils in the states of Minas Gerais and Goiás, and in the Distrito Federal in 1985.

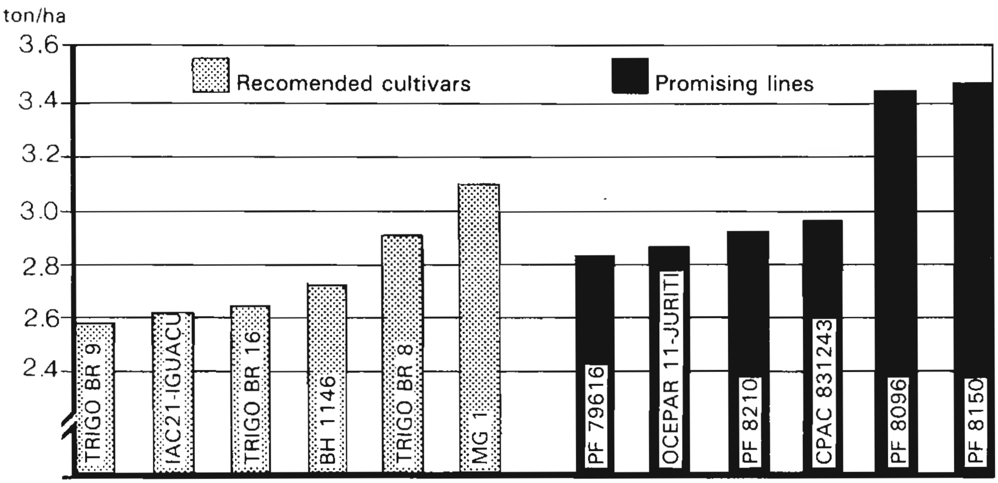

Figure 7. Maximum yields obtained under rainfed conditions in the states of Minas Gerais and Goiás, and in the Distrito Federal in 1985.

Table 6. Yield performance of some recommended cultivars and promising lines in São Paulo State in 1985

Material		kg/ha	% of average of checks
Recommended Cultivars:			
BH 1146	PONTA GROSSA 1//FRONTEIRA/MENTANA	2319	104
IAC 18-XAVANTES	BH 1146*4/S 12	2149	97
IAC 21-IGUAÇU	7 CERROS/LAGOA VERMELHA	2672	108
IAC 22-ARAGUAIA	PEL 21414.66/IAC 5	2713	100
IAC 24-TUCURUI	IAS 51/IRN 597.60	2167	98
OCEPAR 11-JURITI	IAC 5/ALDAN''S''	2398	112
PAT 72247	AMZ''S''//TZPP/SON64A	2401	98
Promising Lines:			
IAC 27	SONORA 63*2/LAGOA VERMELHA	2518	111
IAC 72	TOBARI 66/IAC 5	2242	114
IAC 90	IRN 641.70/BH 1146	2589	119
IAC 120	IRN 33.70/IAC 5	2415	112
IAC 126	IRN 641.70/BH 1146	2413	112
IAC 160	IRN 393.70/IAS 20	2436	122
IAC 163	PEL A 403.65/BH 1146	2487	115
OCEPAR 13-ACAUA	IAC 5/3/IAS 20/PATO B//BB/INIA	2293	116
PF 7942	PF 71130/CNT 10	2342	121
PF 81191	BH 1146*3/ALONDRA''S''	2421	113

Table 7. Yield performance of some recommended cultivars and promising lines in Mato Grosso do Sul State in 1985

Material		kg/ha	% of IAC 5-MARINGA
Recommended Cultivars:			
BH 1146	PONTA GROSSA 1//FRONTEIRA/MENTANA	1501	92
IAC 13-LORENA	CIANO 67/IAS 61	1578	96
IAC 18-XAVANTES	BH 1146*4/S 12	1466	89
Promising Lines:			
IAC 90	IRN 641.70/BH 1146	1746	102
IAC 93	CIANO 67/IAS 51	1576	112
IAC 99	PEL 4178.87/S12	1784	104
IAC 160	IRN 393.70/IAS 20	1339	104
IAC 171	IRN 641.70/BH 1146	1791	125
IOC 856	HORK"S"	1487	105
MS 815	VEERY"S"	1798	103
OC 851	IAS 54/VEERY"S"/BACKA/ALONDRA"S"	1597	112
PF 81191	BH 1146*3/ALONDRA"S"	1684	105
PF 81228	BH 1146*3/ALONDRA"S"	1681	105

Table 8. Yield performance of some recommended cultivars and promising lines, under rainfed conditions, in central Brazil (Minas Gerais and Goiás States, and in the Distrito Federal) in 1985

Material		kg/ha	% of best check
Recommended Cultivars:			
BH 1146	PONTA GROSSA 1//FRONTEIRA/MENTANA	2522	100
IAC 18-XAVANTES	BH 1146*4/S 12	2399	94
IAC 21-IGUACU	7 CERROS/LAGOA VERMELHA	2037	102
MG 1	IAS 64/ALDAN''S'' CM47207-16M-2Y-3F-704Y-7F-700Y	2115	106
TRIGO BR 8	IAS 20/TP//PF 70100	2376	93
TRIGO BR 9-CERRADOS	BH 1146/IRN 595.71	2065	103
TRIGO BR 16-RIO VERDE	PF 70402/ALONDRA''S''//PAT 72160/ ALONDRA''S'' B 19789-H-508M-1Y-10F-701Y-1F-700Y	2314	116
Promising Lines:			
CPAC 8393	PF 70338/NYU BAY	1987	120
CPAC 831243	GLENNSON M 81	2940	118
CPAC 831252	MONCHO''S''/ALONDRA	2672	107
OCEPAR 11-JURITI	IAC 5/ALDAN''S''	2846	114
PF 79616	IAS 64/ALDAN''S''	2037	102
PF 8096	PAT 7241/KAVKAZ	3431	138
PF 8150	IAS 58*3/EAGLE	1766	121
PF 81216	BH 1146*3/ALONDRA	2898	116
PF 8210	ALONDRA''S''/BH 1146	1813	110

Table 9. Yield performance of some recommended cultivars and promising lines, in limed and irrigated soils in Central Brazil (Minas Gerais and Goiás States, and in the Distrito Federal) in 1985

Material		kg/ha	% of best check
ANAHUAC	II 12300//LR 64/8156/3/NOR67	4686	100
CANDEIAS	CARDENAL//SONORA 64//KLEIN RENDIDOR	4476	96
CPAC 831035	F3.71/TORIM	4693	100
CPAC 831052	JUP/EMU"S"//GJO"S"	5249	111
CPAC 831054	JUP/EMU"S"//GJO"S"	5902	110
CPAC 831063	BUC"S"/BJY"S"	5186	110
CPAC 831064	BUC"S"/BJY"S"	5544	111
CPAC 831230	LIRA"S"	4419	101

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Development of Wheats with Enhanced Nutrient Efficiency: Progress and Potential

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Abstract

Nutrient efficiency is defined as the ability of a genotype to grow in a soil too deficient in that nutrient for a standard genotype. Considerable genetic diversity for Cu, Zn, and Mn efficiency exists within wheat and breeding for these traits and their combination in a single genotype appears possible. High efficiency exists in rye and it appears possible to transfer these characters from rye to wheat via chromosome translocation. Triticale inherits nutrient efficiency from its rye parentage. Progress for greater P efficiency is hampered by lack of knowledge of what is involved biochemically and by lack of effective screening procedures. It is argued that wheat is already as N-efficient as is necessary. Nutrient efficiency may confer greater disease and drought resistance/tolerance, deeper rooting, and greater responsiveness to the use of other fertilizers, especially N.

Little effort has been made to apply modern breeding techniques to adapt crop plants to soils of poor nutritional status, even though this is genetically feasible. Rather, the use of fertilizers to solve these problems agronomically has encouraged plant breeders to concentrate on other objectives, such as disease resistance and quality.

Some nutritional problems do not appear to be easily resolved agronomically and a case for breeding adapted varieties can be made in these instances. The most obvious problems are those of nutrient toxicities. With toxicities, the cost of removal is usually much greater than that of fertilizer additions and so breeding solutions are commonly sought, often with much success. With certain deficiencies also, such as iron and manganese deficiencies induced by high pH agronomic solutions to the problem are not satisfactory and a genetic solution is necessary.

In this paper, I wish to outline the case for breeding for nutritional characters in crop plants which confer adaptation to problems of nutrient deficiency in soils. In this context, a deficient soil is one that contains reasonable amounts of the limiting nutrient, but it is relatively unavailable to common cultivars of the crop in question. Low availability may be induced by low or high pH or by large amounts of reactive clay minerals and organic matter. An improved cultivar is able to mobilize the limiting nutrient in greater amounts and yield better than a standard cultivar. Such a genotype is termed "nutrient-efficient."

The Case for a Breeding Program

Three criteria must be satisfied for a genetic approach to improving the nutritional level of the wheat crop (8):

1. There must be genetic diversity for the character.

2. The soil must be capable of supplying the nutrient to an improved genotype.

3. There must be sound agronomic and economic reasons for pursuing a breeding solution to the nutrient limitation.

The genetic potential for improvement of nutrient efficiency is readily apparent in a diverse literature including symposium proceedings and reviews of which one author (2) lists 20. Among wheat and its near relatives, rye is especially nutrient efficient and may be viewed as a standard to achieve in wheat with sufficient breeding effort. Rye is more capable than wheat in the uptake of copper (Cu), zinc (Zn), manganese (Mn), iron (Fe), and phosphorus (P), all elements of relatively low ironic mobility in the soil. In our Adelaide-based research on Cu, Zn, and Mn, we have shown that rye's adaptability to utilize these elements is inherited by the amphiploid hybrid triticale and are thus immediately available in a more wheat-like cereal (8). Diversity within wheat for tolerance to these deficiencies is also considerable (Tables 1, 4, and 8).

The outstanding efficiency of rye also demonstrates that the soil is capable of supplying the extra nutrient. Calculations (6) show that even the most impoverished siliceous sand contains sufficient quantity of the immobile nutrients for hundreds, if not thousands of crops, if they were only capable of extracting them. The exception is N for which there is sufficient quantity for only a few dozen crops.

The agronomic and economic criteria are less obvious and we are only just developing the case for breeding nutritional characteristics into wheats for our semi-arid rain-fed cropping zone. In this environment, soils are dominantly high in pH and, therefore, low in availability of P, Cu, Zn, Mn, and Fe (as well being low in total N). All our cereals appear to be remarkably Fe efficient (in contrast to maize and sorghum (2); and P deficiency is treated with fertilizers, adding annually three to five times what is recovered in the crop.

The most difficult nutritional problem is the chronically Mn-deficient soils for which Mn fertilizers are quite inefficient, lasting only a matter of weeks in these alkaline soils before becoming fixed in unavailable forms. A breeding solution in the case of Mn is therefore highly desirable.

Topsoil drying in our environment occurs quite frequently after 2 to 3 weeks without rain. The bulk of the roots, all the recently added fertilizer, and most of the residual fertilizer are immobilized as the topsoil dries. The crop must survive for water and nutrients on the subsoil. If the nutritional status of the subsoil is low (almost universally so in South Australia), nutritional stress can result; and if this occurs during microsporegenesis, yield depression can be severe. In this way, crop failure occurred in Queensland due to Cu deficiency (11) in spite of heavy soil applications of Cu. Foliar sprays of Cu on wheat partly solved the problem, but the use of Cu-efficient crop (triticale or sunflowers) has been the best solution. We have simulated this situation experimentally in the glasshouse, inducing deficiency in an otherwise nutritionally adequate system by drying the topsoil where the Cu fertilizer was placed. Nutrient-efficient genotypes capable of mobilizing nutrients from less available subsoil forms can overcome this type of growth reduction, as

Grundon (11) demonstrated. Most importantly, they may present as more drought-tolerant owing to better development of the subsoil root system.

South Australian soils are not only severely nutrient deficient but also promote severe root disease problems. We have repeatedly shown that micronutrient-deficient crops are less tolerant and/or resistant to pathogens (9, 18, 20); and moreover, nutrient-efficient genotypes are more resistant. This factor may prove to be the most pressing argument for nutrient-efficient genotypes since locally-placed fertilizer bands in the soil may not protect the whole root system from diseases (7).

Finally, there is the problem of subclinical deficiency that is common for P and the micro-nutrients. Some cultivars of wheat show no symptoms of Cu deficiency, yet at anthesis may prove to be completely male sterile; that is the extreme, but in general 10-30% of the yield potential can be lost without any visible indication of a nutritional problem. Nutrient-efficient genotypes can restore that potential yield. Figure 1 shows an extra 1.0 t/ha yield due to Cu efficiency above that of foliar Cu-treated inefficient control genotypes (recurrent parental lines).

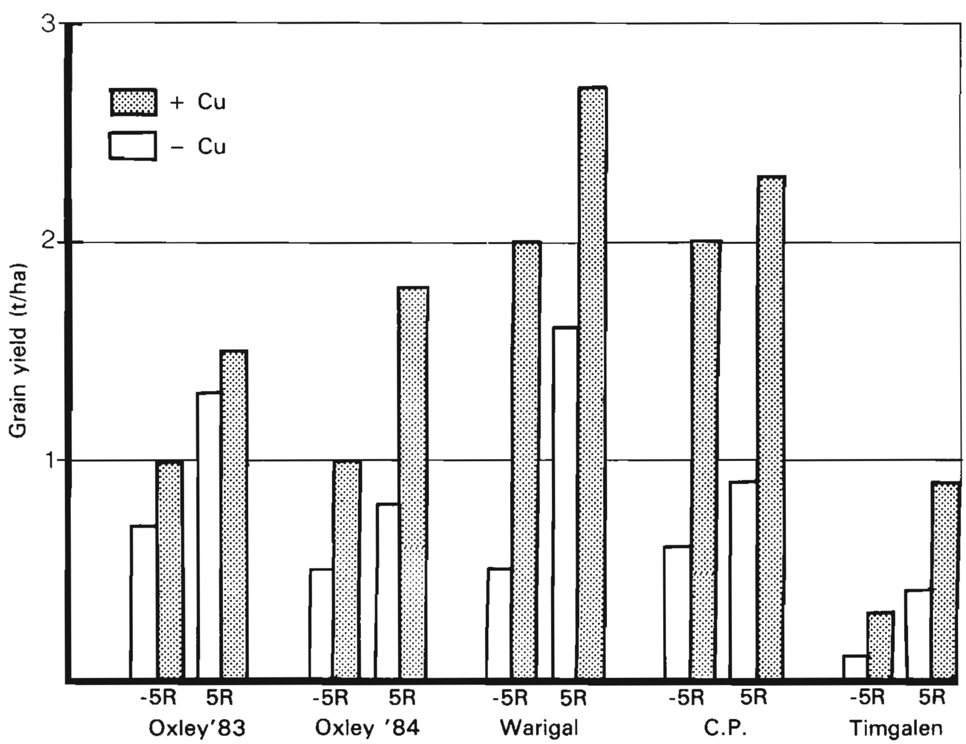

Figure 1. Grain yields of 5RL translocation lines in comparison to their recurrent parent lines with and without supplemental Cu fertilizer at Ungarra (1983) and Keppoch (1984) in South Australia.

Progress in breeding nutrient-efficient lines of wheat

Nitrogen—The light-textured soils generally, and especially in the semi-arid zone of southern Australia are least endowed with N. Continuous cropping for a mere 2 or 3 years will materially lower the yield potential through N depletion if fertilizer N is not supplied. The root systems of modern cultivars of wheat are capable of lowering the soil mineral N to less than 1 ppm at which level there must be little loss through leaching or denitrification. Further, the harvest index of N is so high, so that most available plant N is removed in the grain.

I wish to argue then that there is little point in breeding for greater N efficiency in wheat. Nitrogen, being principally of atmospheric and biological origins (rather than mineralogical, as is the case with most other nutrient ions) cannot be replaced by weathering of soil minerals. It is simply imperative that an N balance be struck and maintained, by whatever means: additions must equal removal plus losses.

A more limited aim would be a genotype, which, in the juvenile phase, more effectively scavenged fertilizer N before it was subjected to the usual losses to weeds, leaching and denitrification. Whether such a character, distinct from "general seedling vigor," is worth selecting for consciously, is a matter for debate.

Phosphorus—The question of whether soils generally could sustain more P-efficient crops, was argued previously (8). The real problem is how to identify and select for the P efficiency character. Many have tried and failed (5) owing to the magnitude of the genotype-environment (G-E) interaction, which confounds any interpretation of P efficiency in terms of yield, since P is involved in both DNA and ATP and therefore participates in every known plant process. Perhaps the most interesting approach to date is that of Coltman et al. (3), who used an artificial silica-alumina medium of low P availability to identify genotypes capable of mobilizing P from alumina-fixed forms. Interesting as it is, this technique will need to be capable of identifying types that consistently perform well in the field where the G-E interaction varies widely over time, and is always quite different form that in the glasshouse. Success may await the identification of the key biochemical steps in each of several pathways, which need to combine complementarily to produce P efficiency, as the data of Coltman et al. suggest may be happening in tomato.

Potassium—The situation with K, based on its soil chemistry, is probably midway between that for N and P. Breeding for K-efficiency, at least in wheat, is probably marginal.

Copper—Deficiency of this element is widespread in Australia and globally, being most notable on peats and light sandy soils. While it is usually easily corrected by soil dressing of Cu, subclinical deficiency of this element is perhaps the most serious of all the trace elements. In a few soils, the residual value of added Cu is low. Our interest in breeding for Cu tolerance in wheat arose from its obvious sensitivity to this deficiency when compared to rye and to the wheat-rye hybrid, triticale (6). Since many interesting wheat-rye hybrid genotypes exist, it was easy to show that Cu efficiency in rye (and triticale) was carried on the 5RL chromosome arm (8). We have some evidence that a single gene is involved. The 5RL translocation lines, being readily available for backcrossing to locally adapted wheats, were used to produce adapted, Cu-efficient advanced lines (10). The Cu efficiency of these lines is shown in Table 1 (for other years and sites see [10]).

Over 4 years, four of these translocation lines have been the top-yielding lines on Cu-deficient soils (-Cu treatment) and among the best also where Cu was applied (+Cu treatment). At other, non-deficient sites, these lines have yielded equal to their respective recurrent parent lines, indicating no yield-suppressive effects of the presence of the 5RL chromosome segment.

More importantly, the presence of the 5RL/4A translocation does not depress the baking quality of the grain (Table 2) even though the protein content was lower, as might be expected from the much higher yield. The 5RL/5BS translocation actually improved the quality scores. Both 5RL translocations virtually

Table 1. Copper efficiency of wheat varieties and advanced lines grown at Keppoch S.A. in 1985 (means of five replications)

Genotype	Vegetative yield at 12 weeks (g/m of row)		-Cu/+Cu (%)	Grain yield (t/ha)		-Cu/+Cu (%)
	-Cu	+Cu		-Cu	+Cu	
Cook	76	85	89	1.39	6.13	23
Timgalen	69	81	85	0.60	2.80	21
Timgalen-5RL/5BS	85	94	90	1.93	2.93	66
Gabo	77	86	90	0.79	3.35	23
Gabo-5RL/5BS	101	102	99	2.96	3.69	80
Oxley	51	59	86	2.19	4.18	52
Oxley-5RL/4A	82	80	103	3.38	4.40	77
CP	77	78	99	1.91	3.82	50
CP-5RL/4A	96	103	93	3.14	3.49	90
Warigal	80	92	87	2.11	4.06	52
Warigal-5RL/4A	97	95	102	4.56	5.08	90
Warigal-5RL/5BS	74	68	109	2.82	2.40	117
Blade	58	101	57	2.25	3.98	56
Bayonet	61	103	59	1.91	3.76	51
Millewa	82	101	81	1.83	4.12	44
RAC520	70	65	108	1.42	4.15	34
Halberd	103	97	105	1.69	3.85	44
Aroona	74	105	70	1.79	4.60	39
LSD($P < 0.005$) Genotype	1.73			1.00		
Copper	22			0.30		
Geno x Cu	NS			1.64		

NS = not significant

eliminated the adverse effects of Cu deficiency on quality, which are clearly evident in the comparison of -Cu Warigal with +Cu Warigal. These adverse effects of Cu deficiency on baking quality are similar to those documented in detail by Flynn et al. (4). The Warigal-5RL/4A line, the best performer to date should, carry *Sr15* and three other minor genes for stem rust resistance (from Warigal), which are effective against most current biotypes of stem rust in Australia. This advanced line, together with the other 5RL lines, is available from the author.

Table 1 shows considerable diversity of response to the Cu deficiency and the environment. Cook has the highest yield potential (6.13 t/ha) but is clearly Cu-inefficient, perhaps best shown in the relative grain yield expressed as the -Cu/+Cu ratio (23%). Timgalen and Gabo (-Cu/+Cu of 21 and 23% respectively) are varieties so Cu-inefficient that the +Cu-treated plants were still Cu-deficient, and as a result their yield level is far below the potential. For nontranslocation lines, Blade is quite Cu-efficient and is particularly interesting, as it is also reasonably Mn- and Zn-efficient (see below), whereas Cook, which is Mn-efficient (see below), is Cu-inefficient.

The Cu concentrations and Cu uptake data (Table 3) show that Cu efficiency is due to greater absorption of Cu (both -Cu and +Cu treatments) and not to more efficient utilization of Cu. There is no evidence that efficient genotypes produce more dry matter with less Cu; they all absorb more Cu and generally retain higher tissue Cu concentrations. In Table 3, Timgalen would be the least Cu-efficient genotype and has the lowest Cu uptake (Cu concentration in dry matter at 17 weeks). There is some evidence that the 5RL/5BS translocation is more Cu-efficient than the 5RL/4A (for example compare the Warigal triplet) but the 5RL/4A translocation has the higher potential yield.

Zinc—Screening for Zn efficiency in South Australian cereal genotypes was begun recently after marked increase in the incidence of Zn deficiency in our crops. This was

Table 2. Baking quality of Australian wheats affected by Cu deficiency and the rye 5RL translocation (from Keppoch 1985, mean of three replications)

		Flour		Farinogram	Extensigram			Baking report		
Identification		Yield %	Protein 13.5% mb	Salt water absorption %	Height[a]	Extension (cm)	H/E	Volume (cc)	Score 10 ppm	Total[b]
W[c]	+Cu	70.3	11.0	59.3	170	16.0	11	560	32	68
W	-Cu	68.5	12.9	61.4	108	20.4	5	570	31	62
W-5RL/4A	+Cu	71.0	10.0	60.2	147	15.7	9	600	37	66
W-5RL/4A	-Cu	70.4	10.5	60.2	162	17.3	9	530	28	61
W-5RL/5BS	+Cu	65.6	12.7	60.2	238	17.5	14	575	32	71
W-5RL/5BS	+Cu	66.5	12.8	61.0	218	17.8	12	580	32	71

[a] Brabender units
[b] Total = Total baking score, which is the sum of scores at 10 ppm and 20 ppm
[c] W = Warigal

precipitated by farmers changing from dependence on the traditional superphosphate as their P fertilizer to the new high-analysis products such as diammonium phosphate. The latter contain much less Zn as a natural contaminant.

Table 4 presents a selection of results from 1985 trials. The performance of cultivars at maturity was well correlated with yields at 12 weeks. This is a characteristic of Zn, which differs in this respect from Cu. Kite, Aroona, Blade, and the breeder's line 426QKMH yielded well under -Zn treatment, and also have high relative yields. Durati, a durum wheat, is particularly Zn-inefficient, displaying severe foliar symptoms at an early age, and producing the lowest grain yield and relative yield. Gatcher and Gabo are also poor. The 5RL/4A translocations improved the Zn efficiency of Gabo and Warigal, but not of Oxley. In any case, the translocation lines were not as good as other released cultivars. Rye and triticale are, however, Zn-efficient (Table 5), but from an addition line study, it appears that chromosomes 2R, 3R, and 7/4R contribute more to Zn efficiency than chromosome 5R.

The analytical data of Table 6 confirm that most cultivars were Zn-deficient at 12 weeks (-Zn treatment), but these Zn concentrations are poorly correlated with final grain yield from the same plots (-Zn).

Table 3. Copper concentration and uptake of wheats and wheat-rye translocation lines grown on a copper deficient soil at Keppoch, South Australia, in 1984

	Cu Concentration ($\mu g/g$)		Cu Uptake (g/ha)	
Genotype	**-Cu**	**+Cu**	**-Cu**	**+Cu**
Aroona	0.66	0.93	1.30	3.50
Kite	0.83	1.01	1.34	2.95
Spear	0.79	0.96	1.88	3.79
Bindawarra	0.88	0.85	2.08	3.90
Warigal	0.69	0.87	1.51	3.72
Warigal-5RL/4A	0.77	1.01	1.98	3.94
Warigal-5RL/5BS	0.91	1.07	2.43	4.37
Oxley	0.74	0.82	1.22	3.14
Oxley-5RL/4A	0.74	0.96	2.75	2.96
CP	0.74	0.97	1.75	4.21
CP-5RL/4A	0.83	1.13	2.73	5.06
Timgalen	0.71	0.92	1.22	3.74
Timgalen-5RL/5BS	0.91	1.16	2.11	5.23
LSD($P<0.05$) Genotype	NS		0.92	
Cu	0.04		0.24	
Genotype x Cu	NS		NS	
5RL effect[a]	0.07		0.23	

NS = not significant
[a] Main effect of 5RL, excluding first four genotypes from the analysis

Aroona, 426QKMH, and Blade have lower Zn concentrations than Durati, but in terms of yield they lie at opposite ends of the efficiency spectrum. Zn uptake is a better indicator of subsequent grain production under Zn deficiency than is Zn concentration.

A comparison of Tables 1 and 4 shows little association of Cu efficiency and Zn efficiency. Blade and Oxley perform reasonably in both environments.

Manganese—Mn deficiency is the most intractable trace element deficiency in South Australia, and a program to develop Mn-efficient cereals has been stimulated by a sequence of observations and events. First, rye has been shown to be particularly Mn-efficient relative to wheat (Table 7) and this character may be transferred to triticale. On the other hand, three widely grown wheat cultivars, Condor, Millewa, and Bayonet, one triticale (Coorong) and one new barley (Galleon) proved to be exceptionally sensitive to Mn deficiency. The release of Galleon, especially since barley is the preferred crop on Mn-deficient soils, has increased the awareness of the extent and severity of the natural Mn deficiency of many of the soils of the state.

Table 4. Zinc efficiency of Australian wheats grown at Lameroo, S.A., in 1985 (means of five replications)

Genotype	Yield at 12 weeks (g/m-row) -Zn	+Zn	-Zn/+Zn (%)	Grain yield (t/ha) -Zn	+Zn	-Zn/+Zn (%)
Kite	26	24	111	1.34	1.41	95
C8MM	16	16	100	1.15	1.09	105
Raven	24	25	95	1.05	1.11	95
Cook	19	22	89	1.18	1.36	87
Millewa	22	23	96	1.16	1.35	86
Halberd	25	27	94	1.24	1.41	88
Durati	18	25	72	0.81	1.02	79
Aroona	29	32	91	1.54	1.54	100
426QKMH	30	38	80	1.90	2.19	87
Gatcher	20	22	90	0.97	1.06	91
Gabo	20	19	103	0.74	0.88	84
Gabo-5RL/4A	27	32	82	1.26	1.43	88
Oxley	18	21	90	1.18	1.25	95
Oxley-5RL/4A	13	16	83	1.09	1.23	89
Warigal	15	17	85	0.94	1.07	88
Warigal-5RL/4A	26	21	121	1.29	1.40	92
Blade	26	27	96	1.43	1.61	89
LSD Genotype P=0.05	10.7			0.32		
LSD Zinc P=0.05	1.5			0.03		

A study of the rye addition lines of wheat revealed that chromosome 2R contributed significantly to Mn efficiency in rye with lesser contribution from 6R. This would appear to be the basis of the poor Mn efficiency of Coorong, an Armadillo-type triticale lacking the 2R chromosome. Beagle types, such as Venus and Currency, containing all seven rye chromosomes, have an agronomically useful degree of Mn efficiency. Armadillo types are disappearing from our triticale breeding program; Coorong is no longer grown, not only because of its susceptibility to Mn deficiency, but also because of susceptibility to stem rust.

Table 5. Grain yield (g/pot) of wheat, triticale, and rye grown at deficient and adequate levels of zinc in the glasshouse in 4-kg pots of calcareous-siliceous sand at pH 8.4 (12)

	-Zn	+Zn	-Zn/+Zn (%)
Wheat (Halberd)	0.08	3.38	2
Triticale (Armadillo-T22)	1.56	3.48	44
Rye (S.A. Comm.)	1.77	1.88	94

LSD
(P = 0.05) Genotype x Zn:0.48

Table 6. Zinc concentration and uptake of Australian wheats grown at Lameroo, S.A., in 1985 (means of five replications)

Genotype	Concentration in tops (μg/g) -Zn	+Zn	-Zn/+Zn (%)	Zn uptake (μg/m of row) -Zn	+Zn	-Zn/+Zn (%)
Kite	10.5	20.7	51	273	497	55
C8MM	8.2	13.7	60	131	219	60
Raven	7.1	14.6	49	170	365	47
Cook	9.3	18.3	51	177	403	44
Millewa	7.6	14.1	54	167	324	52
Halberd	8.1	15.9	51	203	429	47
Durati	7.7	19.0	41	139	475	29
Aroona	7.5	14.2	53	218	454	48
426QKMH	7.3	15.2	48	219	578	38
Gatcher	9.2	18.4	50	184	405	46
Gabo	7.2	14.6	49	144	277	52
Gabo-5RL/4A	7.7	14.5	53	208	464	45
Oxley	10.6	15.3	70	191	321	59
Oxley-5RL/4A	8.5	13.4	63	111	214	52
Warigal	8.0	13.2	60	120	224	54
Warigal-5RL/4A	7.6	13.7	56	198	288	69
Blade	7.2	14.7	49	187	397	47

Work with barley has stimulated the quest for Mn-efficient cereal genotypes since a wide genetic diversity exists in *Hordeum* and also within our current barley breeding program (8, 19). Nearly all progeny of the old English landrace barleys were Mn-efficient, but nearly all progeny of C13576, an introduced breeder's line from Alexandria, were exceptionally Mn-inefficient. Although these observations, together with an analysis of F_2s from an Mn-efficient x Mn-inefficient cross (Figure 2) indicate a relatively simple inheritance, the relationship between putative genes for efficiency and inefficiency has not been resolved.

In wheat, the genetics can be expected to be more complex because of the ploidy level, but it has been easy to demonstrate a wide range of Mn efficiency that is of considerable agronomic importance (Tables 7 and 8). Karkoo and Tooligie, on the Eyre Peninsula, are sites of only modest potential productivity, having infertile, light sandy soils, and 400 mm rainfall annually. After additions of superphosphate and nitrogen, these are, in nutritional terms, dominantly Mn-deficient sites. The previously mentioned Mn-inefficient cultivars Bayonet, Condor, and Millewa, together with Durati, consistently performed poorly in all Mn-deficient sites, regardless of yield potential (Table 8) showing more severe chlorosis, lower plant Mn concentration, lower plant Mn uptake (Mn content of shoots at tillering), and lower relative yield.

The product of Mn concentration and yield gives Mn content (uptake), a parameter with a wider relative range than any other parameter, and is considered a useful index of Mn efficiency. Also, relative yield and relative Mn uptake (the ratio -Mn/+Mn) are useful parameters since they, to some extent, minimize the contribution of other characteristics of the genotype (eg.,

Table 7. Manganese efficiency of cereal cultivars grown in small cups of Mn-deficient calcareous soil in a growth chamber at 15°C for 4 weeks

Genotype	Chlorosis rating (0-3)	Shoot Mn concentration (μg/g)	Shoot Mn content (μg/plant)	Seed Mn content (μg/seed)	Relative yield %
Bayonet wheat	2.5	8.3	0.28	0.45	58
Oxley wheat	2.5	9.5	0.32	0.76	65
Halberd wheat	2.5	10.3	0.34	0.73	80
Gatcher wheat	0	12.7	0.50	1.55	83
Bodallin wheat	0	18.3	1.00	2.99	97
Venus triticale	0	15.0	1.12	2.13	90
S.A. Commercial rye	0	17.9	0.66	0.95	117

Note: Control plants with manganese were also grown to determine relative shoot yield (-Mn/+Mn). Means of four replications (14) earliness, rust resistance, yield potential) to any Mn efficiency index based on yield. A breeder's line (C8MM-A.J. Rathjen) has consistently produced well on Mn-deficient sites with Cook, Blade, Bodallin, Aroona, RAC520, Raven, and Halberd above average.

In an attempt to screen for Mn efficiency in a fast, routine way, seedling bioassays have been developed growing three seedlings for 4 to 5 weeks in 250 g of Mn-deficient soil, scoring for symptoms and harvesting for yield and Mn content (Table 7). The results were found to depend heavily on Mn content of the seeds sown (15), a factor which may be partly genetic (acquired from the Mn efficiency of the mother plant, and therefore heritable) or environmental. The seedling screening technique has so far proved unreliable, unless all seed is produced under the same conditions; on the other hand, the Mn content of the seed has proved to be important in the field. On Mn deficient soils, seed from elsewhere, higher in Mn content, has outyielded locally grown seed of the same cultivar. The genetics of loading Mn into seeds has not yet been explored, but could be a useful Mn efficiency trait.

Mn efficiency appears to be an important character for disease resistance and/or tolerance. Not only does Mn deficiency predispose cereals to diseases, especially root disease as discussed earlier, but Mn efficiency rankings are well correlated with disease resistance scores (compare take-all rhizoctonia, and eelworm ratings of G.J. Hollamby, et al. (13); rhizoctonia ratings of barley, MacDonald and Rovira, (16). In particular, N.S.

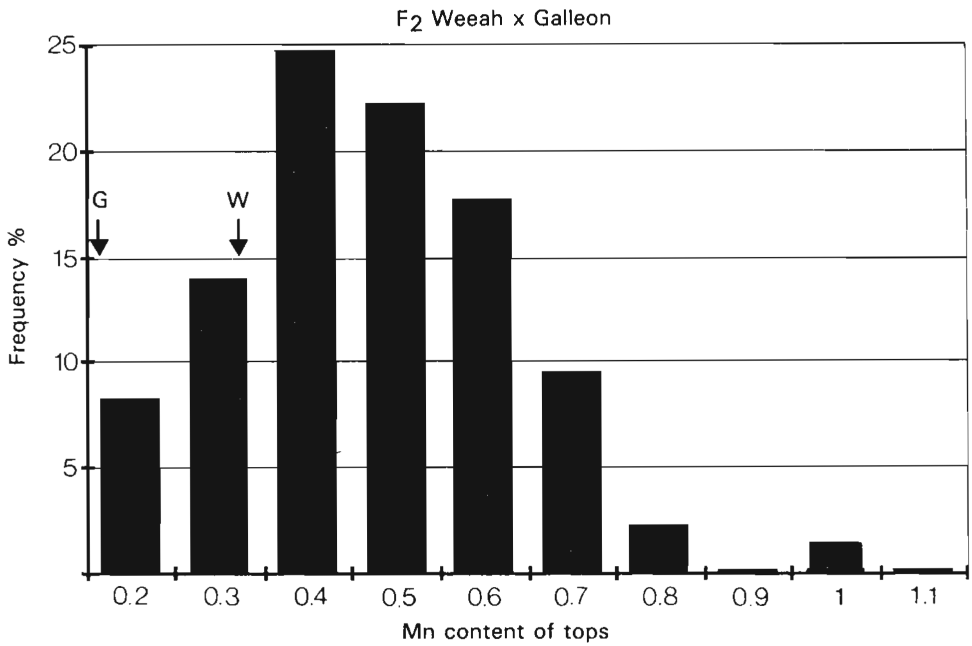

Figure 2. Frequency distribution of the manganese content of seedlings from an F_2 of Weeah x Galleon grown in Mn-deficient soil. Parental values are indicated by arrows.

Wilhelm (personal communication) has shown that Mn-efficient wheat is more resistant to take-all than Mn-inefficient wheat when both are grown in Mn-deficient soil inoculated with the fungus. In a similar vein, Zn-efficient wheats are also more tolerant of *Fusarium graminearum* (see scores of Burgess et al., [1]).

Durati, Gatcher, and Songlen are nutrient inefficient for three elements, Cu, Zn, and Mn, whereas others are efficient in only one element (Millewa, Zn; 5RL lines, Cu) or two (Aroona, Zn, Mn; Raven, Zn, Mn; 426QKMH, Zn, Mn; Kite, Cu, Zn; Cook, Zn, Mn; Coorong triticale, Cu, Zn). Blade, Warigal, C8MM, and Halberd have a moderate degree of efficiency for all three elements, while Venus and Currency triticales have good, and rye, outstanding, efficiency in all three elements.

Summary of progress

1. Useful genetic diversity exists within wheat for tolerance of deficiencies of Cu, Zn, and Mn in the soil.

2. Efficiency for each element appears to be independent of other efficiency factors, but to date there is no evidence that these traits may not be combined in a single genotype.

Table 8. Grain yield (t/ha) of Australian wheats at three manganese-deficient sites of different severity (means of five replications)

	Karkoo 1984 severely deficient			Karkoo 1983 mod-severely deficient			Tooligie 1985 moderately deficient		
Genotype	-Mn	+Mn	Rel	-Mn	+Mn	Rel	-Mn	+Mn	Rel
Bayonet	0.06	0.12	50	0.42	0.88	48	0.65	0.91	72
Gatcher	0.19	0.30	63	0.47	0.63	74	0.89	1.10	81
Condor	0.09	0.30	30	0.69	1.12	62	0.74	0.83	89
Halberd	0.13	0.24	54	0.26	0.50	52	1.02	0.96	107
Bodallin	0.18	0.33	55	0.79	1.12	70	1.02	1.03	99
RAC520	0.13	0.34	38				1.28	1.16	110
Kite	0.05	0.09	56	0.32	0.54	60	0.96	0.91	105
Aroona	0.24	0.37	65	0.65	1.11	59	0.74	0.99	75
Millewa	0.06	0.10	60				0.78	1.08	72
426QKMH							0.74	1.06	69
Oxley	0.12	0.32	38	0.61	0.99	62	0.95	1.20	79
Blade	0.19	0.43	44				1.12	1.29	87
Raven	0.08	0.28	29	1.03	1.18	87	1.08	1.23	88
Cook	0.22	0.34	65				0.92	1.02	91
C8MM	0.47	0.62	76				1.28	1.23	104
Warigal	0.10	0.28	36	0.75	1.03	73			
Miling	0.07	0.24	29	0.73	0.92	79	1.09	1.29	85
Songlen	0.04	0.15	27	0.48	0.61	78			
Durati	0.07	0.32	32	0.17	0.41	40			
Olympic	0.05	0.13	38	0.26	0.52	50	0.85	1.13	75
LSD									
(P=0.05) Gen:	0.14			0.2			0.37		
Mn:	0.02			0.4			0.06		
Gen x Mn:	0.07			0.25					

Note: Rel = relative yield = -Mn/+Mn ratio expressed as a percentage

3. Rye and triticale have agronomically valuable efficiency for Cu, Zn, and Mn, except for Armadillo types, which may not be Mn-efficient.

4. Cu efficiency in wheat has been greatly enhanced by a rye translocation.

5. At least in the case of Cu efficiency from rye, there is no cost in terms of yield potential on nondeficient sites.

6. Micronutrient efficiency appears to confer disease resistance, especially to root pathogens.

7. Minimal evidence, to date, indicates the genetics of these characters is simple, and generally, efficiency is dominant (8). However a dominant Mn inefficiency character was found in barley, which is apparently closely linked to desirable traits.

8. All the evidence points to efficiency being a greater ability to acquire more of the limiting nutrient from the soil rather than more efficient internal utilization of the element for yield production. Additionally, better accumulation of the liming element in the seed, leading to greater seedling vigor may be a manifestation of nutrient efficiency or a second contributing factor to efficiency.

9. Our current techniques for selecting nutrient-efficient genotypes in diverse genetic backgrounds are barely adequate. Nutrient uptake and relative grain yield (-n/+n ratio expressed as a percentage) have proved to be useful indices.

The Potential for Nutrient-Efficient Wheat

Macronutrients

As far as can be ascertained, the prospects for breeding for greater N efficiency in wheat are limited to improving the scavenging ability of the seedling root system for mineral N. This could, if there is genetic potential for improving such a trait, increase the recovery of fertilizer N.

In many situations, an improved P efficiency could decrease farmers' dependence on annual phosphate dressing without mining the reserves of soil P. There is, however, little satisfactory evidence that genetic diversity exists within wheat for P efficiency characters that are combinable with high yield potential in a modern wheat cultivar. There exists, to my knowledge, no known satisfactory screening technique for P efficiency that is free of P x environment interactions on yield, which is the most common criterion of P efficiency or a component of that criterion. Basic research into the question of how wheat acquires P from various soil pools should lead to the second question of the mechanism of putative P efficiency characters in *Triticum*.

The situation for K is probably intermediate between that for N and P, considering its soil chemistry and plant requirements. Because it is an expensive fertilizer, the potential for improved K efficiency deserves to be assessed, but where soils are deficient it seems intuitively that greater K efficiency in terms of uptake, would only be "buying time." However the question of better K utilization efficiency through genetic tolerance to the partial substitution of Na for K should be the initial approach to this question, as it has been in other crops.

Micronutrients

In both high-input and low-input agricultural systems, micronutrient deficiency problems are common. This is due not so much to the cost of inputs, but to lack of awareness by farmers of the problem or lack of techniques for resolving agronomically the limitation to yield. Micronutrient-efficient genotypes could eliminate these problems in most cases and lead to increased yields, increased efficiency of use of macronutrient fertilizers (especially N and P), increased resistance to foot rot diseases, increased root penetration into extremely infertile, high pH subsoils, and by virtue of the latter, increased drought tolerance (avoidance). In particular, subclinical deficiency and transient deficiency due to cold or were surface soils, would be eliminated. It is suggested that these latter conditions may permit the entry of pathogens, such as the take-all and crown rot fungi, which events do not manifest themselves as yield losses until months later.

An advantage of a different kind for nutrient-efficient wheats is the improved nutritional value of the grain for human and animal consumption where cereals are a major part of the diet.

The immediate prospects for such an approach to wheat improvement is the successful combination of our best known levels of Cu, Zn, and Mn efficiencies in a single genotype. We know of no reason why this objective is not attainable and have begun crossing. At the same time, it is desirable that a much greater range of wheat germplasm be explored for genes, at least as efficient as those in rye.

Greater expression of these characters and genetic markers for them would materially assist in a necessary research project: the study of the genetics of these traits, their heritability and combining ability. Allied to this is the urgent need to know what biochemical/physiological processes are involved in nutrient efficiency characters. A thorough and elegant research program (17) has recently unveiled a sophisticated mechanism in cereals for the acquisition of Fe, and it seems possible that the traits discussed in this paper are physiologically and biochemically no less elaborate.

Much more research is needed on the link between genetically controlled micronutrient efficiency traits and resistance to such root diseases as take-all, crown rot, and rhizoctonia. In this lies one of the most compelling reasons for breeding for micronutrient efficiency characters.

Other areas deserving attention include the genetics of the nutrient loading of seeds, and the transfer of rye efficiency genes to wheat via chromosome translocations (Zn and Mn).

On the technical side, the most compelling need is for efficient screening techniques for the nutrient-efficiency traits. To begin with, empirical approaches will be necessary since the mechanisms remain obscure, and some lateral thinking may produce much needed improvements in screening effectively large numbers of genotypes. The approach to screening will most likely be very different from that derived from the empirical approach once the underlying mechanisms are discovered.

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Integrated Pest Management Practices Relevant to Tropical Wheat Environments

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Abstract

An integrated pest management (IPM) strategy employs multiple tactics to maintain pest populations at levels below those causing economic losses, while minimizing directional selection on those pest populations and reducing adverse effects on the environment. IPM concepts are relevant and applicable to the culture of wheat introduced into traditional cropping systems of the tropics. Development and deployment of pest-resistant cultivars, cultural tactics, biological control tactics, and seed-applied pesticides will each be important in tropical wheat management. Successful IPM implementation is dependent on the conduct of research relevant to local cropping systems and the presence of an effective extension network.

Demand for locally grown wheat in tropical and subtropical developing nations is increasing steadily in association with urbanization, changing food preferences, and the draining effect of wheat imports on foreign exchange (14). In response, CIMMYT, in cooperation with national agricultural programs, has accepted the challenge of developing wheat germplasm better adapted to tropical environments. Other papers in these Proceedings address the identification and elimination of specific production constraints that currently prevent the successful introduction of wheat into warmer, nontraditional wheat-growing environments.

It is clear from these papers that pests, i.e., all biotic agents that produce adverse effects on crop yield or quality, comprise one of the most formidable obstacles to the successful culture of wheat in the tropics. Plant pathogenic microorganisms (especially fungi) are most often cited as serious pests, but arthropods, nematodes, and weeds can also severely limit yields. Because of the magnitude and complexity of pest problems in the tropics, it has been suggested that integrated pest management (IPM) strategies be employed to manage wheat pests in warmer, nontraditional wheat-growing environments (8, 12, 15, 18). The objective of this paper is to outline the basic concepts and tactics of IPM and to discuss the relevance of IPM strategies to tropical wheat environments.

There is no single definition of IPM; the term means different things to different people. The U.S. Council for Agricultural Science and Technology has defined IPM as "the use of a variety of tactics to control pests in the efficient production of food and fiber while holding to a minimum the overall unfavorable effects of the various practices" (2). The United Nations Food and Agriculture Organization in 1967 defined integrated pest control, the forerunner of IPM, as "a pest management system that, in the context of the associated environment and the population dynamics of the pest species, utilizes all suitable techniques and methods in as compatible a manner as possible and maintains the pest populations at levels below those causing economic injury" (1). We prefer the latter definition because it reveals the biological, environmental, and socioeconomic dimensions of IPM.

The concept of IPM arose initially in the 1960s in western academic institutions as a reaction to the negative consequences of reliance on synthetic chemicals for control of pests in intensively managed crops such as cotton and apples (2, 3, 4, 9, 20, 21). Concern over environmental contamination is the primary force in public and political support of the IPM philosophy in developed countries. In addition to environmental contamination, the overuse of synthetic chemicals for pest control also resulted in numerous examples of resurgence of target pests, outbreaks of secondary pests, and the increased selection of pesticide-resistant pest strains.

The IPM concept has evolved considerably over the past 2 decades and has been influenced by the disciplines of ecology, systems science (engineering), and economics. The core biological principle of IPM is that all control tactics impose some type of selection pressure on pest populations. A combination of control tactics, therefore, limits the directional selection influence of any one control tactic. Conceptually, although seldom in practice, IPM integrates considerations of all pests and all management tactics, as well as the social, economic, and ecological factors that impinge on the system (1, 2, 3, 4, 9, 20, 21). In the IPM philosophy, pest management is but one part of the overall management of the agroecosystem (4,20).

Tropical Wheat Cropping Systems Context

IPM strategies are only relevant in the context of an agroecosystem that interacts with an economic and a social system. We are concerned here with tropical wheat agroecosystems of diverse description. Pest management is an important factor wherever wheat is grown, but it may be even more critical in the tropics. Warm temperatures, rainfall patterns, and humidities typical of many tropical environments tend to accelerate epidemics and reduce pest generation times in comparison to many temperate environments. It has been suggested that warm temperatures may induce higher rates of mutation in pest species (12), perhaps resulting in pest populations more diverse genetically in terms of virulence and host range spectra than temperate pest populations.

One characteristic that most tropical wheat systems have in common is that the wheat crop is a new addition to the cropping system and is usually subordinate in importance to another crop, such as rice. The introduction of wheat is a major change in these cropping systems and one should anticipate that new pest problems will occur as a result. Endemic organisms may become pests on the new crop and the new crop may also affect the pest situation on the existing crop. For example, several rice pathogens have been shown to infect wheat plants under certain conditions (Table 1) (16). Likewise, rice insects such as rice stem borer are readily adapted to wheat as a food source (10).

It is reasonable to speculate that, if the winter fallow period in the paddy rice cropping system were replaced by a dry season wheat crop over large agricultural regions, there would be an increase in populations of several pests of significance to both crops. When wheat is introduced into traditional cropping systems, other problems may be encountered. For example, wheat introduced into cropping systems with maize may experience increased problems with scab, caused by *Fusarium* spp. (15). Significant differences between various tropical wheat ecosystems should also be considered when developing IPM strategies.

Another feature that most tropical wheat systems have in common is that they are being accommodated into traditional farming systems managed by peasant farmers. It is quite unlikely that these systems will be amenable to the type of IPM programs being implemented in modern agricultural systems, i.e., programs that are highly dependent on energy, synthetic chemicals, infrastructure, trained personnel, information management, and decision-making. However, it is erroneous to think that ecologically sound pest management always requires that level of sophistication.

Tactics Available for IPM

The basic categories of tactics available to manage crop pests are genetic, cultural, chemical, biological, and regulatory (4). Some tactics overlap in category. Tactics of each category potentially could be useful in pest management of tropical wheat, but each has its inherent strengths and weaknesses.

Genetic tactics
Genetic pest management tactics, i.e., germplasm improvement for resistance or tolerance to pests, are discussed first because they are the primary thrust of CIMMYT's efforts and the area in which the greatest gains are likely to be realized. Incorporation of strong, race-specific genes for resistance to rusts and other diseases played an important

Table 1. Some rice pathogens documented as infecting wheat (16)

Rice disease	Pathogen(s)
Blast	*Pyricularia oryzae* Cav.
Brown leaf spot	*Cochliobolus miyabeanus* (Ito & Kurib.) Drechs. ex Dastur
Downy mildew	*Sclerophthora macrospora* (Sacc.) Thirum. et al.
Hoja blanca	virus
Leaf spots (various)	*Helminthosporium* spp.
Root knot nematodes	*Meloidogyne* spp.
Scab	*Fusarium* spp.
Seedling blight	*Sclerotium rolfsii* Sacc.
Sheath blight	*Rhizoctonia solani* Kuhn

role in the development of the green revolution wheat cultivars (23). However, because of the strong directional selection that this type of resistance places on pest populations, the usefulness of a particular gene is usually short-lived. The average commercial life of a rust-resistant cultivar in temperate areas is 5 years, but may actually be shorter in tropical areas. This tactic is expensive to maintain over time and, without effective monitoring and early warning systems for shifts in the pathogen population, it risks catastrophic pest-induced losses. IPM strategies to prolong the usefulness of strong genes include the regional deployment of specific genes (also a regulatory tactic), pyramiding several genes into one cultivar, and using multilines, cultivar mixtures, or crop mixtures to enhance disruptive selection on the pest population.

Major gene, race-specific resistance will undoubtedly be an important means of controlling leaf and stem rusts in tropical environments because genes are readily available and easily incorporated into adapted cultivars (23). However, incorporation of race-nonspecific, quantitative resistance (i.e., rate-reducing or horizontal resistance) genes into tropical wheats may ultimately be more cost-effective. This type of crop improvement undoubtedly was practiced inadvertently for centuries by subsistence farmers when they selected land races. Slow-rusting cultivars may be combined with other tactics to give satisfactory control.

Genetic resistance is appealing from an environmental standpoint but, when used as the sole management tactic, is subject to many of the same pitfalls as reliance on chemical control (9). Cultivars selected for strong resistance to one pest may create opportunities for secondary pests to become primary pests. For several important wheat diseases and insects, only low to moderate levels of genetic resistance can be incorporated easily into cultivars (8, 15, 18, 23). This is true for helminthosporium leaf spot diseases, scab, and most crown and root rots. Also, certain genotypes exhibit satisfactory resistance at moderate temperatures but give disease reactions indistinguishable from susceptible reactions under high temperatures (e.g., the reaction of the Brazilian wheat BR 8 to *Cochliobolus sativus* at 20°C vs 28°C) (6). Thus, integration of genetic control with other tactics is necessary.

Selection of wheat germplasm for tolerance (i.e., the ability to achieve acceptable yields in the presence of pest populations while supporting at least moderate growth and reproduction of the pest) to diseases, weeds, and insects is an ecologically sound tactic that has received relatively little emphasis. Tolerance has been used successfully, for example, in the management of barley yellow dwarf in certain oat cultivars. A disadvantage of tolerance is that high pest populations are maintained that continue to affect local, nontolerant cultivars and, in the case of highly changeable pests, increase the chances of new pathogenic variants arising.

Cultural tactics

The possibilities of cultural manipulation within a cropping system are myriad, and every perturbation causes changes at other levels in the agroecosystem. Evaluation of cultural tactics comes by empirical experimentation and observation over long periods of time (9, 20, 22); cultural tactics are not amenable to the sort of screening procedures available for genetic, chemical, and even for biological tactics. Therefore, while they are very relevant to control of wheat pests, cultural tactics will not likely predominate in the early stages of wheat IPM in the tropics.

Pest management has played a very important role in the evolution of traditional agricultural cropping systems (9, 20, 22). The paddy rice system provides an excellent example of cultural tactics for pest management. In addition to being highly effective for weed control, flooding reduces the survival of many fungi, insects, and nematodes between rice crops. The dry season fallow period following the wet season rice crop also reduces bridging of pests between crops. Ironically, the introduction of wheat as a dry season crop may partially reverse these advantages for rice. Valuable insights into potentially useful cultural controls could perhaps be gleaned from experiences in the few subtropical or tropical areas where wheat has been successfully cultivated for many years (19).

It is likely that cultural practices that promote vigor and early root development in wheat seedlings will be useful in IPM strategies to manage seedling blights and root rots, caused by opportunistic parasites such as *Sclerotium rolfsii* Sacc., *Rhizoctonia solani* Kuhn, and *Fusarium* spp. Plant stress and soil environment factors are very important in determining the severity of these problems (8).

Chemical tactics

Synthetic chemicals, used in conjunction with economic thresholds and in concert with other tactics such as genetic resistance and cultural controls, potentially could contribute to ecologically sound pest management in certain tropical wheat environments. The chemical tactic most frequently proposed for tropical wheat is the use of foliar fungicides for the control of fungal leaf spots; insecticides and herbicides have been prescribed to a lesser extent. While highly destructive diseases such as spot blotch, incited by *Cochliobolus sativus*, can be controlled effectively by protectant or systemic fungicides, their use is inconsistent with the needs and resources of most subsistence farming systems. This presents a serious dilemma. Many developing countries lack the necessary infrastructure for pesticide production, distribution, application, and monitoring (9, 10, 17, 20, 22). And the increased health risk to peasant farmers from exposure to improperly applied pesticides may outweigh any benefits realized from increased yields (20). The effects of wide-scale pesticide use on environmental quality (including water supplies) of villages and regions, i.e., common property values, should be included in any economic assessment of pesticide use. Some scientists (9, 20) have suggested that IPM implementation in the tropics bypass the intensive chemical use phase that has characterized modern agricultural development.

Even where the environment and human health could be safeguarded, agricultural chemicals exact a significant production cost. Their efficient use is predicated on a detailed knowledge of pest/pest control/yield loss relationships and economic thresholds that is lacking in most tropical wheat environments. Widescale use, especially of selective, systemic pesticides, can cause shifts in the pest spectrum and, while one pest is controlled, secondary pests can become major ones. For example, where selective fungicides have been applied to control powdery mildew, septoria tritici blotch, and leaf rust have increased in severity (13). Integration of control tactics, including the coincident use of wide-spectrum protectant chemicals, can help to limit this type of selection pressure. Reliance upon pesticides also imposes selection on pest populations for pesticide-resistant strains. Again, by combining IPM tactics such as crop rotation, partially resistant cultivars, and the mixing or alternating of chemicals with differing modes of action, the impact of directional selection on pest populations by selective pesticides can be reduced.

Granular pesticides applied in the furrow at planting and seed-applied pesticides are an order of magnitude safer than most aerial sprays. However, no pesticide should be applied without care being taken to protect the health of the applicator. Seed-applied, systemic, and protectant fungicides show considerable efficacy in management of certain seedborne and soilborne diseases and early season control of certain aerially disseminated foliar diseases. Seed treatment has been a very effective means of smut and bunt control on temperate wheat. Certain ergosterol biosynthesis-inhibiting fungicides such as triadimenol, when applied to wheat seed, have given excellent early season suppression of powdery mildew, leaf rust, and tan spot on the foliage, and have significantly reduced damage by soilborne diseases such as take-all.

Seed treatment may also be a promising tactic for partial control of seedling blights (caused by *Sclerotium rolfsii, Rhizoctonia solani, Fusarium* spp., *Pythium* spp., and other fungi) in tropical environments (8). Seed treatment is quite amenable to integration with other management tactics. However, even this IPM tactic is subject to special problems in developing countries. The more promising of the seed-applied materials are active at very low concentrations and require precise and sophisticated application technology carried out for the farmer by commercial or government technicians. The reliability and quality of such regionalized programs have been less than impressive in several developing countries (10). Also, there is the problem that subsistence farmers find it difficult to decide what amount of seed can be treated and set aside for next year's planting and what will be needed for food.

Biological tactics

Biological control has not to our knowledge played an important role in IPM for wheat in temperate regions, and it is unlikely that it will for wheat in the tropics either. However, biological tactics may be very useful to integrate with cultivar resistance and cultural controls on wheat in the future. Most biological controls are neither hazardous to the environment nor to the farmer, and they are appropriate for use in developing countries. The biggest impediment to biological tactics is the high cost involved in research to develop them.

Potentially, the introduction of predators and parasites from the pest's center of origin could be an important means of controlling many wheat insect pests in the tropics. This strategy is most likely to be effective against pests that occupy a limited habitat, i.e., their populations are regulated by intraspecific competition (4).

The most promising area for biological control of wheat diseases is the enhancement of natural biological control of root and crown rotting fungi. The use of leaf surface antagonists for control of foliar diseases also holds some promise (7), but practical applications are many years ahead. The use of insects and pathogens for biological control of weeds in wheat may have some utility where this tactic is combined with other tactics that stress the weeds (4, 5).

Regulatory tactics
Regulatory tactics include government-imposed implementation of genetic, cultural, chemical, and biological tactics. Seed certification programs, enforced planting and crop-free periods, and mandatory sanitation programs are examples of regulatory tactics (4). If properly conceived, many of these tactics are ecologically sound. In fact, the development of programs for seed certification on wheat in the tropics might greatly lessen the impact of seedborne diseases and several weeds. However, because of bureaucratic fraud and inefficiency, many of these systems have not worked well in developing nations. Goodell (10) argues that in the long run centrally controlled agriculture is less efficient than diversified ecosystem management.

The record of success on quarantine/eradication programs aimed against exotic pests is also mixed (4, 9, 20, 22). Where it has been established that an exotic pest would seriously affect yields if introduced, a quarantine can buy valuable time for development of effective control tactics. However, quarantines are very expensive and they tend to overshadow the fact that many important pests started out as endemic, secondary pests.

Research and Implementation

Table 2 is a subjective rating of the potential efficacy of various tactics for management of five diseases of importance on tropical wheat. For the reasons elaborated previously, it is unlikely that chemical tactics, with the possible exception of seed-applied pesticides, will be adapted to traditional cropping systems. Pest-resistant cultivars, cultural tactics (much research is needed on this), and biological control (especially for insects but potentially also for weeds and soilborne diseases) will be the backbone of IPM programs for tropical wheat.

Table 2. Potential utility of IPM tactics for disease management on tropical wheat

	Resistance		Cultural	Chemical		Biological
Disease	Major gene	Partial		Foliar	Seed	
Leaf rust	+ + +	+ +	+	+	+	
Loose smut	+ +				+ + +	
Root rot complex[a]		+	+ + +		+ +	+ +
Scab		+ +	+	+		
Spot blotch		+ +	+	+	+	

[a] Includes *Cochliobolus*, *Sclerotium*, *Rhizoctonia*, *Fusarium*, and *Pythium* spp.

The need for and importance of IPM research on specific local cropping systems cannot be overemphasized (11). Detailed, comprehensive pest surveys should be done. These programs should be long term since pest problems can be expected to change over time. Agronomic research on yield loss assessment is desperately needed for prioritizing other pest management research and for establishing economic thresholds. Social scientists should be involved in the development of treatment thresholds so that they reflect farmers' perceptions of risk (10). IPM decision criteria should be easy to understand and tactics simple and safe to implement (9, 10, 17, 20, 22).

Goodell (10) states that IPM extension in many developing countries is overshadowed by IPM research, and that IPM packages developed by researchers are often irrelevant to local needs. An effective extension program with direct contact between adequately trained advisors and local farmers is an essential component of IPM implementation.

In conclusion, the basic concepts of IPM are relevant and applicable to the culture of wheat in traditional cropping systems of the tropics. These systems are complex and require continual IPM research. However, it is appropriate that useful IPM tactics be implemented as they are developed.

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A Perspective of Research Needs for Nonirrigated Tropical Conditions

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Abstract
The research needs of the nonirrigated tropical wheat areas are discussed taking the Southern Cone of South America as an example. The wheat crop is the single most economic alternative for the winter cycle of this region, primarily in rotation with soybeans and maize.

The environmental stresses, such as unpredictable climate, higher temperature regime, lower solar radiation, and drought are discussed and the consideration of these within a breeding program is analyzed. In addition, the role of soil problems, pre-harvest sprouting, diseases, and insect pests in developing high-yielding and stable germplasm for this region is considered. The analysis demonstrates a need to maintain the wide adaptation base of the germplasm for above-mentioned characteristics and the merits of the multilocation testing system.

From the crop management standpoint, the lack of moisture at different crop stages is seen as the most limiting factor. The use of minimum tillage for moisture conservation, reduced soil compaction, and erosion is discussed. The removal of soil chemical barriers through amelioration is seen as essential to improve the root penetration and to increase water use efficiency.

The area under wheat in the nonirrigated tropical and adjacent subtropical regions of South America reached approximately 4 million ha during 1986. Wheat remains the single most economic alternative for the farmers of this area in rotation with summer crops such as soybean, maize, cotton, sunflower, and sorghum. While the good farmers using appropriate technology have been able to harvest more than 3.5 t/ha. of wheat, the average yield oscillates between 1.2-1.5 t/ha. It is this tremendous yield gap that needs to be filled in the short term, while future research programs to stabilize yield at the higher level or increase it further.

When discussing nonirrigated tropical conditions, we are usually referring to a climatic transition zone, ranging from a well defined winter dry season to a marked dry winter season, but where the rainfall is adequate for wheat production. Such an area is typified by south central Brazil, southern Bolivia, and Paraguay.

Climodiagrams presented in Figures 1 and 2 represent the two extremes of this area in Brazil. One is Londrina at latitude 23° 23'S and the other is Belo Horizonte at 19° 50'S. Although the overall annual climatic data such as precipitation (1485 mm vs 1561 mm), average monthly temperature (20.8°C vs. 20.6°C), and annual potential evapotranspiration (1092 mm vs. 1139 mm) are quite similar, Londrina is considered to be a wheat growing area, while growing wheat is impossible at Belo Horizonte because of the lack of moisture during the winter growing season. This emphasizes the narrow area in which a winter crop such as wheat can be grown under nonirrigated conditions in the tropics. Although a location such as Londrina is considered feasible for nonirrigated wheat because of an excess of moisture, with the exception of the month of August, the uncertainty of rainfall is still a major limiting factor. This transition area is characterized by a rainfall pattern of infrequent and heavy rainstorms.

The variation in yield caused by direct or indirect effects of unstable climate, gives the research for the tropical and subtropical regions of Latin America a different dimension than the traditional wheat growing regions. This paper covers only the research needs for this region.

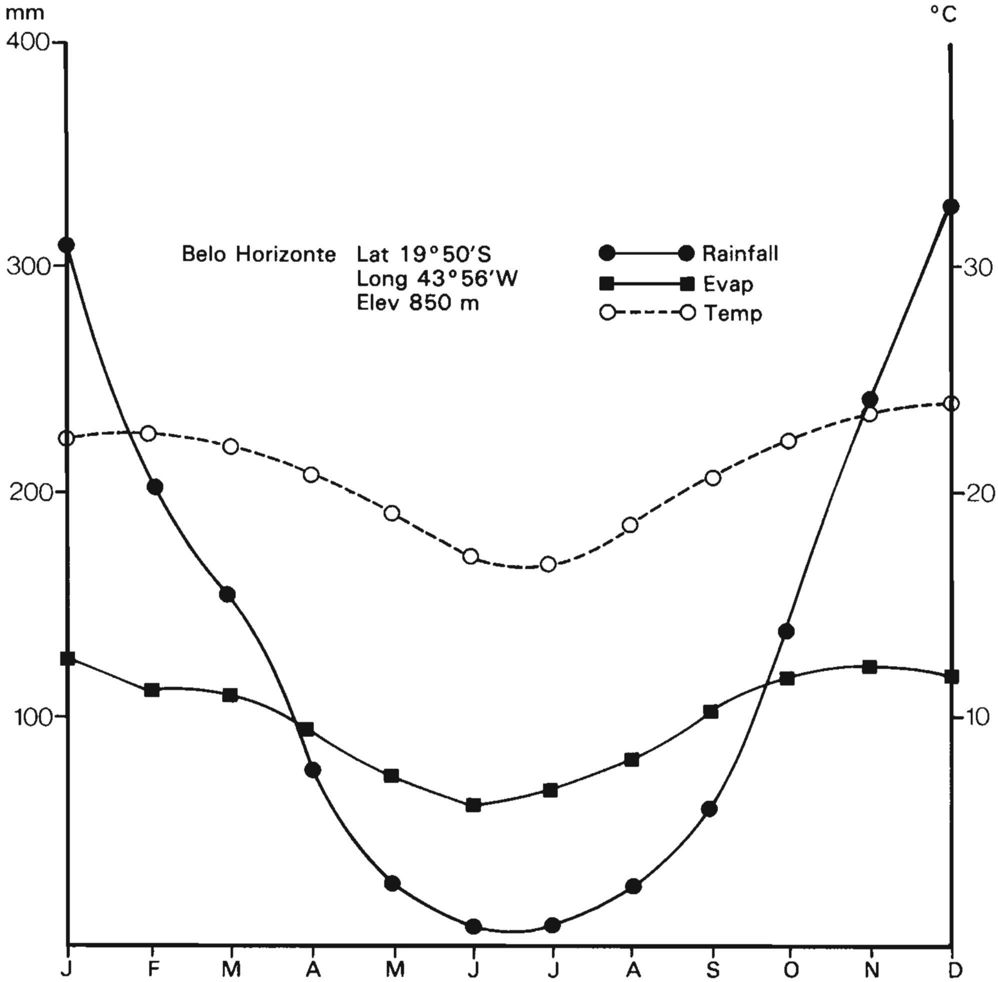


Figure 1. Climatic summary of Belo Horizonte, Minas Gerais, with an average monthly temperature of 20.6°C, an annual rainfall of 1561 mm and an annual potential evapotranspiration of 1139 mm.

Breeding for High Yield and Yield Stability

Several environmental factors condition the development and success of the wheat crop in the warmer areas of the Southern Cone region (Table 1). Some of these factors and their influence on the breeding process are discussed below.

Unstable climate
Unstable climate in the nonirrigated tropics is more of a rule than the exception. The abrupt changes in temperature and rainfall (humidity) conditions of the semitropical region of Latin America were reported in the proceedings of the symposium on Wheats for More Tropical Environments (11, 13, 14). The selection of germplasm under such variable conditions, from one year to another, results not only in the loss of valuable materials, but also in the failure to identify high-yielding varieties.

The yield data reported in the International Spring Wheat Yield Nursery (ISWYN) 1982-83 and 1983-84 from several locations in the region were compared for this purpose (Table 2). Selected widely adapted varieties both old (Siete Cerros and Anza) and new (Veery "S" and Bobwhite"S") were

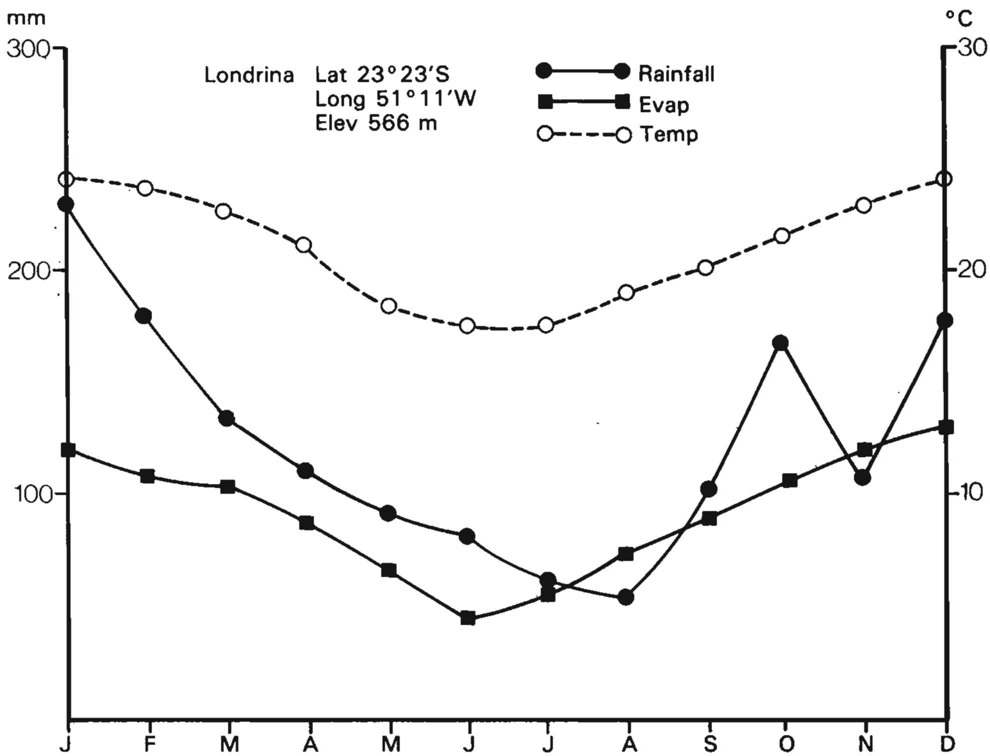


Figure 2. Climatic summary of Londrina, Paraná, with an average monthly temperature of 20.8°C, annual rainfall of 1485 mm, and annual potential evapotranspiration of 1092 mm.

compared with the locally adapted varieties (local checks) at each location. The ranking in the trial demonstrated a clear advantage in favor of widely adapted varieties. Although yield superiority of the new varieties over older varieties is evident across locations, even older cultivars tend to outyield the local check varieties in the absence of diseases.

The selection of germplasm in a specific area with variable climate may seem an attractive methodology, however, the usefulness of multilocation selection and testing in the development of high yielding and stable germplasm can hardly be over-emphasized. The selection of widely adapted parents over many tropical locations for

Table 1. Environmental factors affecting the wheat crop in the Southern Cone region

	Heat			Drought			Frost at	Rains at
	Early	Mid	Late	Early	Mid	Late	flowering	harvest
Northern Argentina	*		*	*	*		*	*
Southern Bolivia	*	*	*		*	*		
Northern Brazil	*	*	*		*	*	**	*
Southern Brazil			*				**	**
Paraguay	*	*	*	*	*		**	*

Table 2. Yield comparison between selected widely adapted varieties and local checks in the ISWYN, 1982-83 and 1983-84

	Yield ranking in ISWYN						
	1982-83				1983-84		
Varieties	Santa Cruz Bolivia	Cerrado Brazil	Londrina Brazil	Caacupe Paraguay	Abapo Izozog Bolivia	Cerrado Brazil	Londrina Brazil
Siete Cerros				30		19	19
Anza	13	18		2			20
Hoopoe "S"	17	14		31	3		
CIANO 79	6	1		5			14
Veery "S"	1	17	3	4	2	11	2
Bobwhite "S"	14	8		19	4		3
Local Check	22	36	11	45	5	24	21
Variety	Bobito "S"	BR 8	Cocoraque	C5849	Pai Cupesi	BR 8	Cocoraque

recombination purposes and multilocation testing of segregating/advanced germplasm will play a key role in the breeding for higher yield potential under unstable climatic conditions.

Heat

A major characteristic differentiating tropical wheat areas from the traditional regions is their high-temperature regime. Average maximum and minimum temperatures during the wheat cycle of several locations in the southern cone region are compared with those of the Yaqui Valley in Mexico (Figures 3 and 4). Note that a greater difference and more variability exists among locations for the average minimum temperature than for the average maximum temperature.

The adverse effects of high temperature contribute to a lack of adaptation and reduced yield potential. The most important aspect of heat is related to the hastening of plant development and shortening of developmental phases during which various components of yield are determined. Fischer and Maurer (8) showed that a 1°C rise in temperature above ambient during the period between the end of tillering to the beginning of grain filling reduced yield by 4%. Yield reduction was associated with a reduced number of spikes per plant and grains per spike.

According to Warrington et al. (18), of the three major developmental stages, the growth stage GS 2 between spike initiation and anthesis was the most thermo-sensitive. Reduction in duration of GS 2 under high temperature conditions resulted in the reduction of number of spikes per plant and of spikelets and/or grains per spike. The partial spike sterility observed at many locations in the Southern Cone region is also

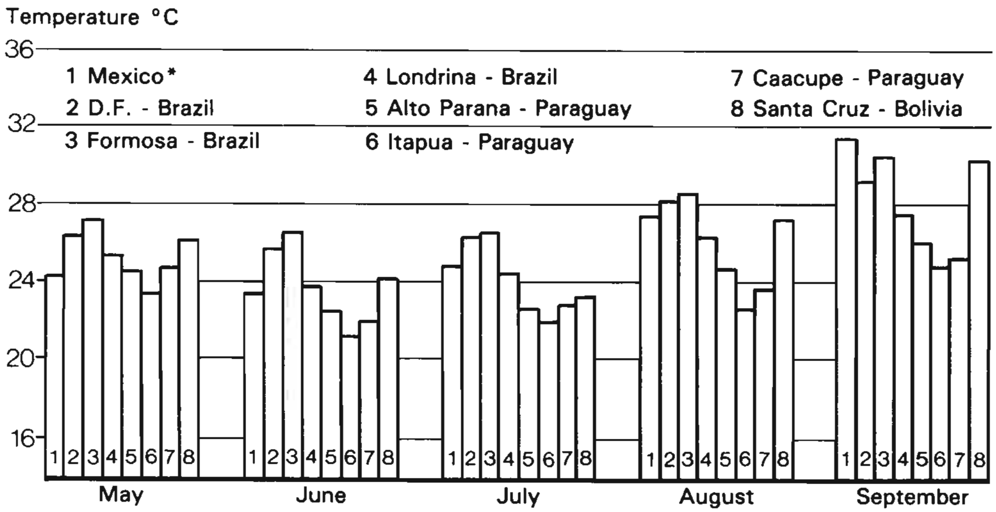


Figure 3. Average maximum temperature during wheat crop cycle in Mexico and selected locations in South America.

* Mexico crop cycle December - April

ascribed to the effects of high temperatures combined with low relative humidity during the flowering period (4).

The strong influence of heat on wheat growth and yield raises an important question regarding available genetic variability and adaptation to the hot environments. Photoperiod and vernalization sensitivities, which delay the rate of development up until flowering, do not improve adaptation to hot areas, as this delay is not related to an increase in number of grains per spikelet or per spike. However, once the vernalization and photoperiod requirements are fully met, wheat varieties differ in the extent of heat effect on number of spikelets per spike (10). The excellent stability in grain number per spike demonstrated by the wheat variety Kalyansona as compared with Condor under increasing temperatures is a remarkable example (1).

Kalyansona (a sister selection of Siete Cerros) has previously been described as a widely adapted variety.

As a result of reduced thermo-sensitivity at GS 2, there are wheat genotypes better able to sustain grain number per spike at higher temperatures, as exemplified by Kalyansona (1). The reduction in the number of grains per spike in hot environments is the result of reduced number of grains per spikelet and fewer spikelets per spike. Both components can be very easily assessed by visual observations. Therefore, the selection of spikes with a higher grain number under hot environmental conditions is likely to result in improved yield and stability.

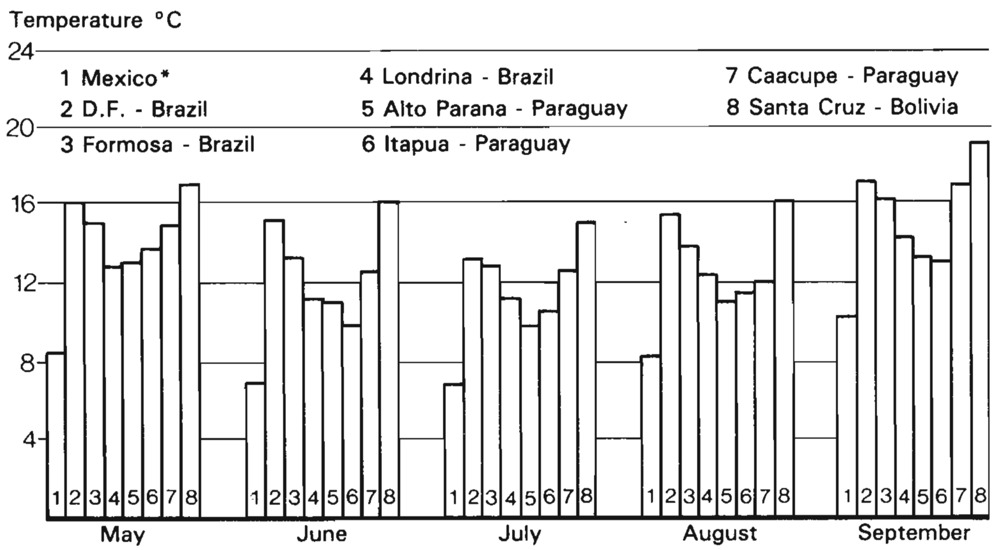


Figure 4. Average maximum temperature during wheat crop cycle in Mexico and selected locations in South America.

* Mexico crop cycle December - April

Lack of illumination (cloud cover)
In the tropical Southern Cone region, heavy cloud cover and thereby reduced solar radiation during the wheat season is a common phenomenon (Table 3). Shading experiments conducted at CIMMYT during the 1972-77 period demonstrated the impact of reduced solar radiation on the total dry matter production and the yielding ability of highly productive varieties (3, 4, 5). The reduction in crop growth (measured by dry matter accumulations) was found to be an amount approximately equal to the percentage reduction in radiation.

The results of these trials indicated that early shading has little or no effect on the grain yield although tillering is substantially reduced. Shading during spike emergence, or just before, has a drastic effect on grain yield through reduced number of grains/per unit area. The result is fewer grains/spikelet with little increase in kernel weight to offset the loss. This is the period of maximum dry matter accumulation in the spike. The anthesis and early grain growth period is relatively insensitive to shading. Kernel weight may or may not be sensitive to post-anthesis shading.

The effect of relatively lower solar radiation at three plant growth stages was recently studied by Wendt and Cayetano (19) in Brazil (Table 4). Their shading studies (60% light reduction) on two wheat varieties, IAS 20 and BR 4, indicated the pre-heading period to be most critical in terms of dry matter reduction and yield loss.

Drought
It was stated earlier that the annual rainfall pattern of the region is very unpredictable. Rainfall from Chaco, Paraguay, provides an example of this unpredictability during the wheat crop cycle (Table 5). While there is some variation in the total precipitation received from one year to another, there is strong variation within each year. Lack of knowledge regarding appropriate moisture conservation technology in this area, combined with the unreliable early precipitation pattern, leads to

Table 3. Comparison of long-term cloud cover and solar radiation data in selected locations in Brazil and Mexico

	No. of covered days		Solar radiation cal/cm^2/day			
Month	St. Augusto	S. Borja	S. Augusto	S. Borja	Formosa	Cd. Obregon[a]
May	15	10	255	254	378	350
June	16	13	210	207	377	290
July	16	13	230	216	428	310
August	17	13	262	256	445	400
September	15	13	355	306	423	520
October	15	10	426	422	405	610

[a] Comparable data from November to April

variation in the date of seeding. This latter factor in turn increases crop production variability from year to year. Mid-term drought around the heading period is more common all over the region, which seriously reduces the yield potential of the crop. Since the pattern of moisture availability is different among seasons and from one location to another, the drought tolerance of a variety must be location- and season-specific. The pyramiding of other traits, such as high and stable yield potential on top of drought tolerance, may provide flexibility and plasticity of response.

In general, there is a highly significant correlation between grain yield and maturity under drought situations, with early flowering favoring higher yields under stress conditions. However, there is evidence that some late lines are also less affected by drought conditions such as, C5849 (Paraguay), E. Lusitano (Uruguay), and Chaqueño INTA (Argentina). The use of yield reduction as a criterion to measure drought tolerance must take the yield potential of a variety, under well watered and highly fertilized conditions, into consideration. For varieties with low yield potential that do not benefit greatly from high fertility or abundant water, the percent reduction in the yield by drought will be similar compared with a larger reduction in the high-yielding varieties.

Table 4. Average effect of 4 weeks of shading on the dry matter production of different plant parts of wheat (19)

Crop stage	Percent dry matter reduction		
	leaf	stem	spike
22	39.5	49.4	
45	23.3	28.8	40.9
68	11.4	21.1	19.4

Table 5. Rainfall pattern during wheat season in Chaco, Paraguay

Month	Rainfall (mm)					
	1981	1982	1983	1984	1985	1986
May	50	33	108	7	12	188
June	16	32	30	33	0	24
July	0	17	117	14	37	0
August	58	5	0	115	28	10
September	16	76	14	23	79	20
Total	140	163	269	192	156	242

Thus, yield performance under stress, as well as the drought experiments per se, have limited value because conditions are unlikely to be sufficiently similar to extrapolate one site to another, especially with the corresponding influence of soil types. It is suggested that international yield and screening trials are likely to be better indicators of performance under drought conditions than the drought trials specifically designed to measure the resistance or tolerance of a germplasm (5). The alternative approaches—a) to select segregating populations under well watered conditions and to test the advanced lines under multiple-drought stress locations or b) to begin selection under well watered conditions and the testing of one or two alternating segregating generations under drought stress, with later identification of the high yielding lines under optimum conditions—may allow a much more rapid success in the identification and development of the drought tolerant germplasm. Such germplasm is likely to perform better under drought stress, but also stands a chance to respond to any additional moisture available.

Pre-harvest sprouting

The predominantly summer rainfall pattern of these tropical areas causes a serious problem with pre-harvest sprouting in the commercial wheat crop in some years (11). During 1986, serious deterioration in grain quality and sprouting damage were observed in parts of Brazil and Paraguay.

The work on pre-harvest sprouting under controlled conditions has demonstrated genetic variation with regards to resistance to this character. However, the work to incorporate sprouting resistance into high-yielding germplasm is limited to Australia, northern Europe, and recently Brazil. Some earlier work done in southern Brazil led to the identification of the Frontana variety, which maintains a high degree of sprouting resistance. Efforts are needed to intensify incorporation of known sources of resistance into high-yielding, tropically adapted germplasm. Sources of resistance such as Frontana, Kleiber, Jufy I, WW9941, Takabe, and RL4173 can form the basis of a crossing program designed to develop sprouting-resistant germplasm.

The positive correlation between "falling number," an indirect method to measure Alpha-amylase activity in the seed, and resistance to sprouting serves as a useful technique to screen large populations. The modification used by Rosa et al. (16) in Brazil to correlate "wet" falling number with resistance seems to provide a more accurate measure.

From a practical standpoint, considering the number of complex characters that need to be combined in a wheat breeding program, the testing for resistance to sprouting may have to come in the advanced generations. Although early screening through the use of "falling number" is possible, the field screening by leaving the material standing past maturity into the rainy season provides another effective and practical selection pressure. It may also be necessary to screen the selected advanced germplasm at several key locations (especially with different temperature regimes) to identify stable resistance to sprouting.

Acid soils with aluminum toxicity
This topic has already been dealt with in great detail earlier so we will only discuss it briefly. The problems of soil acidity combined with toxicities of aluminum, manganese, or iron, individually or in combination, are important in some parts of Latin America and also in Africa.

The Brazil-CIMMYT shuttle breeding program over the past 13 years has been able to combine the tolerance to aluminum toxicity of the Brazilian wheats with the short stature, stiff straw, and highly fertile traits of the Mexican types. The additional advantage of improved disease resistance in the resultant germplasm has been a key to the recent release of six varieties from this program in Brazil.

In addition to improving further disease resistance in these wheats, it may be useful to broaden their adaptation by adding an efficient phosphorus extracting mechanism to the newer germplasm. The superior phosphorus uptake ability of the varieties PG-1, Toropi, and Alondra need to be exploited further.

Several wheat breeding programs including that of CIMMYT are using aluminum screening techniques in the laboratory for both segregating populations and advanced generations. The use of this method to discard a large number of susceptible plants in the early generations, combined with field testing of resistant plants, may prove to be very efficient. The laboratory screening technique allows the testing of various levels of mineral toxicities individually, or in combination to suit the need of a particular region. Some work on phosphorus uptake efficiency is also being done in the laboratory by C. Camargo (personal communication) at Campinas, Brazil, which may prove beneficial to achieve the overall objectives of developing high-yielding wheats for acid soils areas.

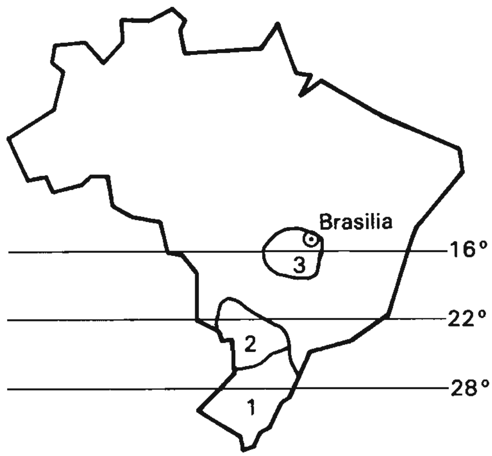
Breeding for Disease Resistance

The importance of diseases in the tropical wheat growing regions was emphasized during the 1984 Symposium in Mexico. The complexity and importance of some diseases present in Southern Latin America are shown in the Table 6. During a normal year, one or more diseases are present in several parts of the Southern Cone. Leaf rust, spot blotch, and scab can be severe every year. However, the development of other diseases depend more on the seeding date, management practices used, and the climatic conditions during the crop season. Although most wheat breeding programs in this region dedicate a bulk of their efforts to improve disease resistance in general, the advances have been slow.

A large number of disease control experiments done in wheat over the past 10 years indicate severe disease-induced losses, approaching 60 to 100% in some cases (6). Such production losses have forced farmers to adopt commercial chemical control measures. Even then, losses ranging from 12 to 19% are still observed in some parts of Brazil, every year (Figure 5).

The dynamic changes in the virulences of rusts and small variation in the sources of resistance to foliar diseases and scab have been a major barrier to the progress in the breeding for resistance. The predominance of a particular disease in a given year and that of another the next, causes a serious problem in the selection process. Effective breeding for disease resistance can hardly be successful without adequate artificial inoculation techniques under field conditions.

While it is essential to identify a high degree of resistance in the parents, it is becoming quite evident in the region that the "zero susceptibility concept" of some alien genes is of limited value. Several varieties carrying Lr9 (*Aegilops umbelullata*), Lr24 (*Agropyron elongatum*), and Lr26 (*Secale cereale*) for leaf rust resistance have lasted only 1 or 2 years in commercial fields before becoming highly susceptible. Preliminary work on *Helminthosporium sativum* (12) and *Septoria tritici* (7) indicates the presence of extensive variability in these pathogens in the region. It has also been observed that some sources of resistance to scab from Argentina are susceptible in Brazil and those from the whole region are susceptible in China. Under such circumstances, to look for a high degree of resistance to any one of these diseases or their combination seems like a futile effort.



Diseases	Estimated Percent Loss Region 1	Region 2	Region 3
H. sativum	3	6	4
Leaf rust	3	3	4
Stem rust	1	1	3
Fusarium	2	2	1
Septoria nodorum	4		
Root rot	2		
Ophiobolus graminis	2		
Soilborne mosaic virus	2		
Total	19	12	12

Figure 5. Annual estimated losses caused by the diseases in the wheat crop in Brazil. These losses occur despite chemical control.

Table 6. Disease problems of wheat in the Southern Cone region

	Rusts		Powdery	*Helminthosporium* Leaf blotch		*Septoria blotch*			Root		
	Leaf	Stem	Mildew	Spot	Tan	Leaf	Glume	Scab	rot	Bacteria	BYDV
Northern Argentina	**	**	*	*	*	*	—	*	—	*	*
Eastern Bolivia	**	**	*	**	*	—	—	*	—	*	*
Northern Brazil	**	**	**	**	**	—	—	**	*	**	*
Southern Brazil	**	**	**	*	*	**	**	**	—	**	**
Paraguay	**	**	**	**	*	*	*	**	*	**	*

* Important (limiting factor); ** Very important (critical factor)

Limited work to transfer known genes for resistance into agronomically acceptable germplasm is being done. While it is an appropriate approach to develop germplasm, it needs to be complemented strongly by efficient disease screening techniques. In addition, the tendency to recover the complete resistance through five or more backcrosses instead of pyramiding resistance from different sources seems to lead to a status quo situation in terms of productivity.

It is, therefore, suggested that the identification of reliable "hot spots" for selection of segregating and advanced populations is of prime importance in breeding for disease resistance. In some cases, it may still be necessary to artificially inoculate to get the infection started early and increase effectiveness of selection.

The cycling of outstanding (broadly adapted and resistant) germplasm in multiple crosses and larger segregating populations will yield agronomically useful recombinants at a faster rate. Shuttle breeding to enhance the selection of germplasm in more than one region before cycling may also be another alternative. Multilocation testing, thus, will play a key role in any effort to breed for the complex disease picture presented earlier.

Insects Pests

Insects are a much more serious problem in wheat in the tropical than in the traditional wheat regions. Fewer studies have been done with regards to their importance in the crop or the losses they cause. Yet, it is common to observe farmers applying insecticides to control one insect or another each year. Some data regarding farmer-reported insect damage in southern Bolivia during 1985 are presented in Table 7. Although Gassen (9) included a large list of insects associated with the wheat crop in Brazil, the most predominant this in the region are aphids, stem borers, and armyworms.

Considering the difficulties involved in the identification of resistant germplasm to insect pests and availability of efficient screening techniques to incorporate such resistance into new varieties, efficient control measures (biological or chemical) will keep playing an important role against insect pests in the tropical regions.

Agronomic Constraints

When we think of moisture available for plants we have to think not only of the amount that falls in precipitation, but also of the amount that is stored in the soil and

Table 7. Insect damage in southern Bolivia region, 1985

Insect	Percent farmers reporting	Damage reported: Light	Moderate	Severe
Aphids	97.8	20.0	31.1	46.7
Stem borers (*Diatraea* sp.)	40.0	37.8	2.2	–
Armyworms (*Spodoptera* sp.)	28.9	20.0	8.9	–

available for plant growth. If rooting is limited by acidity or a plow pan, then this further reduces moisture available for plant growth in an already uncertain situation. We believe the moisture problem to be the main agronomic constraint in this area. We also believe that reduced or no-tillage practices could be a solution for this problem. From an agronomic research perspective, this could be the most important area of research to be pursued in the near future for nonirrigated wheat in this tropical transition zone.

Erratic rainfall, plant establishment, and moisture utilization

The moisture instability discussed earlier can be ameliorated by better moisture control in the top 10 cm of the soil, which can be achieved with better tillage practices. Zero-tillage reduces soil moisture loss from the top 5 cm thereby giving the farmer better control of the sowing date. This is shown in Figure 6 where soil moisture is higher in the top 5 cm under no-tillage vs conventional tillage.

As the crop develops, the total amount of water stored in the profile becomes critical as a water deficit can occur during heading and grain filling (June, July, and August) again due to erratic rainfall. Low rainfall during this period accompanied by inadequate soil moisture reserves reduces wheat yields severely. No-tillage will reduce soil moisture losses early on the season when need for moisture is less. This additional stored moisture will help in the potentially deficit periods of June, July, and August. The effect of no-tillage and conventional tillage in Paraná is shown in Table 8. In years of inadequate rainfall, no-tillage is far

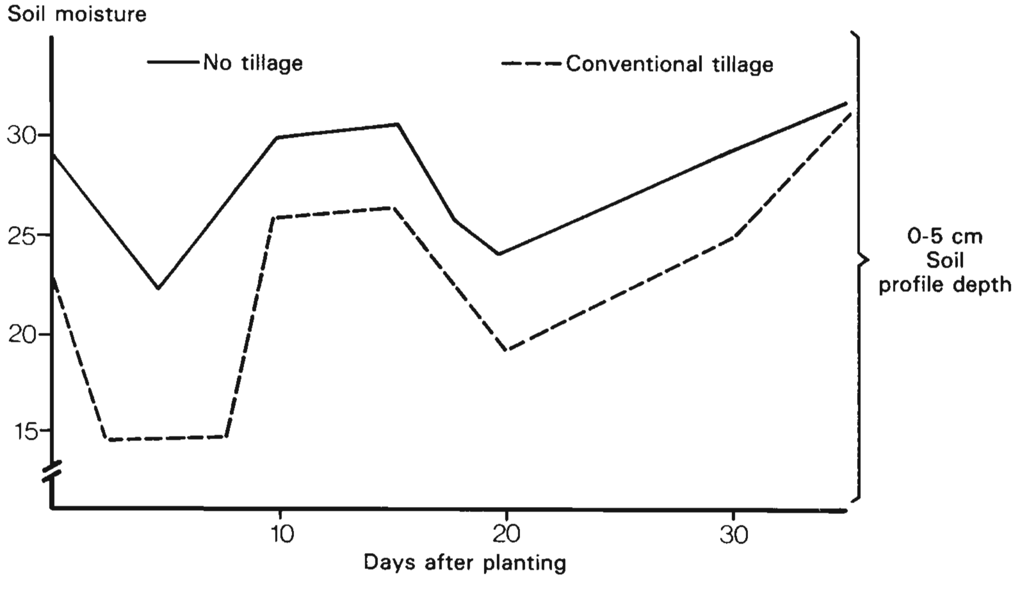


Figure 6. Soil-water availability under conventional and zero tillage systems in an Oxisol soil, northern Paraná, Brazil. Source: Muzilli (13)

superior to conventional tillage. Its yield relative to conventional tillage was 159% and 402% in the 2 years of inadequate rainfall, respectively. In what was classified as a normal year, the yields were relatively similar.

In the no-tillage system of crop production, a mulch consisting of plant residues is present on the soil surface during the growing season. The rate of water loss through mulches is generally very slow in comparison to the rate of water loss from a moist soil surface. The reasons for this are threefold:

1) In order for water to be lost by evaporation from a mulched soil, the water must change from a liquid to a vapor at the soil surface. The water vapor must then diffuse through the thickness of the mulch which significantly reduces the rate of loss when compared to a bare soil surface.

2) The mulch reduces the quantity of direct solar radiation reaching the soil surface, thereby reducing the amount of energy available for evaporation. This is a factor that is very important under these subtropical conditions.

Table 8. Comparison of wheat yields under inadequate and normal rainfall conditions related to tillage systems, Northern Paraná, Brazil, 1977 to 1980 (17)

	Wheat yields (kg/ha)	
Rainfall/year	**Conventional**	**No-Tillage**
Inadequate		
1977	609	967
1978	507	2036
Normal		
1979	1854	1281
1980	1867	1799

3) Mulches act as insulators to the downward conduction of heat into the soil.

A schematic representation of cumulative evaporation versus time for a bare soil and for the same soil with a mulch is shown in Figure 7. The mulched soil retains the same rate of evaporation all through the time shown in Figure 7 while the bare soil has a much higher rate initially. If given sufficient time without rainfall, the cumulative evaporation of the mulched soil can exceed that of the bare soil because in the mulched soil water will be lost from greater depths. Soil water will be conserved in the mulched or no-tillage soil if rainfall occurs before the two curves cross each other. This time will vary for each soil type and location, but can be easily determined. In order that the maximum amount of water be conserved due to a mulch or no-tillage, rainfall should occur at about time A. When sufficient rainfall occurs to rewet the surface of the bare soil, evaporation will start again at an initial high rate and the curve shown in Figure 7 will be repeated. The more often this occurs, the more water is conserved by no-tillage or mulch. This increased amount of water may then be transpired by the growing crop.

The above principles of soil water evaporation apply in the early part of the growing season before a full crop canopy develops. After a full crop canopy develops, soil water evaporation is significantly reduced for the conventionally tilled soil. Therefore, most of the value of the conservation of soil water due to no-tillage or a mulch occurs before the development of a full crop canopy. This early conservation is important because it conserves soil moisture during crown root initiation which ensures adequate tillering. This extra moisture may also carry over into the pre-anthesis and anthesis periods when a moisture deficit may be more critical.

Effect of tillage on compaction and erosion

These tropical areas, as mentioned earlier, are characterized by precipitation with a very high index of erositivity and intensities of up to 160 mm/hour during 15 or 20 min. This, coupled with a system of excessive soil tillage in an inadequate double cropping system, has led to increased erosion, removing organic matter and nutrients.

Erosion studies at the Paraná State Agronomic Research Institute (IAPAR), based on a 6% slope, have shown that, when the slope is tilled up and down, soil losses can be as high as 700 t/ha per year, equal to a soil layer of 7 cm. With contour tillage, losses can be up 400 t/ha per year, but if the combination of terraces and good tillage practice is used, erosion losses can be reduced to 100 t/ha per year. Despite the effect of terraces in reducing soil erosion, soil losses are still too high to fully maintain soil fertility.

One principle holds in limiting soil erosion, and that is that water which penetrates the soil and percolates

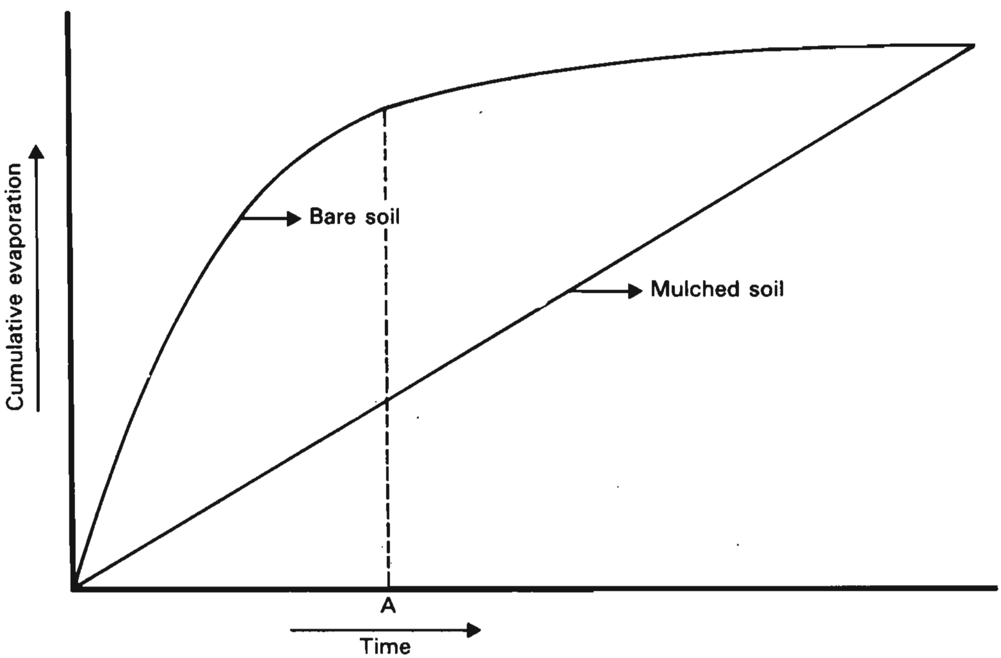


Figure 7. Schematic representation of cumulative evaporation of soil water as a function of time for a bare soil and the same soil with a mulch on the soil surface.

Source: No-tillage Agriculture Principles and Practices. R.E. Phillip and S.H. Phillips, eds. Van Nostrand Reinhold, New York. 1984.

through it cannot cause erosion. Permeability is highly correlated with the volume of macropores in the soils found in this area, such as Oxisols and Alfisols (Figure 8). The macropore volume is also correlated with soil compaction—the lesser the volume, the greater the compaction. Compaction due to tillage occurs very quickly on these soils, usually at about the 20-cm depth. Not only does this compaction lead to increased erosion, but also to decreased root penetration and decreased use of subsoil moisture. No-tillage practices should maintain the high natural porosity of these soils and avoid a compacted soil layer. This in turn should increase water infiltration, reduce soil erosion, increase root penetration, and therefore, increase moisture use.

Chemical barriers to root penetration

Many of these soils, i.e., Oxisols and Alfisols, are characterized by an acid subsoil which inhibits root growth and decreases water use. Thus, to overcome water deficits during critical periods of crop growth, it is necessary to mitigate acidity in the subsoil so that roots can grow more deeply and explore a larger volume of soil.

Ritchey et al. (15) report the behavior of two neighboring maize crops on a typic haplustox at Brasilia during a dry period. Both crops were approximately at the same stage of development. One crop was wilted while the other showed no signs of drought stress. The nonstressed crop had received 559 kg P/ha as ordinary superphosphate several years before

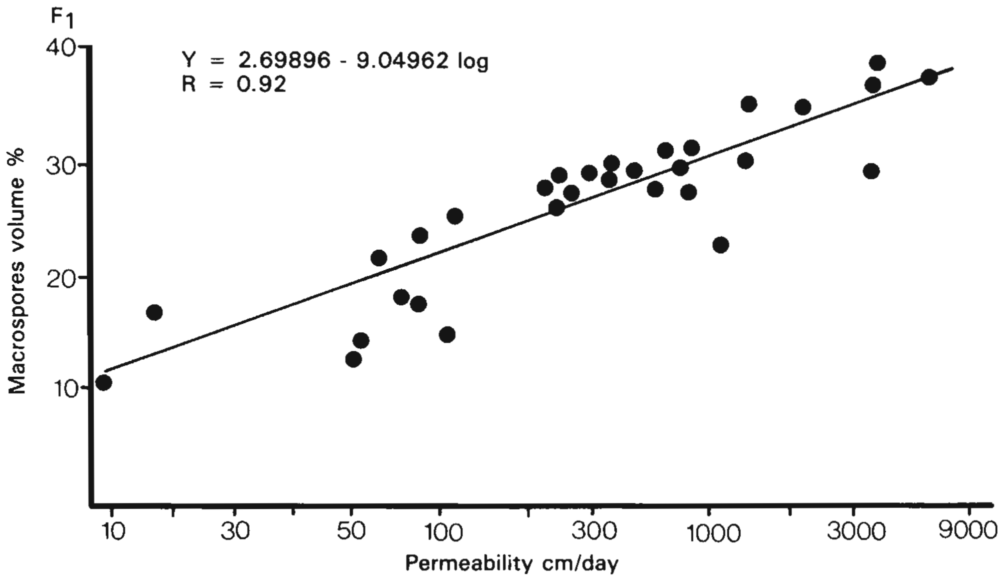


Figure 8. Relation between the volume of macrospores and the permeability of different soils in Paraná.

Source: Kemper & Derpsch. Soil Compaction and Root Growth in Paraná *In*: The Soil/Root System in Relation to Brazilian Agriculture. R.S. Russel et al., eds. IAPAR 1981.

and was found to have roots extending to 120 cm. The wilted maize, which had been fertilized more recently with 148 kg P/ha as triple superphosphate, had roots to only 45 cm. This difference was attributed to the large quantity of calcium sulphate added in the ordinary superphosphate. The downward movement of calcium sulphate in these soils had greatly increased the amount of Ca in the subsoil. It has been shown that in the absence of toxic or competitive cations, at least 2 ppm Ca should be present in nutrient solution for normal development of maize plants. However, in many of these tropical subsoils, the level of Ca in the soil solution is below this.

Calcium cannot be incorporated to depths greater than 30 cm, therefore, it has to be leached into the subsoil. The Ca ion cannot leach alone. To maintain electro-neutrality, an anion must move with it. The rate at which Ca is leached is dependent on the mobility of the accompanying anion. Ritchey et al. (15) concluded that the carbonate of the limed treatment is neutralized by reaction with acidity in the surface soil and hence no anion is available to accompany the Ca which is almost entirely sorbed on the exchange complex. Calcium added as calcium chloride leached most rapidly and calcium sulphate (gypsum) was intermediate. The quantities of gypsum necessary to reduce aluminum toxicity throughout the soil profile can be considerable because the lower the pH, the higher the level of sulphate sorption. This would lead to the conclusion that the pH in the surface soil should be raised with $CaCO_3$, so that the gypsum added later would be more easily leached.

Summary

Wheat in the nonirrigated tropics is a relatively new phenomenon. There has been a virtual explosion in the area sown in South America (Brazil, Paraguay, Bolivia, and Argentina) over the past 15 years. This has been mainly because much new land was opened in this area for the summer cultivation of soybeans, and wheat has offered the best potential for winter cropping. This new cropping pattern has presented many new challenges for wheat research. Most of this work is new, but great progress has been achieved over the past 10 years.

Sources of germplasm have been identified for the solution of the various constraints and there are many strong breeding programs in the area. Agronomic problems have also been tackled on a broad front.

Some of the soil problems have been solved and some of these solutions are being applied in practice. Reduced tillage methods are being projected and this has led to a greater control of erosion and a build-up of organic matter, as well as better moisture control.

New liming methods are being investigated and in some cases have shown great promise in increasing effective rooting depth. It is now obvious that, with further progress in research, wheat production will be a very viable alternative in these areas of South America.

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Integration of Wheat Research and Production in Bangladesh

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Abstract
Wheat expanded phenomenally in Bangladesh between 1974 and 1983 due in part to the efforts of the Wheat Centre research team at the Bangladesh Agricultural Research Institute. These scientists have faced the challenge of increasing wheat production in an increasingly volatile socioeconomic environment for wheat by taking the products of their research directly to growers through on-farm demonstrations of new varieties and cost-saving production techniques such as reduced tillage. Training efforts have encouraged interaction between scientist and farmer.

Since its rapid rise as a crop in Bangladesh starting in 1974, wheat has become the country's second most important cereal crop. About 1.2 to 1.4 million tons of grain are produced annually. This production provides millions of farm families a source of food/income essential in this country of low agricultural productivity, shrinking land resources, and burgeoning population growth. Appropriately, the Government of Bangladesh has supported wheat production by mandating the varietal improvement and production research activities of the Bangladesh Agricultural Research Institute (BARI).

The research team at the Wheat Centre, BARI, has combined the introduction of appropriate varieties and production practices with intensive interaction with officers of the Department of Agricultural Extension (DAE), the Bangladesh Agricultural Development Corporation (BADC—the national seed producing agency) and growers (2). As a result, wheat production rose from about 120,000 ha of low-yielding, late-maturing, lodging-susceptible varieties producing about 120,000 tons in 1974 to a high of about 607,000 ha of high-yielding, early-maturing, lodging-resistant varieties producing 1.4 million tons by 1984/85 (Figure 1).

In 1985/86 wheat area dropped dramatically, to about 500,000 ha, due to the lack of timely pre-winter rains, late harvest of rice crops, reduced subsidies on fertilizers, and increased competition from other winter crops. This reduction was not because of a lack of confidence in wheat as a crop by farmers. Figure 1 indicates the volatility of wheat production since 1979. This increasing volatility, resulting from the aforementioned reasons in addition to the problems associated with growing wheat in a rice-based culture, is the present challenge to national wheat scientists. I am proud to be a part of this effort and pleased to have the opportunity to describe the problems that are addressed by members of the wheat improvement team in Bangladesh and their efforts toward integrating the products of their research into practical use on the farm.

Research

Varietal improvement

The national wheat breeding effort has been structured to identify varieties that are sufficiently flexible to produce well in the country's complex rice-based cropping systems, rather than attempt to change the systems to provide favorable conditions for the wheat crop. Such "flexibility" has meant relative yield stability across a range of 1) planting dates, from about mid-November to the first of January, and 2) moisture availability.

History has not been kind to varieties that did not measure up to these imposing standards. An indication of this lesson can be seen in Table 1, which lists the percent availability of various varieties of certified seed through BADC from 1976 to 1983/84. Pavon, for example, was released in Bangladesh in 1979. If planted by mid-November, it is a higher-yielding variety than Sonalika (which occupies 80% of the wheat area). However, demand for Pavon declined soon after its release, as its yields tend to decrease dramatically when it is sown late (Table 2). This confines its use to the small percentage of farmers who can consistently plant at a favorable date.

On the other hand, the yield of the earlier-maturing Sonalika is more reliable across planting dates, which accounts in part for its endurance in much of South Asia, including its position as de facto "traditional" wheat variety in Bangladesh. Despite

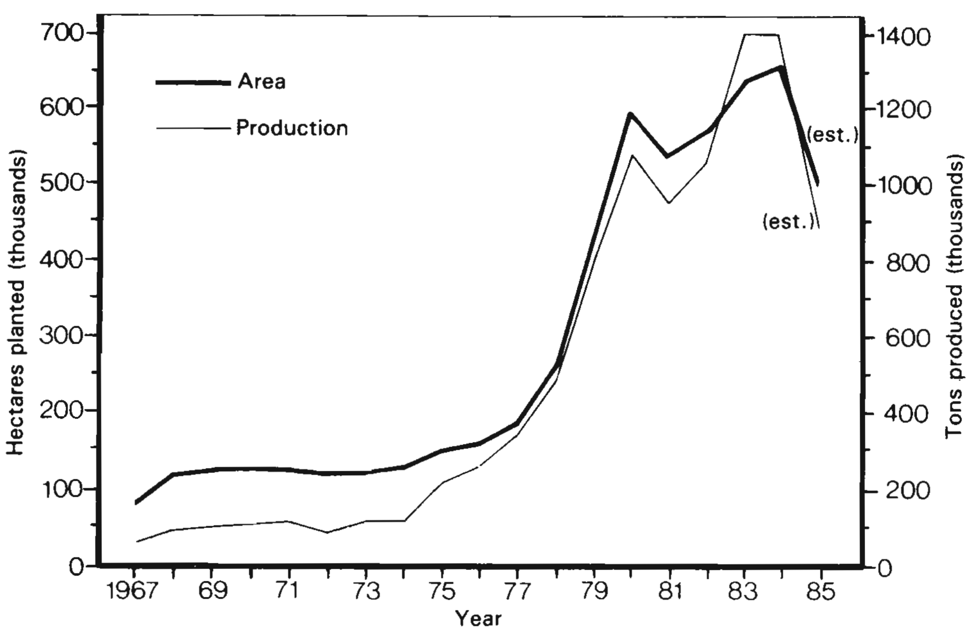

Figure 1. Area and production of wheat in Bangladesh since 1967.

Source: Bangladesh Bureau of Statistics

its well-deserved popularity, Sonalika is dangerously susceptible to leaf rust (*Puccinia recondita*) and must be replaced or, at least, supplemented by resistant varieties. Leaf rust resistance, per se, is not a sufficient reason for replacement to farmers in Bangladesh who have not yet experienced widespread destructive epidemics; a yield advantage must also be shown.

The breeding objective has been to identify resistant lines demonstrating a yield advantage relative to Sonalika across planting dates and moisture availabilities. The methodology of the varietal improvement program (Figure 2) for the past 5 years has been the multilocational, simultaneous selection of lines against Sonalika under dryland and irrigated conditions and at two dates of planting (4, 5).

Kanchan and Akbar, varieties released in 1983, and Aghrani, released in October 1986, although not products of the new selection program per se, have been used as check varieties since the program's inception and are exemplary models of the standards we expect. Kanchan in particular has consistently demonstrated stability, as illustrated in Figures 3 and 4, similar to that of Sonalika and a yield advantage across environments (5). So imposing have been the standards set by the three varieties, in fact, that release of new varieties does not appear likely in the near term given the responses of lines in advanced yield trials (3). The selection program and the date of seeding vs. variety experiments (7, 8) have confirmed the value of these varieties.

Pathology
All pathology work at the Wheat Centre thus far has been related to the varietal improvement program, including generation of leaf rust epidemics and disease recording/ monitoring of experimental nurseries. The Plant Pathology Division of BARI also conducts occasional field surveys (10) and responds to calls for assistance in disease identification and treatment. However, further work directly significant to on-farm production, such as damage assessment and control of the root and crown rots caused by *Helminthosporium* spp. and *Sclerotium rolfsii*, could be conducted.

Agronomy
Research efforts in agronomy are in their infancy at the Wheat Centre and have been directed in the main toward 1) information relevant to varietal performance and management on-station, as date-of-seeding vs variety and seed rate/configuration experiments, and 2) development of cost-saving production techniques such as reduced tillage. Although date-of-seeding experiments have provided valuable data, we are particularly encouraged by the results of reduced tillage experiments (9). These have been directed particularly toward crops following transplanted rice crops, where the soils are puddled and difficult to prepare by conventional methods and rice harvests are often late, thereby delaying — or even deterring — planting. Results have suggested that on many types of soils no yield loss would be incurred by reduction of tillage (Figure 5), but significant savings in time and animal energy would be gained.

Table 1. Varietal availability of certified wheat seed as percentage of the total available quantity since 1976-77

Financial year	1976-77	1977-78	1978-79	1979-80	1980-81	1981-82	1982-83	1983-84
Total (kg) available quantity (all varieties)	42,848	90,945	143,446	377,228	929,574	342,336	359,812	451,900
Sonalika	35	24	45	50	40	42	33	86
Tanori 71	12	2	7	1			0.5	
Jupateco	14	12	15	2	0.3	2	5	5
Inia 66	5	56	22	47	17	38	61	0.5
Kalyansona	31	2	2					
Sonora 64	3	5	5	1				
Norteño 67		0.2	0.4	0.1	0.04			
Pavon F-76					43	19	1	3
Balaka							0.1	5

Source: Walter (12)

Table 2. Yields of wheat varieties included in the first IRRI/CIMMYT Rice-Wheat Integrated Trial planted at BARI, Joydebpur

Entry	Rank		Yield (t/ha)	
	Favorable	Late	Favorable	Late
Ananda	7	6	3.9bcd	2.8bcd
Kanchan	1	4	4.9a	3.1bc
Aghrani	3	1	4.4abc	4.1a
Barkat	5	3	4.0bcd	3.2bc
BAW 40	13	9	2.9e	2.5bcde
BAW 42	6	8	3.9bcd	2.6bcde
Balaka	4	2	4.3abc	3.2b
Zaragoza	14	15	2.0f	0.9g
Celaya	11	7	3.6cd	2.6bcde
Texcoco	8	11	3.9bcd	2.2def
Abasolo	12	10	3.5de	2.2def
Seri	10	13	3.6cd	2.0e
Pavon	2	12	4.5abc	2.1ef
Siete Cerros	9	14	3.8bcd	1.8f
Sonalika	–	5	–	3.0bc
LSD (t/ha)			0.74	0.65

Favorable = mid-Nov. to early Dec. sowing date
Late = sown after Dec 15.

Extension

Varieties

The success of a variety, of course, is measured in terms of its acceptance by farmers and not experimental data. The variety must be demonstrated successfully to farmers to create a demand and its seed multiplied to meet that demand. Due to past experience with "shotgun" releases, BADC has been justifiably reluctant to multiply a large amount of seed of a variety with no proven demand. Seven varieties were released between 1976 and 1979 and a total of nine were multiplied (12). Six of these survive today, but only Sonalika, released in 1976, has not declined in popularity. The remaining were not sufficiently adapted to the uniquely "Bangladeshi" conditions. In contrast, the four varieties — Kanchan, Akbar, Barkat, and Ananda — released in 1983 are all products of the national selection program. Aghrani, released in 1986, is similar if not identical to Punjab 81, grown in the Punjab, Pakistan; however, it was initiated as an unnamed advanced line into the selection program in 1979, well before its release in Pakistan.

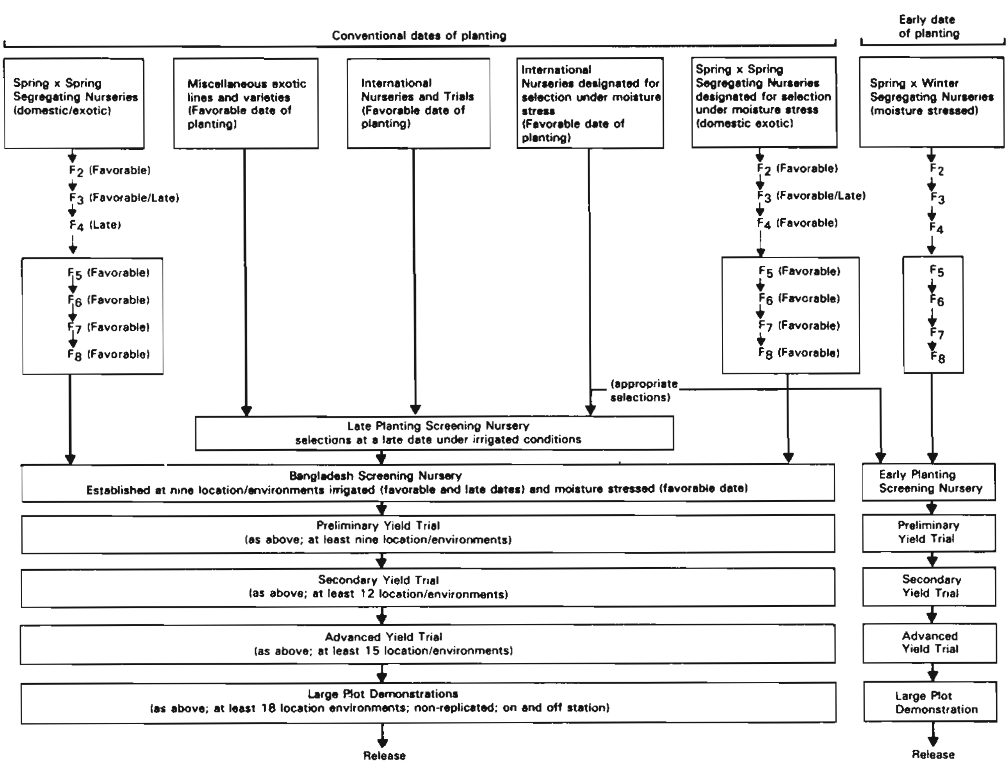

Figure 2. Flow of germplasm in the Bangladesh National Wheat Improvement Program.

During the early stages of the introduction of high-yielding varieties of wheat in Bangladesh, Dr. Sufi Ahmed, now Project Director of the Wheat Centre, and his small team personally attended and spoke at numerous farmers' meetings arranged by the DAE and even preached alone in rural market places to extend the new technology. The rapid speed at which both seed and information spread can only be accounted for by farmer-to-farmer contact, rather than institutional efforts. Although such media as radio and informational pamphlets are increasingly used, the structure of the extension efforts is grounded in the belief that farmer-to-farmer contact is the most effective means of promoting new but proven technology. Accordingly, we have taken the case for the "Bangladesh" varieties directly to the farmers in cooperation with the DAE.

Extension Demonstration Kits, composed of sufficient seed and fertilizer to cover 0.04 ha of each new variety and a Sonalika check, are financed, arranged, and distributed by the Wheat Centre and planted on farmers' fields by DAE personnel. In the first year of the program in 1983/84, 1000 kits composed of only a single new variety plus Sonalika were planted, due to the lack of an equal amount of seed of each new variety. However, 500 complete demonstrations were planted in 1984/85 and 1985/86; 750 have been planted in 1986/87.

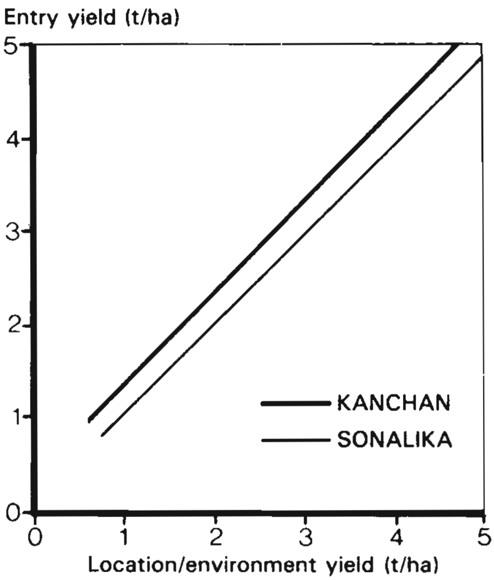

Figure 3. Linear regressions of individual yields of check varieties Sonalika and Kanchan against mean nursery yields of the 1984-85 Preliminary Yield Trial at nine location/environments.

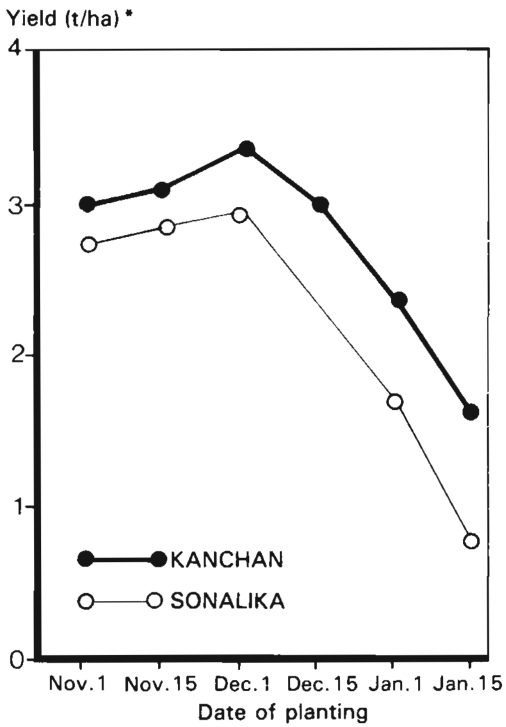

Figure 4. Yield response of Kanchan and Sonalika at six dates of planting.

* Mean yields of three locations

The location of demonstrations has been at DAE discretion, but half were previously measured and designated for irrigated-favorable date of planting and the remaining dryland-favorable date of planting. Due apparently to the success of the program thus far, the DAE has accepted our suggestion that for maximum impact and relevance, demonstrations should also be directed toward a variety of unfavorable production environments. The additional 250 kits in 1986/87 are designated for late planting. We will continue to exert pressure toward demonstrating these varieties under increasingly marginal growing conditions.

However, both the DAE and CIMMYT feel the program already has been successful. The DAE has been provided a foundation on which to support various extension efforts; farmers' "rallies" are organized around particularly good demonstrations, for example. The Wheat Centre has been provided 1) a door through which we may introduce new varieties directly to the farmers without having to wait at least 2 years for certified seed from BADC to become generally available to farmers; and 2) a quick reading as to how successful we may expect these varieties to be on the basis of yield results and cooperators' opinions. The latter information has been also welcomed by BADC. Tables 3 and 4 indicate the yield responses and rankings of demonstration varieties during the 1985/86 season and clearly corroborate our previous confidence in Kanchan and Akbar. Such results and the views of their own certified seed contract growers influence the

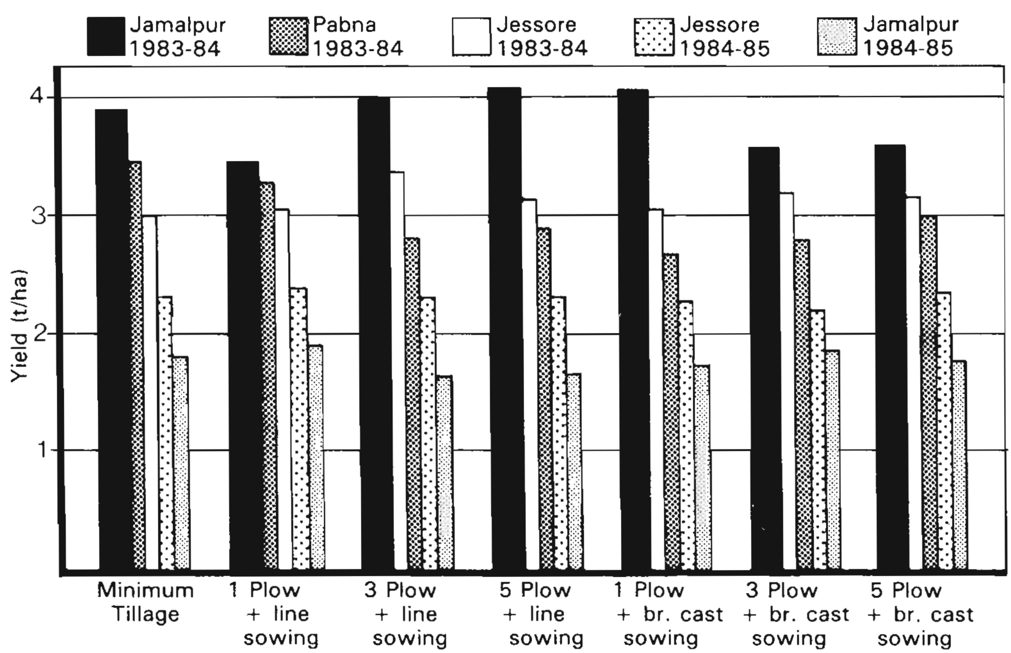

Figure 5. The effects of different tillage methods on wheat yields.

Source: Guler et al. (9)

priorities of BADC. Table 5 indicates the target production of foundation and certified seed of various varieties; note that ranking of the target values of the varieties released in 1983 relative to each other roughly follows the performance ranking observed in the demonstration yield results.

Production agronomy
The creation of the On-Farm Research Division at BARI and its establishment of numerous on-farm testing sites have provided widely-distributed locations, not only at which new varieties are demonstrated under various cultural practices, but also as a means by which Wheat Centre agronomists can participate in the extension of production technology. Wheat Centre designs and encouragement for reduced tillage experiments have resulted in the establishment of such experiments on-farm (1), which have produced convincing results (Table 6) and considerable farmer interest.

We are particularly excited about a variation of minimum tillage: relay cropping. Wheat is broadcast in a standing, maturing crop of transplanted rice about 15 to 21 days before its harvest; the actual date of sowing of the wheat is

Table 3. Yield results of varietal demonstrations under irrigated conditions, 1985-86

District	No. of locations	Mean yield (kg/ha) Ananda	Kanchan	Barkat	Akbar	Sonalika
Dhaka	6	3095 (3)	3493 (1)	3102 (2)	3012 (4)	2867 (5)
Mymensingh	10	1875 (5)	2005 (3)	2031 (2)	2186 (1)	1938 (4)
Tangail	8	2540 (4)	2972 (1)	2544 (3)	2658 (2)	2081 (5)
Jamalpur	6	2133 (4)	2525 (1)	2317 (3)	2475 (2)	1800 (5)
Faridpur	15	3438 (2)	3711 (1)	3206 (4)	3397 (3)	3020 (5)
Barisal	6	2492 (4)	2600 (1)	2438 (5)	2505 (2)	2504 (3)
Kushtia	20	3643 (4)	3987 (1)	3715 (3)	3944 (2)	3321 (5)
Jessore	16	3835 (4)	4065 (3)	4162 (2)	4277 (1)	3446 (5)
Khulna	1	4146 (3)	4883 (1)	4514 (2)	3409 (4)	2815 (5)
Pabna	11	3409 (2)	3393 (3)	3161 (4)	3495 (1)	2934 (5)
Bogra	8	3172 (3)	3336 (1)	3093 (5)	3116 (4)	3192 (2)
Rajshahi	12	4293 (2)	4425 (1)	4199 (3)	4064 (4)	3854 (5)
Rangpur	15	2678 (2)	2827 (1)	2445 (4)	2466 (3)	2344 (5)
Dinajpur	19	2694 (2)	3019 (1)	2573 (4)	2638 (3)	2565 (5)
Comilla	17	2623 (3)	3041 (1)	2665 (2)	2596 (4)	2581 (5)
Noakhali	2	1998 (1)	1934 (2)	1515 (4)	1412 (5)	1752 (3)
Sylhet	11	2244 (5)	2552 (1)	2349 (4)	2468 (3)	2524 (2)
Chittagong	3	3312 (4)	3525 (2)	3475 (3)	2911 (5)	3906 (1)
Variety mean	186	3033	3290	3018	3091	2815
Yield increase over Sonalika (%)		7.74	16.87	7.21	9.80	

( ) = rank in district

determined by the visual moisture condition of the soil, which should be saturated, or nearly so, but with no free water available on the surface. Moisture is conserved by the shading of the soil by the rice. Remarkably, plants become deeply rooted and ensure a crop without subsequent irrigation. Given appropriate circumstances, the benefits of this practice may be greater than reduced tillage (1) (Table 7).

Far from being a product of research, relay cropping in Bangladesh is a product of farmer initiative. A Wheat Centre scientist happened to observe the practice, which was confined to about 20 ha in an isolated location at the time. Wheat Centre and On-Farm Research Division scientists now conduct experiments on-farm to study the effects of seeding date, seed and fertilizer rate and variety on the system. Interestingly, except that Kanchan was determined and accepted by many farmers to be superior to Sonalika in the system, few improvements over the basic system as initiated by the farmers appear to be needed (1). However, now that studies are being conducted at a number of locations throughout Bangladesh and generating interest by farmers and

Table 4. Yield results of varietal demonstrations under nonirrigated conditions 1985-86

District	No. of locations	Mean yield (kg/ha)				
		Ananda	Kanchan	Barkat	Akbar	Sonalika
Dhaka	6	2305 (3)	2553 (1)	2383 (2)	2230 (4)	2111 (5)
Mymensingh	7	1743 (3)	1859 (2)	1699 (4)	2019 (1)	1473 (5)
Tangail	8	1666 (5)	1948 (2)	1975 (4)	2025 (1)	1801 (3)
Jamalpur	7	2147 (2)	2302 (1)	2084 (4)	2109 (3)	1923 (5)
Faridpur	15	1809 (1)	1799 (2)	1654 (4)	1673 (3)	1421 (5)
Barisal	5	1810 (2)	1905 (1)	1405 (5)	1680 (4)	1800 (3)
Kushtia	14	2545 (3)	2773 (1)	2500 (4)	2639 (2)	2265 (5)
Jessore	16	1778 (4)	2121 (1)	1942 (3)	1948 (2)	1758 (5)
Khulna	1	1763 (4)	3528 (2)	3675 (1)	3528 (2)	2645 (3)
Pabna	10	2088 (4)	2125 (1)	2111 (3)	2115 (2)	1849 (5)
Bogra	7	2182 (4)	2356 (1)	2204 (3)	2324 (2)	2132 (5)
Rajshahi	15	2366 (2)	2613 (1)	2189 (5)	2333 (3)	2196 (4)
Rangpur	15	1917 (2)	1925 (1)	1764 (4)	1875 (3)	1741 (5)
Dinajpur	19	1927 (4)	2342 (1)	2010 (2)	2001 (3)	1824 (5)
Comilla	18	1857 (5)	2274 (1)	2005 (3)	2076 (2)	1881 (4)
Noakhali	1	850 (2)	900 (1)	750 (3)	700 (4)	400 (5)
Sylhet	10	1495 (4)	1626 (2)	1466 (5)	1697 (1)	1542 (3)
Chittagong	3	1917 (5)	1945 (4)	1950 (3)	2184 (2)	2366 (1)
Variety mean	177	1968	2187	1967	2055	1851
Yield increase over Sonalika (%)		6.32	18.15	6.27	11.02	

( ) = rank in district

extension personnel alike, the practice may spread among traditional wheat farmers and perhaps tempt those who have been unable to grow wheat as a result of time and/or energy constraints.

Training

Extension and training are not easily separated in terms of the ultimate objective; however, extension connotes a working relationship and training a more formal association between farmer and agent. Both opportunities of contact have their use.

Eighty percent of the wheat seed sown annually is stored on-farm. This seed must be of reasonable viability to ensure a successful crop. Despite the problems of storage during the monsoon season, viability can be successfully maintained if simple procedures are followed. Further, Clements et al. (6) found in a 1984 survey that practices and seed quality had significantly improved from those observed in a previous survey conducted in 1976 (11), apparently as a result of information passed from farmer to farmer. Consequently, Wheat Centre scientists have given formal demonstrations to hundreds of farmers (and extension personnel) over the past 4 years on seed storage. We are now considering seed-storage extension efforts directed at women, who are usually given the responsibility of maintaining seed stocks on the farm.

Table 5. Multiplication targets of BADC for production of foundation and certified seed during 1986-87

Variety	Foundation seed (tons)	Certified seed (tons)
Sonalika	400	5,000
Kanchan	800	7,200
Akbar	400	2,000
Barkat	40	400
Ananda	40	400
Balaka	100	2,000
Pavon	10	–
Aghrani	10	–
Total	1800	17,000

Table 6. Effect of tillage methods on the yield and economics (in Taka) of irrigated wheat (var. Kanchan) in farmers' fields at Ishurdi under irrigated conditons

Treatments	Yield (t/ha)		Gross benefit (Tk/ha)	Total power cost (Tk/ha)	Gross margin (Tk/ha)	Benefit cost ratio
	Grain	Straw				
Minimum tillage (Furrow)	2.58	3.17	13,729	3933	9797	3.49
Reduced tillage (1 plowing)	2.14	2.80	11,456	2245	9211	5.10
Conventional tillage (5 plowings)	1.59	1.87	8,428	3687	4741	2.29
CV%	10	15	–	–	–	–
LSD (0.01)	0.54	0.57	–	–	–	–

Source: OFRD, BARI 1985-86

Farmers' Seminars are full-day programs initiated in 1984/85 in an effort to combine formal instruction with an informal traveling seminar in which farmer participants were encouraged to give their views. Wheat Centre on-station programs are formally, and briefly, demonstrated and explained as to objective and philosophy. The remaining and major part of the day is spent traveling to DAE varietal demonstrations and On-Farm Research Division multilocation sites to observe and discuss varietal performance and cultural procedures. Groups are held to a maximum of 30 farmers and 5 DAE officers to encourage fullest participation. This program has been initiated no less to "train" our own officers and selected DAE personnel than farmers; interaction, impossible with large crowds, is imperative. Two such "seminars" have been held each year since 1984/85 and, although the program is small, the quality of training per person is high. Farmer response has been very encouraging and we feel that the impact of such quality instruction, if sustained, will eventually be felt in terms of acceptance of new technology.

Conclusion

Bangladesh experienced phenomenal growth in wheat production in the mid-1970s and early 1980s. As a result of pressures to procure and multiply seed of adapted varieties, many inappropriate imported varieties, such as Pavon, were hurriedly evaluated and released. The now more experienced wheat research team of the Wheat Centre is meeting the challenge of an increasingly volatile socioeconomic environment through the development of varieties more stable across production opportunities severely limited by a traditional rice agriculture. The philosophy governing the extension of research products is grounded in the belief that farmer-to-farmer contact is the best vehicle for their dissemination.

Table 7. Cost (in Bangladesh Taka) and benefit analysis of wheat under different tillage methods

	Jamalpur				Tangail			
Treatments	Gross benefit (Tk/ha)	Cost (Tk/ha)	Net benefit (Tk/ha)	Benefit cost ratio	Gross benefit (Tk/ha)	Cost (Tk/ha)	Net benefit (Tk/ha)	Benefit cost ratio
No tillage (relay)	8235	4035	4200	2.04	6,650	5798	861	1.15
Minimum tillage (Furrow)	4612	4590	22	1.05	15,100	6509	8591	2.32
Reduced tillage (1 plowing)	4387	4750	-363	0.92	13,350	6029	7321	2.21
Conventional tillage (5 plowings)	3825	5085	-1260	0.75	16,900	6989	9911	2.42

Market value: Tk. 4.50/kg.

Source: OFRD, BARI, 1985-86

Accordingly, the case for new varieties and cost- and time- saving production techniques such as reduced-tillage has been taken directly to the farmer through on-farm demonstrations and trials in cooperation with government extension and on-farm research services. The opinions and active participation of farmers are sought through such efforts and "farmers seminars."

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Wheat Seed Storage Under Tropical Conditions

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Abstract
Wheat seed storage under tropical conditions presents problems not associated with storage in traditional wheat growing areas. High temperatures and relative humidity levels are not conducive to efficient, low-cost storage methods. Farmers have adapted very well to the new matrix of problems associated with wheat seed production. A major constraint to improving the quality and quantity of seed stored at the farm level is the availability of appropriate storage containers. Another important constraint is the inability of small farmers to afford even to set aside part of their crop for seed purposes due to cash and food requirements.

Seed storage methodology is nothing new as prehistoric man is known to have developed methods of storing small quantities of seed for his own use. Nor is research into seed preservation new with publications relating to seed storage being published as early as the second quarter of the 19th century (4). For historical reasons, the research carried out, has, for most crops including wheat, been carried out under temperate climate conditions.

Wheat storage conditions in tropical environments differ in many ways from those of temperate climates. Some differences are very obvious, such as high temperatures and humidity and a larger number and wider range of insects and pathogens. Yet other differences are related to social and economic conditions in developing nations where the thrust of wheat expansion in the tropics takes place. The high level of farmer illiteracy, small farm size, scarcity of working capital, and the absence of a sophisticated seed or an agro-chemical distribution network also contribute to form a new set of problems of seed preservation.

Levels of Seed Storage

Seeds must be stored, whether at the research, seed grower, or farmer level. The requirements at each level differ due to the economic importance of the seed. At the research level, the importance of preserving germplasm and breeding material warrants investment in high-cost equipment such as cold stores, specialized containers, and full-time staffing. As the chain progresses through the breeder seed, pre-foundation, and foundation levels and up to the certified seed level, investment per kilogram of seed declines. As the seed leaves the commercial seed sector, it takes a steep drop in value and is often only slightly above the value of food grains.

Through heavy investment by government, the seed storage facilities in many countries are well designed and principles and practices of seed storage learned in temperate climate are more or less applicable. This is not the case once the seed leaves the commercial seed sector and enters the farm. This paper will center on the issues relating to wheat seed storage at the farm level and point to areas for potential reduction of seed losses in storage.

Seed Quality Deterioration Under Tropical Conditions

In South and South East Asia, wheat is grown in the dry winter season and seed must be stored throughout the hot, humid monsoon season until the next winter's planting. For a period of 3 to 5 months, temperatures range from 20 to 35°C with a relative humidity of 75 to 100%. It is practically impossible to store wheat seed in open air containers without repeated sun drying and the use of insecticides and fungicides. There are four major causes of loss of seed vigor: high rates of respiration, insect and fungal infestations, and rodent damage.

Respiration
At a temperature of 25°C, wheat seed reaches an absorbed equilibrium moisture content of 15.0% at 75% humidity. At 90% humidity the equilibrium is 19.7% (4). The critical moisture content for wheat that increases the rate of respiration is 14.6%. The average relative humidity in Bangladesh during June to August is between 70% and 80% and average daytime temperatures are 32 to 35°C. Grain left unprotected will obviously undergo fairly rapid respiration if periodic drying is not carried out. The effects of respiration on seed viability are a result of the raising of temperature and moisture levels above the critical limits as well as a depletion of the seeds' food reserves.

As nearly all of the farmers seed is only stored for a period of about 8 months, the role respiration plays in the deterioration of seed quality may not be as great as expected as once thought. The storage period is too short to allow the deterioration to reach a critical stage unless the grain is extremely damp when stored.

Insect damage
Insect damage is a problem for seed storage whether in the research station, the commercial seed store, or on the farm. Under conditions of poverty, illiteracy, and the relative inexperience with chemicals, chemical seed treatment presents a risk to human health. In Bangladesh, even certified seed is not treated for fear that it will find its way into the food grain market. At the farm level, insect control open to the commercial seed sector, such as artificial drying and the use of fumigants, is not available.

The monsoon climate is ideally suited for insect activity and reproduction rates, which increase with the increase in temperature. Insects such as the rice weevil (*Sitophilus oryzae* L.), lesser grain borer (*Rhizopertha dominica* F.), the angoumois grain moth (*Sitotroga cereallea* O.), and the khapara beetle (*Trogoderma granerium*) require high levels of moisture to live. Dry seeds therefore, in addition to being generally more resistant to insect attack, provide a poor environment for such pests. There are, however, insects that are capable of attacking even dry seed. Among these are the ant (*Monomorium pharanois*) which, in a recent survey of seed storage in Bangladesh (1), was found to be capable of attacking even very dry, hard wheat seed. Although seeds may be capable of germinating even with insect damage, the seeds are more susceptible to fungal attack both during storage and after planting.

Fungi
The most common fungi in stored wheat are the numerous species of *Aspergillus* and *Penicillium* (2). Heavy infestations may occur under conditions of high temperature and humidity which can result in either the death of the seed or a weakened plant after germination.

Rodents
Rodents, mainly black field rats (*Bandicota bengalensis*), cause damage to stored seed through two means. The obvious effect is the eating of the seed. The less obvious, but probably more important damage, is done by creating holes in the farmers' plastic storage bags which results in an increase in moisture in the seed and subsequent insect infestation.

On Farm Wheat Seed Storage in Bangladesh

The relatively short, but very successful history of wheat in Bangladesh has been well documented (1). In the 10 years between 1971 to 1981, local varieties were nearly completely replaced by high-yielding varieties. Production increased at a rate of 20% per year (3) of which nearly 40% of the increase was due to yield improvements. Wheat area increased from 150,000 ha in the mid-1970s to 600,000 ha by the mid-1980s.

The supply of institutional seed has been instrumental in enabling the farmers to shift from local to high yielding varieties. Yet the institutional seed supply, whether imported or locally produced, normally accounts for only 20 to 25% of the national wheat seed requirements. Although institutional seed supply is the cornerstone of the introduction of new higher yielding or disease-resistant varieties and the maintenance of pure seed stocks, it is evident that the seed stored on the farm has a pivotal role to play in a country's wheat production performance. A review of the Bangladesh experience may help to shed some light on the problems facing the smaller farmers in other tropical environments.

Farms in Bangladesh are small. The area planted to wheat by farmers ranges from 0.1 ha up to 1.5 ha with an average of about 0.2 ha. Seed requirements therefore range from a few kilograms up to 150 kg. The type of storage used depends not only on the quantity to be stored, but also the financial capacity of the farmers and their knowledge of storage techniques. Generally farmers do not differentiate between grain and seed and simply retain enough of their wheat stocks for the next season's planting.

In Bangladesh, the typical storage method of wheat seed is to carry out five to eight sun dryings until the seed has a moisture content of around 12-13.9%. The farmer estimates the moisture content by biting down on the kernel. After cooling overnight, the seed is placed in a container. If the container is not airtight, sun drying every 3 to 4 weeks throughout the summer will be necessary.

Storage containers
The most common types of containers used are:

Metal drum—If sealed, a metal drum can be used to store dry wheat seed throughout the monsoon season with little or no deterioration in quality. Drawbacks are the price (US$10) and the capacity (170 kg) which are beyond the capabilities and requirements of the small farmer.

Biscuit or kerosene tin—If sealed, seed quality can be maintained in a biscuit or kerosene tin as well as in the metal drum. Advantages are that the capacity is appropriate for small farmers and the costs are within their reach. A major drawback is that the tins are susceptible to rust and easily damaged. If the damage is not detected, insect infestation and moisture increases may occur.

Polythene-lined bags—The effectiveness of the poly bags will depend greatly on the condition of the bag as well as the care that the farmer takes. Certain insects such as ants can eat through thinner grades. All grades are susceptible to rat damage. Much more care must be taken by the farmer than for the metal containers, but if properly maintained, high levels of seed can be sustained throughout the monsoon season. The capacity of 40 to 70 kg is also appropriate for the small to medium farmer.

Earthen pots—The low cost plus availability makes the earthen pot a very popular, although inefficient, means of storage. Moisture can enter through the walls unless the container is lined with tar or a polythene bag. Often the lids are not properly sealed and insects can enter. Unless periodic sun drying is carried out, deterioration in seed quality will undoubtedly occur.

Insect and Rodent Control

Insect infestation is a constant hazard and farmers have developed a number of ways to combat it. Less than 10% of the farmers use commercial insecticides due to the dual purpose nature of the seed (food and seed) plus the cost and availability. The use of natural insect control measures such as the leaves of neem (*Azadirachta indica*) or Bishkatali (*Rumex obtusifolius*) is not widespread although it is apparently effective if used in the proper form and concentration (1). In India, the Directorate of Non-Edible Oils and Soap Industries is recommending an application of 0.8 kg of Neem oil per 100 kg of stores to give a uniform protective coating around the grain for a period of up to 7 months (3).

Farmers also mix sand or wood ash with the grain, which has the effect of scratching the cuticle of the insect's body and the insect loses moisture through the scratches. If the grain is comparatively dry, the insects will not get enough moisture to replace the moisture loss.

By far the most common form of insect control is through sun drying as most insects will leave the grain when temperatures reach 40 to 44°C.

Rodent control is mainly through using rodent-proof containers or placing the seed in a location where it is difficult for the rodents to reach. Otherwise, rodent control measures are simply those commonly carried out by farmers to keep the rodents out of their living quarters.

Constraints to Improving Farm Storage of Wheat Seed

Except for the introduction of new varieties, the ideal situation would be for all other seed to be produced and stored by the farmers themselves. In reality, there will always be a need for an annual input of certified seed to maintain the purity of seed stocks used by the farmers. If the wheat production area is to increase in the tropics, farmers must be capable and willing to improve seed storage, both in terms of quantity and quality.

Quality constraints
The quality of a seed lot can be judged by both the purity of the sample, in terms of varieties and foreign material, and the vigor of the individual seeds, which is normally determined by the germination percentage. Major areas where seed quality can be adversely affected are:

1) Impure crop stands being harvested for seed purposes.

2) Inclement weather during harvesting/threshing.

3) Lack of proper seed cleaning prior to storage.

4) Storage of improperly dried grain.

5) Ineffective storage containers resulting in moisture buildup and/or insect infestation and fungal infection.

6) Lack of sufficient sun drying storage period for seed stored in non-airtight containers.

The constraints to improving the quality of wheat seed stored under tropical conditions are:

1) Availability of appropriate storage containers.

2) Availability of appropriate technical packages for small-scale farm level storage.

3) The presence of a well trained, well motivated extension service for imparting the appropriate technology to the farmers.

4) The availability of capital or credit facilities to enable farmers to purchase storage containers.

Quantity constraints
The quantity of seed farmers intend to store will depend on their expectations of their own requirements in the following year, plus their estimates of the potential market for seed during the coming season. The amount they actually successfully store for the next planting season will depend on:

1) The farmers' ability to store the seed free from major insect, fungal, or heat damage.

2) The farmers' financial position through the storage period. Cash or food requirements may force the farmers to sell or consume part or all of their seed stocks.

The Role of Research

There are a number of areas where research is still required to reduce some of the constraints discussed above. These include:

1) Appropriate cost-effective storage containers.

2) Use of extracts from indigenous plants for the control of seed storage insects pests.

3) The economic importance of fungal infestations of seed in relation to the effects not only on germination but also on crop yields.

4) More coordination and exchange of information regarding research on seed storage under tropical environments.

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7

Reports of Discussion Groups to Identify Future Research Objectives, Establish Priorities, and Identify Areas for International Cooperation

During the conference's final session, the participants divided into three discussion groups:

- Breeding • Pathology • Agronomy

Their tasks were to identify future research objectives, establish priorities, and identify areas for international cooperation.

Breeding Research Priorities
E. Alarcon, chairman, J.E. Hernandez, reporter

During its discussions, the breeding group identified the following 12 research priorities that must be addressed to improve the adaptability and yield potential of wheat in tropical countries:

- Resistance to helminthosporium leaf blotch.
- Early, medium, and late tolerance to heat and drought.
- Aluminum tolerance and its relationship to phosphorus extraction efficiency.
- Resistance to fusarium head scab.
- Resistance to septoria tritici blotch and septoria nodorum blotch.
- Resistance to leaf and stem rusts.
- Resistance to *Alternaria* leaf blight.
- Resistance to sclerotium wilt
- Proper maturities and appropriate length of vegetative and reproductive phases.
- Tolerance to frost at flowering.
- Tolerance to waterlogging.
- Tolerance to minor element toxicities/deficiencies.

These research priorities were further grouped into problems that are:

- Common in most tropical countries.
- Regional in scope.
- National in scope.

Problems common in most tropical countries
The group agreed that the solutions to these problems should be worked on by establishing shuttle breeding

programs. CIMMYT will contribute by providing the segregating populations (F_2-F_3) to the following countries:

Problem	Cooperators
Helminthosporium	Philippines, Brazil, Paraguay, Indonesia, Nepal, and Zambia
Heat/drought	Thailand, Argentina, Paraguay, and Nepal
Aluminum tolerance/ phosphorus extraction efficiency	Brazil, Cameroon, Thailand, and Colombia
Fusarium head scab	China, Argentina, Paraguay, and Indonesia
Septoria nodorum blotch	Paraguay and Brazil

Regional problems
For regional problems, the group agreed that the CIMMYT representative should coordinate the exchange of segregating populations and germplasm with the countries in the region. Problems that should be approached on a regional basis include:

Problem	Cooperators
Stem rust	Madagascar and Cameroon
Alternaria leaf blight	India and Bangladesh
Sclerotium wilt	Thailand, Philippines, and Bangladesh
Septoria tritici blotch	Brazil, Madagascar, Argentina, Zimbabwe, China, and Paraguay
Frost at flowering	Brazil, Madagascar, Paraguay, and Argentina
Waterlogging	Thailand, Indonesia, Philippines, Pakistan, and China
Proper maturity	Argentina, Colombia, Cameroon
Minor elements (boron)	India, Thailand, and Brazil

National problems
Problems that can be resolved by national programs include powdery mildew and sprouting.

Next international conference
The group suggested that the next international conference to review the progress and problems of growing wheat in the tropics be held in Brazil in 1989.

Pathology Research Priorities

Y.R. Mehta, chairman, R.H. Raemaekers, reporter

Twenty participants contributed to the pathology session. Several aspects of wheat pathology in tropical areas were discussed with the emphasis on integrated disease management.

The group made the following 13 recommendations for future international collaboration:

- Closer integration between disciplines in cropping systems management is needed, especially as it relates to interactions of biotic and abiotic factors.
- There is a great need for uniform disease scoring methods.
- Methods need to be developed for screening resistance to important pathogens.
- Hot spot disease locations need to be located worldwide.
- The etiology and epidemiology of important diseases under tropical conditions and the losses these diseases cause need to be studied more thoroughly.
- A disease incidence and severity survey and standardized trials at key locations are required to determine the role of biotic factors in crop growth and development.
- Investigations on the efficacy and phytotoxicity of seed treatment formulations are highly advisable.
- The distribution of disease-free seed among international cooperators must be ensured.
- Methods for appropriate on-farm storage need to be established.
- Lab facilities at key locations should be upgraded.
- CIMMYT should serve as the accumulator and processor of abiotic and biotic data generated by collaborators.
- Increased funding for appropriate regional plant protection workshops is desirable.
- Collaborative support for disease identification is necessary.

Agronomic Research Priorities

D.J. Reuter, chairman, A. Majid, reporter

Agronomic research priorities were ranked either high, intermediate, or low within eight broad categories. The discussion group also identified whether cooperation should be on international or regional levels, or both.

Climatic constraints
The group gave a high ranking to establishing a network of meteorological stations on an international basis. On a regional basis, estimating water-use efficiency and yield potential in drier areas, irrigation management for specific soils, and soil drainage were considered essential.

Less importance was given to associating wheat culture with regional weather patterns (plant/harvest date, frost, drought, waterlogging).

Cultural practices and constraints
Crop establishment problems were rated high for international cooperation. On a regional basis, long-term tillage x rotation studies, tillage x disease interaction, stubble retention, and planting time were given top priorities.

Intermediate on the scale for regional cooperation were sowing equipment/seed placement/sowing techniques. Herbicide use and its residual effects, stubble management, and soil erosion were considered less essential.

Crop nutrition/soil fertility
Diagnosis of nutritional stress (symptoms, soil and plant analysis, local fertilizer experiments) was assigned a high priority for both international and regional cooperation. Breeding for genotype tolerance to nutritional stress was considered significant for international cooperation.

On a regional basis, fertilizer technology related to type, rate, method, and time of application; nutrient cycling in rotations; acid soils; and breeding for genotype tolerance to nutritional stress were ranked high by the group.

Lower priority was assigned to fertilizer technology related to the benefits of green manure crops and farmyard manure and estimating the residual value of applied fertilizers.

The discussion group urged that an international conference on Crop Nutrition in the Tropics be held in the near future.

Crop hygiene
This category includes chemical, cultural, rotational, and biological control; regulatory issues, and sanitation. Pest population dynamics and control measures were considered major activities for regional cooperation.

Research on weeds, diseases, insects, and integrated pest control was determined less important for regional cooperation.

Farm mechanization
For regional cooperation, the group ranked cultivation, harvesting, and threshing high. Sowing, traction, grain storage, and spraying equipment were given lower priorities.

Farm finance
Development of local markets for cash crops and cash flow was considered important for regional cooperation.

Technology transfer
Adoption of new technology and involvement of extension staff in local research (including prioritizing of research) were regarded as important activities for regional cooperation.

Training
Training was assigned a high priority for both international and regional cooperation.

8

Summary of the Conference

A.R. Klatt, Associate Director, CIMMYT Wheat Program, Mexico

It is no easy task to summarize what has been taking place during the last 5 days, but I will attempt to do so.

Wide Range of Environments

On Monday we began by learning that there was a large range of environments in the tropical wheat zones of the world. These vary from the rice-wheat rotations common in South and Southeast Asia, to the warm dry environments in Africa, and finally the more humid environments common in certain parts of Latin America. I am sure many of us visualize the rice-wheat areas as the typical tropical wheat environment. However, we now are aware that the tropical wheat region comprises many environments, each with its special problems or constraints.

What Are Tropical Environments?

From our discussions, it is still evident that we do not have a good definition of tropical environments as it pertains to wheat. It might be better to define these areas as nontemperate or nontraditional areas with higher than normal temperatures, generally throughout the growing season. In all cases it is important to point out that we are attempting to introduce a crop during the cool season in the tropics when normally no crop is currently being grown. Under no circumstances are we trying to introduce wheat into the humid tropical areas.

Rice-Wheat Rotation

We then moved into a discussion on the constraints of the rice-wheat rotation. Nearly all of the papers in this section, and probably most of the papers throughout the conference, discussed the problem of high temperatures and its effect on the wheat plant. Obviously, this led us to the conclusion that additional heat tolerance would be needed for wheat to be grown successfully in the tropics.

We learned about the term "PTQ" and received the impression that heat tolerance may not be a major constraint to wheat production in many of the tropical areas—that is if other factors can be controlled so that the wheat plant can develop normally. Critical factors that must be present include sufficient nutrients, water, and sunshine for the plant to achieve this rapid growth. The author also pointed out that 4.5 t/ha have been obtained in the tropics in a period of 100 days. If we think on a plant efficiency basis or a time efficiency basis, 4.5 t/ha in 100 days compares quite favorably with a 7-t/ha crop in a period of 150 days, which is quite typical of the more temperate areas. Please remember that our research in the tropical environments is just beginning and that 4.5 t/ha may be common place within 10-15 years and it might even be possible in the future to compete with yield levels from many of the more temperate environments.

Another common theme throughout the conference was the problems with plant establishment. We even had an opportunity to see the actual problems in the field. We know that this problem is related to waterlogging and to crusting that is common in the paddy soils of this region. Certainly, researchers must try to resolve these problems so that better stands can be obtained in the field, thus leading to higher yield potential.

Quite certainly, where water is available, management of irrigation will be very important—not only to avoid waterlogging, but also to get maximum yield from the environment. In areas with limited water for irrigation, we must determine when is the opportune time to apply the water in order to achieve highest yields.

With the main theme of our conference dealing with the rice-wheat rotation areas of the world, we found that turnaround time between rice and wheat is critical. We had discussion on the benefits of minimum- and zero-tillage and how these practices might reduce this turnaround time and increase yield potential of the subsequent wheat crop. However, there are various problems associated with the minimum- and zero-tillage practices, including the requirement for mechanization and its special equipment, and the problem of increased insect and disease damage due to the carryover of the stubble. There will also be problems of farmer adoption in the South and Southeast Asia regions as well as maybe in other parts of the world.

We then turned our attention to fertility management, discussing both macro- and micro-nutrient requirements. Without a doubt, macro-nutrients will still command the major portion of the researchers attention, but undoubtedly micro-nutrient research must be increased, especially in the rice-wheat rotation areas of South and Southeast Asia. With more intensive cultivation and multiple crops per year, it is quite likely that we will encounter micronutrient deficiencies in many parts of the world in the future years and we must adapt our research to resolve these impending problems.

Without a doubt, diseases and pests will be important throughout the rice-wheat areas. We have heard that stem borer may become more serious on wheat due to its carryover in the rice stubble and this also may lead to increased problems in the subsequent rice crop. Most likely, there will be other insect problems that will become associated with a long-term rice-wheat association. Genetic resistance to these pests is a very long-term proposal and most control will have to be accomplished through management practices.

A potentially severe problem in the tropical environments of South and Southeast Asia is the footrot caused by *Sclerotium rolfsii*. This organism is well adapted in areas of high temperatures and reasonably high humidity and is quite characteristic throughout South and Southeast Asia. We have seen evidence of the organism in the field and, as most of you know, it is capable of attacking a wide range of host crops. Genetic resistance is a possibility but will be a long-term endeavor. Other footrots will also play an important role within the rice-wheat rotation. Among these, we must include the fusariums, helminthosporium, and maybe even others. Quite obviously, more attention must be given to genetic control of these footrots in the future and agronomic practices must be investigated as an alternative means of control.

Foliar diseases will be important throughout the region and the most permanent one will be helminthosporium leaf blotch. This disease was evident in some of the fields that we visited and losses can be quite traumatic if the conditions are conducive to disease development. Unfortunately most of the commercial varieties are susceptible and additional efforts must be made to find sources of resistance and incorporate those genes into adapted genotypes. For sure, we can not forget the other foliar diseases, namely the rusts, but, for these, better sources of resistance are available.

Our discussions then moved on to the breeding strategy that will be needed to resolve the constraints of the rice-wheat rotation. Again, due to the fact that we are dealing with a wide range of environments, we will need genotypes that have wide adaptation, high yield potential, good disease resistance, and drought and heat tolerance. Wide adaptation and high yield potential in tropical environments are two crucial characteristics that must continue to receive attention. Disease resistance will be important and efforts must be made to incorporate even better levels of resistance to the various diseases and to identify sources of resistances to helminthosporium, scab, and the various footrots. Enhanced drought tolerance will be necessary in those areas that have limited irrigation facilities and in those areas that will grow a crop on residual moisture.

Efforts to incorporate these characteristics into adapted germplasm will involve a great deal of cooperative research between CIMMYT, other research institutes, and national programs throughout the region. It is my belief that greater progress can be made by using shuttle breeding with certain national programs to select germplasm in alternate generations in Mexico and in the host country for selected desirable traits. Quite certainly, an international effort involving a wide array of countries and national program scientists, together with CIMMYT, will be required to resolve the various constraints that we have discussed during the last 5 days.

Nonirrigated Environments

We then turned our attention to the constraints in the nonirrigated tropical environments. We had hoped to have a paper dealing with moisture conservation tillage, but unfortunately the speaker could not come and so this topic was not discussed. I believe that you will agree with me that this topic should be discussed in one of our future conferences. We heard that genetic improvement for drought tolerance has achieved some success, but all of us here would most likely agree that there is still more to be done in the future to improve the drought tolerance of the genotypes adapted to tropical environments. Obviously, this will take a concerted effort on the part of all of us to achieve this objective.

Fertilizer management on nonacid and acid soils was discussed during the conference. Researchers in various countries have formulated excellent recommendations for the farmers, but these results need to be disseminated and additional research needs to be carried out in many countries. This is a research topic that will continue to require attention.

Aluminum toxicity tolerance is a major factor in many parts of the world, especially in the acid soils of South America and in certain parts of Africa. Breeding for tolerance to toxic levels of aluminum has been successful, but additional progress can and must be made in the future.

On the general theme of nutrient deficiencies and efficiencies, we discussed the macro-elements and the need for better testing procedures and probably the need for better identification procedures, especially for the micro-nutrients. Among the micro-nutrients mentioned were iron, zinc, manganese, copper, magnesium, boron, molybdenum, and one that surprisingly received little attention at this conference—sulfur. Sulfur will probably become one of the limiting micro-nutrients in the near future—not only throughout the rice-growing areas of this part of the world, but also in many other areas.

Scab resistance was another important topic discussed. We have heard about the progress achieved by the Chinese scientists and these superior materials are being used by many breeding programs around the world, including the CIMMYT program. Genetic resistance to scab obviously is present in the Chinese materials and it is only necessary to transfer this to adapted material for the tropics.

The topic of footrots was also mentioned for the nonirrigated areas and these footrots are probably not that different from those mentioned for the rice-wheat area, but they may have a different ranking in the nonirrigated areas. It is doubtful that *Sclerotium rolfsii* will be a problem in the nonirrigated areas, but many of the other diseases including fusarium and helminthosporium will be present.

In many parts of the wheat growing areas of South America, bacteria is becoming increasingly important. Preliminary indications are it will increase in importance in other areas of the world also. An author has indicated that resistance to bacteria can be incorporated through genetic means and our efforts must increase in this area in the near future.

Quite certainly, we can not forget the other diseases, such as leaf rust, stem rust, and in some areas septoria and, of course, barley yellow dwarf, just to name a few. Excellent sources of resistance exist for leaf rust and stem rust, however we must increase our efforts to enhance septoria resistance for certain areas of South America and Africa. Barley yellow dwarf is a disease that is quite likely to increase in many parts of the world as wheat cultivation becomes more intense. Efforts are currently underway at CIMMYT to identify and incorporate better sources of resistance to this organism.

The Bangladesh Story

We had a short discussion on one of the successes that has occurred in the tropical environment for wheat production—namely the story of Bangladesh. Fifteen years ago, many people in Bangladesh said that wheat could not grow there, but wheat researchers, most of them young, have shown that it can be accomplished. Today, Bangladeshi farmers are growing almost 700,000 ha and have an average yield of almost 2 t/ha. More importantly, wheat has been accepted by the general population and now is eaten widely on a regular basis.

Even more interesting is that in the short span of 10 years, Bangladesh has moved from the ranks of the nontraditional wheat growing countries into what can be called the traditional wheat growing countries. This makes us wonder if a similar change can be accomplished in other countries—such as Thailand.

Seed Storage

One of the speakers also discussed the storage of seeds under tropical conditions and I believe that this will be an important factor if wheat growing is to be a success in many of the tropical areas. Farmers must learn not only how to effectively grow wheat, but also how to store it from one season to another without loosing germination. It was pointed out that very simple technology can achieve this objective and that many farmers are very willing to implement what needs to be done.

Current Status

Where are we today? Quite certainly, wheat can be grown in the tropics as we have seen in farmers' fields during the conference field trip. I have just mentioned the Bangladesh success story, but we also have the example of Burma and it is quite likely that Thailand will be next.

There is also another question. Is wheat an economic crop in the tropics? I doubt that any of us here can answer that question, but we definitely have to think of wheat as a crop that is filling a void, instead of trying to compete with other crops. In other words, tropical wheat is an attempt to intensify the agricultural system, rather than the displacement of existing crops. In this manner, wheat has a bright future in many tropical areas of the world.

Future Research Priorities

Please understand that the following is my ranking of the future research priorities for wheat in the tropics.

Agronomy

For the moment, I will put agronomy or crop management first primarily because I think we need to learn how to grow wheat successfully in the tropics—not only from a yield standpoint, but also from an economic standpoint. To accomplish this will require a great deal of research from many different individuals and institutions.

Among the topics that must be investigated , we must include water management, stand establishment, problems with waterlogging, fertility management (macro- and micro-nutrients), minimum and zero tillage, and crop rotations. Obviously, the overall objective will be to obtain a satisfactory crop with good economic return and then convince the farmers to adopt the same practices. I firmly believe that wheat can be grown in the tropics and that it will become a more predominant crop in the future.

Future research must concentrate on the issue of the sustainability of yields in rotation or in cropping sequences. This not only is a problem in South and Southeast Asia, but is a global problem that must be attacked on several fronts. In many countries, total production per year is beginning to decrease or at best is failing to increase. Further, we must not only find ways to maintain current levels of production, but also to increase yields and total productivity per year in order to maintain pace with population increases and to improve food standards of various peoples around the world.

To accomplish this will require a concerted effort not only on wheat but on the other crops that are grown in the system or in rotation with wheat and will require a team of scientists from various disciplines working together.

Fertility management must command a sizable research component in the future. In the rice-wheat rotation, we are dealing with a fairly fragile environment and I believe we are going to see new problems, especially in regard to the micro-nutrients. The intensive cropping system, which is currently predominant throughout South and Southeast Asia and also in other parts of the world, will probably lead to more micro-nutrient deficiencies and, of course, will necessitate the continued application of the macro-elements.

Tillage practices definitely must be researched carefully and we have to find a way to shorten the turnaround time from one crop to another, thereby giving maximum advantage to both crops. Minimum and zero tillage are possible alternatives to solve this dilemma. Additional research needs to be given to rotations. One of the speakers in this conference indicated that rotations in most areas are fixed, however, I would say that they are fixed today, but farmers can and will change if there is an economic reason to do so. This has been demonstrated by the farmers in South and Southeast Asia repeatedly as they have switched to wheat in many areas.

Government policies
As priority number two, I would list government policies, especially agricultural polices. Maybe this deserves a number one ranking, but for the moment let us place it at a secondary level. Quite obviously, the governments of the world must give support and priority to agricultural research. They need to establish and maintain fair markets for the produce and to furnish incentives to the scientists who have to do the research. Most importantly, governments have to formulate policies that will create an interest on the part of the farmers to grow a crop—especially a new crop such as wheat. This may include price incentives, incentives on inputs, or other matters depending on the country.

Government policies, whether correct or not, will determine the fate of wheat as a new crop in the tropics. If the policies give incentive to the farmers, then wheat will be adopted. If they do not, then quite certainly wheat will never become a commercial crop in the tropical zones.

Germplasm improvement
Even though I am a breeder by training, I will place germplasm improvement as priority number three. It may not have any less importance then the other two, but certainly at this point in time, greater gains can be achieved through agronomy and government policy then through germplasm improvement.

Within the field of germplasm improvement, I rank both breeding and pathology important since they basically go hand in hand. We have to look for better adaptation to the tropical conditions, especially enhanced heat tolerance and characteristics that will resolve the other constraints that have been mentioned in this conference. There is a definite need to identify types with better tolerance to waterlogging and the source of this variation may come from the Chinese wheats.

A wide array of diseases will be constraints throughout the tropical wheat regions of the world. All of these must be confronted and genetic resistance will need to be incorporated. For some diseases, this will be quite simple, while for others this will be quite difficult and time consuming. To achieve these objectives, it will require an integrated approach involving wheat breeders, pathologists, and probably also agronomists.

Epidemiology of diseases in tropical environments is an area that will command more attention in the future. We have very little information about how fast organisms will mutate and new races or biotypes will develop. We may be dealing with an environment where changes occur very rapidly and this will necessitate the incorporation of durable types of resistance or the release of new varieties every 1 or 2 years. Only through research will we be able to determine whether epidemiology differs in the tropics versus what we are accustomed to in the more temperate environments. This research must begin in the near term.

It is my impression that to successfully cultivate wheat in the tropics will require a very precise production technology. A small mistake may lead to disastrous results. For example, even a little bit too much water can result in severe waterlogging of the wheat plant and greatly reduce yield potential or can result in crusting and poor plant establishment. Farmers must be informed of these potential hazards and must make every effort to apply the proper package of techniques to assure good crop production. To develop the technology necessary for wheat production in the tropics will require a concerted and coordinated effort on the part of a team of scientists at the international level. This team must involve breeders, pathologists, agronomists, physiologists, soil scientists, and maybe, most important of all, government officials who are willing to implement good and sound agricultural policies. With sound agricultural policies that support agricultural research and research scientists and with well trained scientists, I have no doubt that wheat will find its place in the marginal and warmer environments of the world.

Perseverance, Tenacity, Quality

We have heard a lot about PTQ during this conference. Since the environment is probably not limiting, we must make every effort to supply the necessary ingredients to take advantage of the conditions that prevail throughout the tropics. However, I want to give PTQ a different definition because I think we need it more now than we have ever needed it before. I would say PTQ stands for perseverance, tenacity, and quality—in that we must have perseverance and tenacity on the part of the researchers to resolve the problems in the various tropical regions of the world and quality as related to quality of research, in order to make wheat a commercial crop for these areas of the world.

Special Thanks

In closing, I would like to give special thanks to the Department of Agriculture for supporting this wheat research effort in Thailand and for helping us organize this conference. This appreciation is extended not only to the DOA, but to the entire group of wheat scientists who are working in Thailand in the various research teams. I think you will also want to join me in thanking the two secretaries who have worked so hard throughout this conference and have helped make it a success—namely Chanya and Pattama. I also want to thank Dave Saunders and Chris Mann for all of the small things that they did in organizing this conference. Finally and most important—to all the participants and speakers at this conference, thank you very much for giving us your insight and expertise and your assistance in making this a very successful conference.

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Field Trip

On Wednesday during the conference, participants inspected the research plots of the Phrae Rice Research Centre and the Agricultural Research and Training Centre (ARTC), Lampang. The participants also visited farmers' wheat fields that were part of an ARTC extension project.

Phrae Rice Research Centre

The Phrae Rice Experiment Station, located 540 km north of Bangkok, was established in 1970 to conduct research and develop new technology related to rice cultivation in three provinces. In 1981, under the National Agricultural Development Project, the station was "upgraded" and renamed the "Phrae Rice Research Centre," with widening responsibility for rice and temperate cereals (including wheat) research and development projects in nine northern provinces.

Scientists here concentrate on growing wheat in wheat-rice rotations. They conduct experiments in growing wheat on heavy paddy soils where waterlogging is a common and serious problem. Germplasm screening is done for these locations. Agronomic investigations include rates of N and P, seeding dates, irrigation frequency and methods of application, seeding methods, and incorporation of organic matter.

The three main tasks of the Phrae Rice Research Centre are to:

- Develop new technology that will improve upland and lowland rice production by solving the major rice yield constraints.

- Serve as the center for initiation of both short- and long-term research programs relating to rice and temperate cereals development.

- Transfer new technology to extension agents, farmers, and agricultural students by training, on-farm trials, and demonstrations.

Agricultural Research and Training Centre

The ARTC, located in Lampang Province, was established in 1975 under the Institute of Technology and Vocational Education (ITVE) to help ITVE accomplish its objectives, which are to:

- Produce vocational teachers at the B.S. level.
- Offer vocational education at the secondary, post-secondary, and degree levels.
- Study and conduct research for the improvement of vocational education and training.
- Provide practical training services for teachers, students, and farmers.

The ARTC accomplishes the ITVE objectives by:

- Conducting experiments for the improvement of agricultural technologies.
- Providing field training for agricultural students.
- Providing short course training for teachers, adult and young farmers, and farmers' wives.
- Producing and multiplying seeds for distribution to interested campuses and local farmers.
- Developing teaching materials for use on agricultural campuses.

The soils at ARTC are lighter than those at Phrae and correspond more to upland conditions. However scientists here still work with the rice-wheat rotation. Both national program materials and germplasm from international nurseries are screened. Agronomic work includes rate of N and P trials, dates of seeding, and stand establishment.

Scenes in the wheat research plots at the Phrae Rice Research Centre.

Scenes at the Lampang Agricultural Research and Training Centre (ARTC).

Farmers' fields in the ARTC Extension Project.

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Appendix

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Identificación de las restricciones a la producción y progreso logrado en el sur y el sudeste de Asia

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Resumen
En los países más tropicales de esta región, como Tailandia, Filipinas e Indonesia, existe un creciente interés en la producción interna de trigo. En esta etapa temprana de la obtención de genotipos y de la definición de las prácticas de manejo, no se puede esperar que el trigo compita con los cultivos tradicionales adaptados. Más bien, se debe fomentar la producción del trigo como cultivo adicional en las rotaciones en las que existe un vacío durante la temporada seca y fría, que, por diversas razones, suele producirse en los medios de tierras altas de secano o en los de cultivo del arroz. En los primeros, ya se han registrado rendimientos en las fincas de hasta 2.5 t/ha y, en los segundos, de hasta 5 t/ha.

Se pueden esperar mayores aumentos del rendimiento como resultado del empleo de germoplasma mejorado (mediante la selección de poblaciones segregantes en los medios que se desea beneficiar) y de las técnicas de manejo del cultivo. La siembra más oportuna, un mejor aprovechamiento del agua, la lucha contra las enfermedades y las malezas, una mayor eficiencia en el empleo de fertilizantes y técnicas más apropiadas para la trilla contribuirán a aumentar considerablemente el rendimiento.

Los costos de los insumos constituyen un factor esencial en las comunidades agrícolas de toda la región y, en algunas zonas, tiende a disminuir la utilización de fertilizantes a causa de las presiones de los precios de esos productos en el mercado. En ciertas zonas nunca se usan fertilizantes. Existe un riesgo en potencia de que el cultivo adicional del trigo agote la fertilidad y esto provoque una reducción del rendimiento en los cultivos para autoconsumo, o sea, el arroz o el maíz.

Identificación de restricciones a la producción y progreso logrado en América Central y del Sur

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Resumen
La mayoría de los problemas relacionados con la producción de trigo en las zonas más cálidas de América Central y del Sur se vinculan con tres factores ambientales básicos: la temperatura, la humedad y los tipos de suelo. Se han usado las definiciones de Papadakis (5) y mapas de suelos para caracterizar distintos medios de acuerdo con las temperaturas invernales, la humedad y el tipo de suelo. Se produce trigo o se experimenta con este cultivo en un variado conjunto de medios de la región.

Las temperaturas elevadas pueden limitar el potencial de rendimiento, pero, en general, los efectos de la temperatura parecen afectar los cultivos menos que los efectos del régimen de humedad o los suelos ácidos. Hay indicios de que las temperaturas muy altas pueden causar trastornos fisiológicos y las heladas suelen representar un problema en zonas restringidas de la región.

Los regímenes de humedad varían mucho en las zonas más cálidas y en muchos medios la falta de humedad es un grave factor limitante. En las partes más húmedas de la región, se producen enfermedades; en este trabajo se analizan las combinaciones de temperatura y humedad necesarias para la aparición de las principales enfermedades encontradas.

Los suelos ácidos abarcan la mayoría de las zonas más cálidas de América Central y del Sur e imponen grandes limitaciones al desarrollo de los cultivos. Se han obtenido variedades de trigo con cierta resistencia a la toxicidad del aluminio. No obstante, es poco probable que las variedades basten por sí solas para superar los problemas que plantean estos suelos y en el futuro será necesario hacer hincapié en las técnicas de manejo de los cultivos y el suelo.

Identificación de restricciones a la producción y progreso logrado en Africa

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Resumen
Si bien la mayor parte del trigo producido en Africa proviene de las tierras altas del este o de los cultivos irrigados de la temporada de invierno en el sur, varios países cultivan el cereal o realizan investigaciones sobre él en medios más tropicales. En este trabajo se caracterizan los medios encontrados en esos países de acuerdo con sus regímenes de temperatura y humedad. Se indican también las principales restricciones a la producción y las probables soluciones en algunos países específicos.

Efectos de las temperaturas elevadas en el desarrollo y el rendimiento del trigo y prácticas para reducir las consecuencias perjudiciales

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Resumen
El potencial de rendimiento del trigo en localidades muy cálidas depende del cociente fototérmico (CFT: recepción de radiación solar por unidad de temperatura). El CFT anual a nivel del mar se reduce en forma lineal con la disminución de la latitud, si bien aumenta con la altura. Por consiguiente, a nivel del mar y en un medio de clima marítimo el potencial de rendimiento anual medio a los 10° de latitud es de sólo unas 3 t/ha. Sin embargo, el CFT cambia cada mes y alcanza su valor máximo a medida que el fotoperíodo aumenta con mayor rapidez. Se incrementa el rendimiento si se hace coincidir con este momento la formación de florecillas entre la aparición de las espiguillas terminales y el espigamiento.

La temperatura elevada produce efectos mínimos sobre el tiempo de la planta (número de días grado requeridos para completar cualquier etapa fenológica u ontogenética). En consecuencia, son escasos los efectos sobre la cantidad potencial de órganos producidos por la planta, como hojas, macollos, espigas, espiguillas y florecillas, que son determinados por el genotipo y el fotoperíodo. Su principal efecto es sobre el tiempo de calendario necesario para completar cada etapa y, por lo tanto, sobre la cantidad de recursos para el desarrollo, como la radiación solar, el agua y los nutrientes, que se requiera para satisfacer el potencial de desarrollo. Si no se proporcionan recursos para el desarrollo en la cantidad mayor que exige la temperatura más alta, se reduce el tamaño de los órganos. Como el potencial de rendimiento es acumulado gradualmente por los macollos, las espiguillas, las florecillas y el grano, cuyas etapas se superponen, es posible manipular los recursos del desarrollo en cualquiera de la etapas del tiempo de la planta para influir sobre el componente apropiado del rendimiento.

Si bien es este trabajo se incluye la "receta" para producir 10 t/ha con temperaturas elevadas, junto con las necesidades de agua según los distintos déficit de presión de vapor y las cantidades requeridas de nitrógeno y radiación solar, también se consideran los efectos de los medios restrictivos sobre el desarrollo del cultivo. Se hace hincapié en las prácticas agronómicas óptimas durante las primeras etapas del desarrollo antes del doble aporcado, y en la selección de un genotipo apropiado para las condiciones de desarrollo previstas. Las características genotípicas que varían incluyen el tamaño de la semilla, la superficie de la primera hoja, el intervalo entre filocrones y la respuesta a la vernalización.

Problemas relacionados con el manejo de suelos en zonas de rotación arroz/trigo

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Resumen
En condiciones de riego, el trigo sembrado después del arroz parece tener grandes posibilidades y su cultivo podría extenderse a zonas de suelos adecuados y clima favorable en el norte y nordeste de Tailandia. Una de las principales limitaciones del rendimiento es el establecimiento deficiente de las plantas, muy frecuente cuando el trigo se siembra en arrozales. En este trabajo se tratan los problemas relacionados con el manejo del suelo y del riego. Se propone la investigación de prácticas alternativas de manejo de labranza.

Uso potencial de la labranza mínima al cultivar el trigo después del arroz

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Resumen
La siembra del trigo después del arroz es un importante patrón de cultivo en alrededor de 17.5 millones de hectáreas en el subcontinente de la India y en China. El retraso de la siembra y el establecimiento deficiente del cultivo son los principales factores que influyen en los bajos rendimientos del trigo observados con esta práctica.

En este trabajo se examinan las posibilidades que ofrece la labranza mínima como práctica de manejo del cultivo. Los resultados presentados muestran que la labranza mínima produce un rendimiento de trigo similar al logrado con las técnicas tradicionales de labranza y es superior a éstas desde el punto de vista económico y en cuanto al empleo de energía. Es preciso efectuar investigaciones para diseñar una sembradora adecuada, estudiar los efectos de las poblaciones de gusanos barrenadores del tallo en el próximo cultivo de arroz y ensayar el empleo de fertilizantes.

Necesidad de macroelementos y aspectos relacionados con el manejo de la fertilidad en las zonas de rotación trigo/arroz

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Este trabajo está dedicado al Dr. Robert Glenn Anderson, ya fallecido.

Resumen
Los estudios sobre fertilizantes (N-P-K) efectuados en 11 localidades del norte, el nordeste y el noroeste de la India, indican que es necesario aplicar 120 kg de N con 40 a 80 kg de P_2O_5/ha al arroz y al trigo en un sistema de rotación de estos cultivos, con el fin de mantener o mejorar la productividad. Preferiblemente se debe aplicar el P al trigo para obtener una mejor respuesta, y el K al arroz, en una proporción de 40 kg de K_2O/ha.

La rotación arroz/trigo se realiza en cierta medida y se intensifica en otros países del sur y el sudeste de Asia. Hay ahora en marcha investigaciones preliminares sobre el empleo de N-P-K en el cultivo del trigo dentro de la rotación. En Pakistán, el trigo sembrado después del arroz respondió con hasta 75 kg de N/ha y hubo una respuesta marginal con 50 kg de P_2O_5/ha. En Nepal y Bangladesh, se ha observado que la siembra del trigo después del arroz agota el suelo. En Sri Lanka, el trigo compite con las hortalizas y aún no se ha adaptado adecuadamente su cultivo al sistema de rotación basado en el arroz. En Filipinas y Tailandia, el trigo sembrado después del arroz respondió a la aplicación de 80 a 120 kg de N/ha, pero no hubo respuesta al fósforo.

En casi todos los tipos de suelo, es posible efectuar el abonado en cobertera con P dentro de los 45 días posteriores a la siembra del trigo. Esto destruye la vieja creencia de que sólo se podía aplicar P antes de la siembra o durante ella. Se ha comprobado que el P, aplicado en su totalidad y junto con el N como abonado de cobertera justo antes del primer riego, o la mitad de la cantidad total del fertilizante en el primer riego y el resto en el segundo, mejora el rendimiento.

Esta práctica contribuirá a ajustar el desequilibrio económico producido por la escasez de fertilizantes durante la culminación de la temporada de siembra.

Carencia de micronutrientes y de azufre en el cultivo del trigo

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Resumen
En este trabajo se sintetiza la función de los micronutrientes y el azufre en el desarrollo de las plantas y el contenido de los mismos en el suelo y las plantas. Se describe brevemente la sensibilidad del trigo y sus genotipos a la carencia de micronutrientes y se examinan los efectos de la carencia de azufre sobre la calidad del trigo. Con base en las pruebas del suelo, el análisis de las plantas y las respuestas del trigo a los micronutrientes y nutrientes secundarios, se identifican zonas donde probablemente exista una carencia o toxicidad de esos elementos y se señalan opciones para superar esos problemas.

Problemas que representan los insectos para los sistemas de cultivo arroz/trigo

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Resumen
Existen en el mundo casi 200 plagas de insectos que afectan tanto al arroz como al trigo, cuyos hábitat, ciclos biológicos y condición de plagas se describen en este trabajo. Se efectúa un análisis de los problemas que pueden causar esas plagas y se examinan las medidas para combatirlas. La estrategia básica de lucha consiste en limitar, mediante la programación de los cultivos en toda la comunidad, la capacidad portadora del medio que favorece la acumulación de insectos en los medios tropicales. El trigo sufre relativamente menos plagas que el arroz ya que a menudo se siembra en cultivo doble y triple, pero es probable que un número mayor de plagas nuevas afecten al trigo a medida que surgen más nichos ecológicos. El problema de plagas potencialmente más grave en los medios con temporada breve es la presencia de un virus u otro organismo patógeno transmitido por un vector a ambas gramíneas.

Se incluyen listas amplias de las plagas del trigo y el arroz y de las enfermedades que afectan a ambos.

Sclerotium rolfsii: Probables repercusiones sobre la producción de trigo y posibles medidas de control

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Resumen
Sclerotium rolfsii, *un hongo patógeno para las plantas que habita el suelo, causa pérdidas considerables en un gran número de especies vegetales, en particular en las zonas tropicales y subtropicales. Los esclerocios producidos por este agente patógeno constituyen las estructuras resistentes que le permiten sobrevivir en el suelo. Germinan en condiciones óptimas de 27 a 30° C, suelos entre húmedos y mojados, con un pH de 2.0 a 4.0 y en los 8 a 10 cm de la capa superior del perfil del suelo. La infección del tejido huésped es favorecida por la producción de ácido oxálico, que secuestra calcio para formar oxalato de calcio y también disminuye el pH, y por la producción de endopoligalacturonasa. El hongo puede propagarse de una planta a otra durante una sola temporada de cultivo mediante el contacto de las raíces. Para reducir la enfermedad, se recomienda sembrar en campos con escasa cantidad de inóculo, arar en forma profunda los campos infestados para enterrar el inóculo y los desechos orgánicos, y aplicar compuestos que contengan nitrógeno y calcio, como urea, bicarbonato amónico y yeso; estas medidas pueden disminuir las pérdidas. Entre los numerosos fungicidas, los que prometen mejores resultados son el PCNB y el vitavax. Tal vez valga la pena investigar el empleo de agentes para la lucha biológica. Los tejidos vegetales lignificados o suberizados son más tolerantes a la acción del ácido oxálico y/o la poligalacturonasa y pueden presentar mayor tolerancia al hongo. Se podría crear una técnica sencilla para seleccionar la resistencia a* S. rolfsii *utilizando metabolitos del hongo.*

Enfermedades del trigo causadas por *Helminthosporium sativum* y las fuentes de resistencia en Zambia

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Resumen

Las condiciones ambientales de Zambia durante las dos últimas temporadas favorecieron el desarrollo de enfermedades causadas por Helminthosporium sativum *en el trigo. Se ha establecido un método para la evaluación de esas enfermedades y se usan calificaciones con dos dígitos en etapas específicas del desarrollo de la planta para identificar el germoplasma resistente. Una matriz de correlaciones indica que existen coeficientes muy significativos de correlación negativa entre las calificaciones asignadas a la infección por* H. sativum, *los parámetros del rendimiento y la altura de las plantas incluidas en los ensayos nacionales y avanzados efectuados en 1986. Está en marcha la obtención de variedades tropicales de trigo resistentes a* H. sativum, *a partir de germoplasma proveniente del Brasil, el CIMMYT y cruzas locales. Se han registrado rendimientos de hasta 3.3 t/ha. Se combate con eficacia la transmisión de* H. sativum *en la semilla usando triadimenol. En Zambia se encuentra* Cochiliobolus sativum, *la forma perfecta de* H. sativum. *Las variedades que se producen en forma comercial son Whydah (PF7748), Hornbill (IAS64/Aldan), PF7339/Hahn'S' y Predg/Nac//PF7748.*

Estrategias de mejoramiento y pruebas para obtener trigos para zonas de rotación trigo/arroz

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Resumen

Se practica la rotación del trigo y el arroz en más de 200 millones de hectáreas en todo el mundo, sistema que incluye dos cultivos con requisitos agronómicos diferentes. Se analizan las rotaciones trigo/arroz existentes y se les clasifica en tres situaciones distintas según el agroclima, las prácticas agronómicas y las restricciones de la producción: i) el subcontinente de la India, ii) la cuenca del Yangtzé en China y iii) la rotación trigo/arroz en países tropicales como Tailandia, Filipinas e Indonesia. Se examinan las estrategias de mejoramiento y pruebas para obtener características como la tolerancia al calor y la resistencia a las enfermedades causadas por Helminthosporium *y a la roña provocada por* Fusarium, *que permitirán superar las principales restricciones de la producción en las rotaciones trigo/arroz. Se requerirá una combinación de esas características en un tipo agronómico adecuado para aprovechar el potencial de rendimiento del trigo cultivado en esa clase de rotación; se puede progresar aún más investigando distintas combinaciones de trigo y arroz de madurez temprana, intermedia y tardía, con el fin de optimar la producción del sistema.*

Perspectivas de la necesidad de investigaciones sobre la rotación trigo/arroz

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Resumen
La rotación trigo/arroz abarca aproximadamente 17.7 millones de hectáreas, el 28% de las tierras cultivadas con trigo en el sur y el sudeste de Asia. En este trabajo se examina la necesidad de realizar investigación sobre el establecimiento de los cultivos y la preparación de la tierra, los fertilizantes, las malezas, la irrigación, patrones alternativos de cultivo, la cosecha, la trilla y el almacenamiento, la lucha integrada contra las enfermedades típicas de los climas muy cálidos con métodos genéticos, agronómicos y químicos, y variedades con características morfológicas y fisiológicas especiales. En conclusión, se propone un enfoque multidisciplinario integrado, que implica la participación de especialistas en biología y ciencias sociales, personal de los servicios de extensión y agricultores, para formular recomendaciones sobre este patrón de cultivo que tengan en cuenta los aspectos económicos y la estabilidad de todo el sistema, en lugar de un producto en particular. La metodología propuesta consiste en un equilibrio de la investigación aplicada en las fincas, respaldada por un programa específico en las estaciones experimentales.

Necesidad de fertilizantes y aspectos relacionados con el manejo en suelos no ácidos de zonas no irrigadas

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Resumen
En Argentina, por una serie de razones económicas, siempre se ha hecho poco uso de los fertilizantes en el cultivo del trigo. Con la introducción de variedades semienanas en el decenio de 1970, se ha vuelto mucho más viable la fertilización. En este trabajo se señala la respuesta del trigo al N y al P en la pampa húmeda y se analizan los parámetros relacionados con el suelo y el clima que condicionan el rendimiento y la respuesta a los fertilizantes.

La humedad, así como la duración del período de barbecho y el cultivo anterior, influyen sobre el rendimiento y la respuesta. El análisis del suelo para determinar la cantidad de nitrógeno no proporciona una correlación cabal de la respuesta al nitrógeno, pero, en el caso del fósforo, la cantidad de este elemento determinada mediante el análisis del suelo está estrechamente vinculada con la respuesta.

Necesidad de fertilizantes y aspectos relacionados con el manejo en suelos ácidos de zonas no irrigadas de Brasil

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Resumen
Los 17 millones de hectáreas de cultivo potencial del trigo en Brasil se pueden dividir en tres regiones climáticas: la meridional, la central meridional y la central. Los principales problemas vinculados con la producción de trigo se relacionan con la conservación y manejo del suelo, su fertilidad y acidez, y las enfermedades y los insectos. En este trabajo se examinan las características naturales de los oxisoles y ultisoles que predominan en esas regiones, y también su respuesta a las prácticas de labranza y la fertilización. La labranza de conservación, aún no adoptada ampliamente en Brasil, ofrece posibilidades de reducir la degradación del suelo.

Técnicas de selección y fuentes de resistencia al tizón de la espiga causado por *Fusarium*

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Resumen
El tizón de la espiga del trigo causado por Fusarium *provoca grandes pérdidas del rendimiento de granos de este cereal y de la producción pecuaria en la región del río Yangtzé en China. Se han seleccionado más de 300 fuentes de resistencia a la enfermedad en el trigo y se han usado unas 40 en el fitomejoramiento del cereal.*

Fusarium graminearum *fue la especie predominante identificada en 2,450 muestras de aislamientos obtenidos en 21 provincias de China. Se detectó una variación significativa en la virulencia de los aislamientos, pero no se descubrió patogenicidad específica en los aislamientos de* F. graminearum.

No hubo diferencias significativas en la patogenicidad de las ascosporas y los conidios o en la de una o dos y 100 esporas por cada 5 μl de suspensión.

Se han comparado métodos de inoculación in vitro *e* in vivo. *Se recomienda que la selección para lograr resistencia al tizón de la espiga causado por* Fusarium *se base en la selección primaria efectuada en grandes ensayos de selección usando el método tradicional en el campo. Los materiales avanzados obtenidos deben ser sometidos nuevamente a la selección usando la técnica de inoculación mediante inyección y el bioensayo del coleoptilo etiolado con el fin de confirmar la resistencia.*

Pudriciones de la raíz del trigo en medios tropicales: Efectos potenciales y medidas de control

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Resumen
En este momento, no están bien definidos los problemas que afrontarán los patólogos y fitomejoradores al intentar obtener variedades resistentes a las pudriciones de la raíz para medios tropicales. Esa labor resultará muy compleja. En este trabajo se hace hincapié en: 1) la importancia de un sistema radicular sano en el trigo, 2) las interacciones entre el huésped y el agente patógeno en el medio, 3) las dificultades para identificar los problemas de pudrición de la raíz, 4) los problemas en potencia que plantean los agentes patógenos transmitidos por el suelo y 5) los métodos para combatir las enfermedades transmitidas por el suelo. Los patólogos y fitomejoradores tendrán la responsabilidad de determinar la importancia de los agentes patógenos y de idear y poner en práctica métodos químicos y de cultivo para combatirlos a corto plazo, con el objetivo de obtener a largo plazo variedades resistentes.

Enfermedades bacterianas del trigo y su importancia en las regiones tropicales

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Resumen

Hay siete especies bacterianas patógenas para el trigo, pero sólo dos de ellas causan pérdidas económicas. Pseudomonas syringae *pv.* syringae *puede provocar daños graves cuando la temperatura es moderada y hay humedad.* Xanthomonas campestris *pv.* translucens, *encontrada en todo el mundo, causa la enfermedad bacteriana más grave del trigo. También se prevé que será la enfermedad bacteriana más importante en las zonas tropicales. La semilla constituye el principal medio de propagación extensa de la enfermedad y es necesario contar con métodos poco costosos para combatir el inóculo así transmitido. En los campos, el agua es la principal vía de propagación y son importantes las prácticas de cultivo que restringen el desplazamiento del agua de riego de campos infestados. Es preciso obtener más información sobre la supervivencia de las bacterias, como parásitos o como epífitas, en las malezas o en otros cultivos, como el arroz, con el fin de formular estrategias de lucha en los sistemas agrícolas tropicales. La resistencia será un elemento fundamental en la lucha contra la enfermedad.*

Tolerancia a la sequía en el trigo harinero: Análisis del aumento del rendimiento del germoplasma del CIMMYT a través de los años

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Resumen

Se presenta un análisis de los datos sobre el rendimiento obtenidos en medios de bajo rendimiento, exentos de enfermedades y afectados por la sequía, correspondientes a los Ensayos Internacionales de Rendimiento de Trigo Harinero de Primavera (ISWYN), y los de un ensayo comparativo del rendimiento con riego completo (600 mm) y reducido (300 mm), efectuado en Ciudad Obregón, al noroeste de México. Se compara el rendimiento de los antiguos testigos Siete Cerros 66 e Inia 66 en medios afectados por la falta de agua durante los años de los ISWYN, con:

- *el rendimiento medio de todas las entradas incluidas en los ISWYN,*
- *variedades producidas por el CIMMYT que se lanzaron más recientemente, y*
- *variedades altas y tolerantes a la sequía desarrolladas en la localidad.*

Los resultados demuestran que, en los dos últimos decenios, se logró un avance continuo en el potencial de rendimiento en medios afectados por la sequía usando variedades semienanas seleccionadas en condiciones casi óptimas. Las dos variedades testigos mostraron una gran estabilidad temporal y espacial del rendimiento en esos medios y produjeron rendimientos superiores a los de las variedades altas, desarrolladas en la localidad. Las variedades obtenidas más recientemente, que constituyen el mejor grupo de trigos de alto rendimiento y adaptación amplia del CIMMYT, se comportaron mejor que los testigos y las variedades más antiguas en prácticamente todas las condiciones, incluso en las de sequía.

Esos resultados indican que se pueden combinar el potencial de rendimiento elevado y la capacidad de respuesta a los insumos en materiales resistentes a la sequía.

Se analizan los resultados en el contexto de distintos métodos de fitomejoramiento para las situaciones de carencia de humedad, incluido el método de fitomejoramiento del CIMMYT para obtener tolerancia a la sequía.

Progreso alcanzado en Brasil en la obtención de trigos con mayor tolerancia a la toxicidad del aluminio

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Resumen

La gran mayoría de los suelos brasileños cultivados con trigo tienen un pH bajo, un alto grado de toxicidad provocada por el aluminio y una escasa concentración de fósforo. El aluminio interfiere en el desarrollo de las plantas y causa una anomalía fisiológica llamada "crestamento". Todas las variedades brasileñas de trigo lanzadas para este tipo de suelo (latosol) son tolerantes a la toxicidad del aluminio. Los problemas del suelo y la incidencia elevada de enfermedades son factores que limitan la producción de trigo. La aplicación de cal para eliminar la toxicidad del aluminio aumenta la productividad del suelo. Actualmente varias instituciones brasileñas llevan a cabo dinámicos programas de fitomejoramiento y contribuyen así a lograr una productividad mayor y más estable del trigo. La evolución de los trigos brasileños pasó por muchas etapas y, entre ellas, tuvo gran importancia la introducción de trigos mexicanos. En los últimos años, gracias a las variedades mejoradas nuevas, se han obtenido rendimientos de grano de hasta 5,000 kg/ha en condiciones experimentales en suelos ácidos. En condiciones de campo se han alcanzado rendimientos de 2,500 kg/ha en las zonas donde se aplican las tecnologías recomendadas. En suelos encalados e irrigados, los trigos mexicanos pueden producir hasta 7,000 kg de grano por hectárea.

Obtención de trigos más eficientes en el aprovechamiento de los nutrientes: progreso y potencial

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Resumen

Se define la eficiencia en el aprovechamiento de un nutriente como la capacidad de un genotipo de desarrollarse en un suelo que carece de la cantidad de ese nutriente requerida por un genotipo normal. En el trigo hay considerable diversidad genética en relación con la eficiencia en el aprovechamiento del Cu, el Zn y el Mn, y parece posible el mejoramiento para obtener esas características y combinarlas en un solo genotipo. Existe una gran eficiencia en el centeno y aparentemente se podrán transferir esas características del centeno al trigo mediante la translocación de cromosomas. El triticale ha heredado la eficiencia en el aprovechamiento de los nutrientes de su progenitor, el centeno. El progreso hacia una mayor eficiencia en el aprovechamiento del P se ve obstaculizado por la falta de conocimientos sobre los elementos bioquímicos que intervienen y la carencia de procedimientos eficaces de selección. Se arguye que el aprovechamiento del N en el trigo es ya tan eficiente como se requiere. La eficiencia en el aprovechamiento de los nutrientes puede conferir mayor resistencia o tolerancia a las enfermedades y la sequía, un enraizamiento más profundo y mayor capacidad de respuesta al empleo de otros fertilizantes, en particular al N.

Prácticas de manejo integrado de las plagas en los medios tropicales donde se cultiva el trigo

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Resumen
En una estrategia de manejo integrado de las plagas (MIP), se emplean múltiples tácticas para mantener las poblaciones patógenas en niveles inferiores a los que provocan pérdidas económicas y, al mismo tiempo, se minimiza la selección direccional en esas poblaciones y se reducen los efectos nocivos en el medio. Los conceptos del MIP son pertinentes y aplicables en el caso del cultivo del trigo cuando se introduce en los sistemas tradicionales de cultivo de las zonas tropicales. La obtención y difusión de variedades resistentes a las plagas, las prácticas de cultivo, las tácticas del control biológico y la aplicación de plaguicidas a la semilla son medidas importantes para el manejo del trigo en zonas tropicales. La aplicación eficaz del MIP depende de la realización de investigaciones relacionadas con los sistemas locales de cultivo y de la presencia de una eficaz red de difusión.

Perspectivas de la necesidad de investigaciones en zonas tropicales no irrigadas

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Resumen
Se analiza la necesidad de investigaciones en zonas tropicales no irrigadas donde se cultiva el trigo tomando como ejemplo el Cono Sur. La alternativa más económica para el ciclo de invierno en esta región es el cultivo del trigo, fundamentalmente en rotación con la soya o el maíz.

Se examinan los factores ambientales desfavorables, como el clima imprevisible, el régimen de temperaturas altas, la radiación solar escasa y la sequía, y se analiza la forma de tomar en cuenta esos factores en un programa de fitomejoramiento. Además, se consideran las repercusiones de los problemas del suelo, la germinación prematura, las enfermedades y las plagas de insectos, en la labor de obtención de germoplasma estable y de alto rendimiento para esta región. El análisis revela la necesidad de mantener la base de adaptación amplia del germoplasma con las características mencionadas, y las ventajas del sistema de ensayos en múltiples localidades.

En cuanto al manejo del cultivo, se considera que el factor más limitante es la falta de agua en distintas etapas del desarrollo del trigo y se examinan el empleo de la labranza mínima para conservar la humedad, la compactación escasa del suelo y la erosión. Se estima que la eliminación de las barreras químicas del suelo mediante el mejoramiento de éste es esencial para favorecer la penetración de las raíces y aumentar la eficiencia en el aprovechamiento del agua.

Integración de la investigación sobre el trigo y la producción del cereal en Bangladesh

L. Butler, Programa de Trigo, CIMMYT, Bangladesh

Resumen
El cultivo del trigo se extendió en forma espectacular en Bangladesh entre 1974 y 1983, en parte como resultado de los esfuerzos del equipo de investigadores del Centro del Trigo del Instituto de Investigaciones Agrícolas de Bangladesh. Esos científicos se han enfrentado al desafío de aumentar la producción de trigo en un medio socioeconómico cada vez más inestable para el cultivo del cereal, llevando los productos de sus investigaciones directamente a los agricultores mediante demostraciones en las fincas con las variedades nuevas y técnicas de producción que disminuyen los costos, como la labranza reducida. Las actividades de capacitación han estimulado la interacción entre los científicos y los agricultores.

Almacenamiento de la semilla de trigo en medios tropicales

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Resumen
El almacenamiento de la semilla del trigo en las condiciones de los medios tropicales plantea problemas distintos de los del almacenamiento en las zonas donde el cereal es un cultivo tradicional. Las temperaturas y la humedad relativa elevadas no permiten aplicar métodos de almacenamiento eficaces y de bajo costo. Los agricultores se han adaptado muy bien a los nuevos problemas vinculados con la producción de semilla de trigo. Una de las principales limitaciones para mejorar la calidad y la cantidad de la semilla almacenada en las fincas es la carencia de contenedores para el almacenamiento. Otra restricción importante es que los agricultores, a causa de su necesidad de alimentos y de dinero en efectivo, no pueden reservar parte del grano cosechado para conservarlo como semilla.

Identification des facteurs limitatifs de la production et du progrès dans le sud et le sud-est de l'Asie

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Résumé
La Thaïlande, les Philippines et l'Indonésie, qui sont les pays asiatiques les plus tropicaux, se montrent de plus en plus désireux d'obtenir une production de blé sur leurs territoires respectifs. Mais il est peu probable qu'à ce stade préliminaire - alors qu'il s'agit encore d'obtenir des génotypes et de définir les pratiques culturales - le blé entre en compétition avec les cultures traditionnelles adaptées. Il est préférable, pour le moment, de promouvoir la production de blé en tant que culture additionnelle dans les rotations où subsiste un vide pendant la saison sèche et froide, ce qui, pour divers raisons, se produit ordinairement dans les hautes terres dépourvues d'irrigation ou dans les plantations de riz. Dans des milieux en altitude, un rendement de 2,5 t/ha a déjà pu être obtenu, rendement qui a atteint 5 t/ha dans les plantations de riz.

Il y a tout lieu d'espérer que ces résultats s'amélioreront grâce à l'emploi de matériel génétique amélioré (sélection pour des environnements ciblés de populations en ségregation) et à l'application de techniques de culture appropriées. Un ensemencement en temps opportun, l'utilisation optimale de l'eau, la lutte contre les maladies et les mauvaises herbes, l'application judicieuse d'engrais et de techniques de battage améliorées contribueront aussi à accroître sensiblement le rendement.

Les coûts de divers facteurs de production jouent un rôle important dans les communautés agricoles de toute la région et dans certaines zones limitent l'emploi d'engrais en raison, précisément, des pris de ces produits sur le marché. Dans certaines zones, les cultivateurs n'emploient jamais d'engrais. La culture du blé à titre additionnel implique un risque potentiel du fait qu'elle affecte la fertilité du sol et provoque un abaissement du rendement de cultures dont la production est destinée à l'autoconsommation, tels le riz ou le maïs.

Identification des facteurs limitatifs de la production et du progrès en Amérique centrale et en Amérique du sud

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Résumé
Les problèmes relatifs à la production de blé dans les zones les plus chaudes d'Amérique centrale et d'Amérique du sud sont, pour la plupart, liés à trois facteurs écologiques essentiels, à savoir: la température, l'humidité et les types de sol. Les définitions de Papadakis (5) ont été utilisées ainsi que des relevés cartographiques des sols pour caractériser divers milieux selon les températures hivernales, le degré d'humidité et le type de sol. Dans un ensemble de milieux de la région offrant une certaine diversité, le blé est déjà cultivé ou sa culture y est expérimentée.

Les températures élevées peuvent limiter le potentiel de rendement, mais en général les cultures semblent moins affectées par la température que par le degré d'humidité ou l'acidité du sol. Apparemment, les plus hautes températures peuvent être cause d'anomalies physiologiques et dans un petit nombre de zones de la région les gelées sont une source de problèmes.

Le degré d'humidité varie considérablement dans les zones les plus chaudes et dans nombre de milieux le manque d'humidité constitue un grave facteur limitatif. Des maladies sont détectées dans les zones les plus humides de la région et les conditions atmosphériques - humidité et température combinées -, propices à l'apparition des principales maladies observées, sont exposées ici.

L'acidité des sols dans la plupart des zones les plus chaudes d'Amérique centrale et d'Amérique du sud limitent considérablement le développement les cultures. Des variétés de blé offrant une certaine résistance à la toxicité de l'aluminium ont été obtenues, mais il est peu probable que ces variétés permettent de surmonter les problèmes que posent ces sols et il y aura lieu à l'avenir de s'efforcer de mettre au point les techniques propres à adapter cultures et sols.

Identification des facteurs limitatifs de la production et du progrès en Afrique

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Résumé
Bien que la majeure partie du blé produit en Afrique provienne des hautes terres situées à l'est, ou des cultures irriguées de la saison d'hiver au sud, nombreux sont les pays du continent africain qui cultivent cette céréale ou en font l'objet de recherches dans des milieux plus tropicaux. Sont caractérisés ici les milieux identifiés dans ces pays en fonction de leurs régimes de température et d'humidité et sont signalés les principaux facteurs qui restreignent la production, ainsi que les solutions possibles dans certains pays en particulier.

Effets des températures élevées sur le développement et le rendement du blé et les pratiques visant à en atténuer les conséquences préjudiciables

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Résumé
Le potentiel de rendement du blé dans des localités de climat très chaud dépend du quotient photothermique (QPT; réception de radiation solaire par unité de température). Le QPT annuel au niveau de la mer diminue de façon linéaire en fonction directe de la diminution de la latitude, mais augmente avec l'altitude. Au niveau de la mer et sous un climat maritime le potentiel de rendement annuel moyen à 10° de latitude n'est que de 3 t/ha. Mais le QPT change chaque mois et atteint son maximum à mesure que la photopériode augmente plus rapidement. Le rendement tend à s'élever si la floraison entre l'apparition d'épillets et l'épiaison coïncide avec ce moment.

Une température élevée n'a que peu d'effet sur le temps requis par la plante (c'est-à-dire, le nombre de jours/degré requis pour compléter toute étape phénologique ou ontogénétique). La température n'a qu'une influence médiocre sur la quantité potentielle d'organes que produit la plante: feuilles, rejets, épis, épillets et fleurs, que déterminent le génotype et la photopériode. Mais elle a un effet notamment sur le temps matériel proprement dit nécessaire pour compléter chaque étape et, par suite, sur la quantité de ressources nécessaires pour le développement, telles la radiation solaire, l'eau et les éléments nutritifs. A défaut de ces ressources indispensables dans les proportions croissantes qu'exige une température plus élevée, les organes végétaux sont de plus petite taille. Le potentiel de rendement étant accumulé graduellement par les talles, les épillets, les fleurs et les graines, dont les étapes de développement se superposent, il est possible de manipuler les ressources du développement au cours de toutes les étapes du développement de la plante de manière à influer sur le facteur approprié du rendement.

Non seulement une "recette" est donnée dans cette étude pour obtenir un rendement de 10 t/ha par températures élevées, en couvrant les nécessités d'eau suivant les déficits de pression de vapeur et les quantités requises d'azote et de radiation solaire, mais y sont également exposés les effets de moyens restrictifs sur le développement de la culture. De même, il y est insisté sur les pratiques agronomiques optimales pendant les premières étapes du développement avant le double chaussage et sur la sélection d'un génotype approprié pour les conditions prévues du développement. Parmi les caractéristiques génotypiques variables figurent notamment la taille de la semence et de la première feuille, l'intervalle entre les phylochrones et la réponse à la vernalisation.

Problèmes liés à l'utilisation des sols en zone de rotation riz-blé

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Résumé
En conditions d'irrigation, la culture du blé après le riz semble avoir un grand potentiel et pourrait être étendue à des zones possèdant un bon sol et un climat favorable dans le nord et le nord-est de la Thaïlande. Un des facteurs limitants majeurs pour le rendement est la mauvaise installation des plantes, largement observée quand le blé est semé dans les champs de paddy. Les problèmes liés au travail du sol et à l'irrigation sont discutés. Des pratiques de labours alternatives sont suggérées pour la recherche.

Possibilités de labour minimal dans la culture de blé à la suite de celle de riz

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Résumé
Sur près de 17,5 millions d'hectares il est d'usage, tant en Inde qu'en Chine, de semer le blé après la récolte du riz et ces semailles tardives, jointes aux conditions déficientes des cultures, sont les principaux facteurs dont l'influence se manifeste dans les faibles rendements du blé obtenu de la sorte.

Les possibilités qu'offre un labour minimal adopté comme pratique culturale sont examinées dans cette étude. Les résultats qui y sont présentés prouvent que ce mode de culture permet d'obtenir un rendement de blé analogue au rendement favorisé par l'application des techniques traditionnelles de labour et constitue même une technique supérieure à ces dernières du point de vue économique aussi bien que de l'emploi d'énergie. Il est nécessaire de procéder à des recherches en utilisant un semoir approprié et d'observer les ravages occasionnés par les populations de larves qui taraudent les tiges pendant la prochaine culture de riz, ainsi que les résultats fournis par l'emploi d'engrais.

Nécessité de macro-éléments et aspects de la fertilisation dans les zones de rotation de culture de blé et de riz

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Résumé
Les études dont ont fait l'objet certains engrais (à base de N, P et K) dans onze localités du nord, du nord-ouest et du nord-est de l'Inde, ont permis d'observer que dans un système de rotation de cultures de riz et de blé il faut appliquer 120 kg N/ha et de 40 à 80 kg P_2O_5/ha pour en maintenir ou améliorer la productivité. Il est préférable d'appliquer P au blé pour obtenir une meilleure réponse et K au riz dans la proportion de 40 kg K_2O/ha.

La rotation de cultures de riz et de blé se pratique dans une certaine mesure das ces régions et tend à se répandre dans d'autres pays du sud et du sud-est asiatiques. Des recherches préliminaires sont en cours sur l'emploi de N, P et K dans la culture du blé dans un système de rotation. Au Pakistan, le blé semé après le riz a répondu à l'application de 75 kg N/ha et a donné une réponse marginale à l'application de 50 kg P_2O_5/ha. Mais au Népal et au Bangladesh il a été constaté que semer du blé à la suite du riz épuise le sol. Au Sri Lanka, blé et cultures maraîchères sont en compétition et il faut une bonne adaptation de leur culture respective dans le système de rotation à base de riz. Aux Philippines et en Thaïlande, le blé semé après le riz a répondu de façon satisfaisante à l'application de 80 à 120 kg N/ha, mais n'a pas réagi au phosphore.

Sur les sols de presque tous types il est possible de répandre des engrais phosphorés dans les 45 jours consécutifs à l'ensemencement du blé, contrairement à une vieille croyance selon laquelle les engrais à base de phosphore ne pouvaient être appliqués qu'avant ou pendant les semailles. Il a été constaté que le volume de P appliqué en totalité et en même temps que N, comme engrais en couverture immédiatement avant le premier arrosage, ou l'application de la moitié du volume total de l'engrais lors du premier arrosage et du reste lors du second, améliore le rendement.

Cette pratique contribuera à corriger le déséquilibre économique qu'occasione la pénurie d'engrais dans la période de semis.

Carence de micro-éléments nutritifs et de soufre dans la culture du blé

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Résumé
Est exposée dans cette étude la fonction des micro-éléments nutritifs et du soufre dans le développement des plantes et de leur contenu dans le sol et les plantes. La sensibilité à la carence de micro-éléments nutritifs y est brièvement décrite et les effets de la carence de soufre sur la qualité du blé y sont examinés. Sur la base de tests portant sur la nature du sol, de l'analyse des plantes et de l'observation des réponses du blé aux micro-éléments nutritifs et aux éléments nutritifs secondaires sont identifiées les zones où se révèle une carence ou la toxicité de ces éléments et sont indiqués les moyens éventuels de résoudre ces problèmes.

Problèmes causés par les insectes dans le cadre des systèmes de culture du riz et du blé

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Résumé
Près de 200 espèces d'insectes dans le monde s'attaquent aux cultures de riz et de blé. Leur habitat, leurs cycles biologiques et les maladies qu'ils occasionnent font l'objet de cette étude. Les problèmes dont ils sont cause y sont analysés en même temps que sont examinées les mesures à prendre pour les combattre. La stratégie de base de la lutte engagée contre ce fléau consiste à limiter, par le biais de la programmation des cultures dans l'ensemble de la communauté, la capacité du milieu ambiant pour favoriser le pullulement d'insectes dans les zones tropicales. Le blé est relativement moins affecté que le riz dont souvent sont obtenues deux ou trois récoltes par an, mais il est fort probable que la prolifération de niches écologiques donne lieu à de nouveaux problèmes constitués par les maladies attaquant le blé. Dans les milieux où la période de culture est courte, le problème potentiellement le plus grave est la présence d'un virus ou d'un autre agent pathogène transmis par un vecteur et qui attaque aussi bien le blé que le riz.

Cette étude comporte de longues listes des espèces qui s'attaquent au blé et au riz et des maladies dont sont atteintes ces céréales.

Sclerotium rolfsii: Répercussions probables sur la production de blé et possibles mesures de contrôle

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Résumé
Sclerotium rolfsii, *champignon qui vit dans le sol, cause des pertes considérables à un grand nombre d'espèces végétales, notamment dans les zones tropicales et subtropicales. Les sclérotes que produit cet agent pathogène constituent des structures résistantes qui lui permettent de survivre dans le sol. La germination de ce champignon requiert des conditions optimales: une température de 27 à 30°C, une terre humide et même très humide, un pH de 2,0 à 4,0 et 8 à 10 cm au-dessous de la superficie de la terre. L'infection du tissu hôte est favorisée par la production d'acide oxalyque qui absorbe le calcium pour donner de l'oxalate de calcium et abaise le pH, ainsi que par la production d'endopolygalacturonase. Le champignon se propage d'une plante à une autre au cours d'un seul cycle de culture par simple contact entre les racines. A titre de mesure préventive il est recommandé de n'ensemencer que les champs où ne se trouve qu'une petite quantité d'inoculum, de labourer en profondeur les terres infestées afin d'enfouir l'inoculum et les déchets organiques et d'appliquer des combinaisons d'azote et de calcium, comme l'urée, le bicarbonate ammoniacal et le plâtre. De telles mesures peuvent diminuer les pertes. Parmi les nombreux pesticides, le PCNB et le vitavax sont ceux qui permettent d'espérer les meilleurs résultats. Il serait bon d'entreprendre des recherches sur l'emploi d'agents dans la lutte biologique. Les tissus végétaux lignifiés ou liégés tolèrent l'acide oxalique et/ou la polygalacturonase et peuvent présenter plus de tolérance au champignon. Une technique simple pourrait être mise au point pour sélectionner la résistance à* S. rolfsii, *basée sur l'utilisation de métabolites du champignon.*

Maladies du blé causées par *Helminthosporium sativum* et sources de résistance en Zambie

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Résumé
Les conditions atmosphériques et agronomiques en Zambie pendant les deux dernières saisons ont favorisé l'évolution de maladies causées au blé par Helminthosporium sativum. *L'application d'une méthode d'évaluation de ces maladies et l'utilisation de qualifications à deux chiffres à des étapes spécifiques du développement de la plante ont permis l'identification de matériel génétique résistant. Une matrice de corrélations indique qu'il existe des coéfficients de corrélation négative très significatifs entre les qualifications assignées à l'infection par* H. sativum, *les paramètres de rendement et la hauteur des plantes dans les lignées inclues dans les essais avancés effectués sur le plan national en 1986. Les travaux sont en cours pour obtenir des variétés tropicales de blé résistantes à* H. sativum *à partir de matériel génétique en provenance du Brésil, du CIMMYT et de croisements locaux. Les rendements obtenus ont pu atteindre 3,3 t/ha. L'emploi de triadimenol permet de combattre efficacement la transmission de* H. sativum *à la semence.* Cochliobolus sativum, *forme parfaite de* H. sativum, *existe en Zambie. Diverses variétés se produisent à l'échelle commerciale, à savoir: Whydah (PF7748), Hornbill (IAS64/Aldan), PF7339/Hahn'S' et Predg/Nac//PF7748.*

Stratégies d'amélioration et d'essais visant à obtenir des blés destinés à être cultivés dans les zones de rotation de blé et de riz

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Résumé
La rotation de blé et de riz est un système de culture pratiqué sur plus de 200 millions d'hectares dans le monde, système dans lequel sont impliquées deux céréales dont les conditions agronomiques qu'elles requièrent sont différentes. L'analyse de ces rotations permet de les classer en trois régions distinctes en fonction de l'agro-climat, des pratiques agronomiques et des limitations de la production: i) les sous-continent de l'Inde, ii) le bassin du Yangtzé en Chine et iii) les pays tropicaux tels que la Thaïlande, les Philippines et l'Indonésie. Sont examinées dans cette étude les stratégies d'amélioration et d'essais pour obtenir certaines caractéristiques dont, notamment, la tolérance à la chaleur et la résistance aux maladies causées par Helminthosporium et à la gale provoquée par Fusarium. *L'acquisition de ces caractéristiques devra permetre une meilleure production dans les rotations de blé et de riz et leur combinaisons dans un cadre agronomique adéquat permettre également de mettre à profit le potentiel de rendement du blé cultivé dans ce type de rotation. Des recherches portant sur diverses combinaisons de blé et de riz de maturité précoce, normale et tardive pourraient optimiser les résultats du système.*

Perspectives des recherches nécessaires sur la rotation de cultures de blé et de riz

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Résumé
La rotation des cultures de blé et de riz se pratique sur environ 17,7 millions d'hectares, soit 28% des terres sur lesquelles s'étendent les cultures de blé au sud et au sud-est de l'Asie. Cette étude met l'acent sur la nécessité de faire des recherches portant sur l'établissement des cultures et la préparation des sols, les engrais, les mauvaises herbes, les cultures optionnelles, la récolte, le battage et le stockage, la lutte contre les maladies caractéristiques dans les régions de climat très chaud au moyen de méthodes génétiques, agronomiques et chimiques, enfin les variétés présentant des caractères morphologiques et physiologiques particuliers. En conclusion les auteurs suggèrent une recherche multidisciplinaire impliquant la participation de spécialistes en biologie et en sciences sociales, du personnel des services de vulgarisation et des agriculteurs. Cette recherche pourrait conduire à formuler des recommandations au sujet de ce monde de culture, compte tenu des aspects économiques et de la stabilité du système dans son ensemble en non d'un produit en particulier. La méthologie proposée consiste à assurer l'équilibre de la recherche appliquée en milieu réel, renforcée par un programme spécifique en stations expérimentales.

Nécessité d'engrais et contrôle de la fertilité dans des sols non acides de zones non irriguées

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Résumé
Pour une série de raisons économiques, l'emploi d'engrais dans la culture du blé n'a jamais été très répandu en Argentine. Mais l'introduction de variétés semi-naines dans les années 70 a contribué à rendre plus nécessaire l'application de méthodes de fertilisation. Dans cette étude les auteurs exposent la réponse du blé tant à l'azote qu'au phosphore dans les terres humides de la pampa et analysent les paramètres liés au sol et au climat qui conditionnent le rendement et la réponse aux engrais.

L'humidité, ainsi que la durée de la période de jachère et de la culture antérieure, influent sur le rendement et la réponse aux engrais. L'analyse du sol effectuée pour déterminer sa teneur en azote n'apporte pas d'information précise quant à la réponse aux engrais azotés, mais en ce qui concerne le phosphore, sa teneur dans le sol, déterminée au moyen d'analyse, est étroitement liée à la réponse aux engrais.

Nécessité d'engrais et contrôle de la fertilité des sols acides de zones non irriguées du Brésil

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Résumé
Les 17 millions d'hectares de culture potentielle de blé au Brésil sont répartis en trois régions définies en fonction de leurs conditions climatiques respectives: méridionale, centrale-méridionale et centrale. Divers problèmes interviennent dans la conservation et l'utilisation du sol, à savoir: sa fertilité et son degré d'acidité, les maladies et les insectes. L'auteur examine dans cette étude les caractéristiques des oxysols et des ultisols qui prédominent dans ces régions, ainsi que leur réponse aux pratiques de labour et à l'application d'engrais. Le labour de conservation, qui n'est pas encore largement répandu au Brésil, permet de pallier à la dégradation du sol.

Techniques de sélection et source de résistance à la gale de l'épi causée par *Fusarium*

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Résumé
La gale de l'épi causée par Fusarium *occasionne des pertes considérables de rendement du blé et de la production de l'élevage dans la région du Yangtsé, en Chine. Plus de 300 sources de résistance à la maladie ont été sélectionnées et il en a été utilisé une quarantaine dans l'amélioration de cette céréale.*

Fusarium graminearum *est l'espèce prédominante identifiée dans 2 450 spécimens isolés obtenus dans 21 provinces de Chine. Une certaine variation quant à la virulence des isolés a été détectée, mais aucune pathogénicité spécifique des isolés de* F. graminearum *n'a été découverte.*

Il n'a pas été observé de différences considérables quant à la pathogénicité entre les ascospores et les conidies ou entre un ou deux et 100 spores pour chaque μl *de suspension.*

Les méthodes d'inoculation in vitro *et* in vivo *ont été mises en comparaison. Il est recommandé que la sélection de résistances à la gale de l'épi causée par* Fusarium *soit basée sur la sélection primaire dans de larges essais de sélection du matériel génétique de blé au moyen de la méthode traditionnelle sur le terrain. Les matériaux avancés obtenus feront l'objet d'une nouvelle sélection suivant la technique d'inoculation par injection et le bio-essai du coléoptile étiolé afin de confirmer la résistance.*

Pourritures de la racine du blé en milieux tropicaux: Effets potentiels et mesures préventives

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Résumé
Les problèmes auxquels seront confrontés les pathologistes et les sélectionneurs pour essayer d'obtenir des variétés résistantes aux pourritures de la racine en milieu tropicaux ne sont pas encore bien définis. La tâche qui leur incombe est en effet d'une grande complexité. Cette étude met l'accent sur: 1) l'importance d'un système de racines saines dans les cultures du blé, 2) les interactions entre l'hôte et l'agent pathogène, 3) les difficultés que présente l'identification des problèmes de pourriture de la racine, 4) les problèmes potentiels que posent les agents pathogènes transmis par le sol et 5) les méthodes à employer pour enrayer les maladies transmises par le sol. Il appartient aux pathologistes et aux sélectionneurs de déterminer l'importance des agentes pathogènes et de concevoir et appliquer des procédés chimiques et des méthodes de culture pour en triompher rapidement afin d'obtenir à la longue des variétés résistantes.

Les maladies bactériennes du blé et leur importance dans les régions tropicales

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Résumé
Des sept espèces de bactéries phytopathogènes qui affectent le blé, deux seulement d'entre elles occasionnent des pertes économiques. Pseudomonas syringae *pv.* syringae *peut causer des graves dégâts à température modérée accompagnée*

d'humidité. Xanthomonas campestris *pv.* translucens, *qui sévit dans le monde entier, est cause de la maladie bactérienne la plus grave qui affecte le blé et il est à prévoir que dans les zones tropicales elle sera la maladie bactérienne la plus conséquente. La maladie est propagée par la semence et il est nécessaire de disposer de méthodes peu coûteuses pour détruire le germe infectieux transmis par la graine. L'eau est, dans les champs, le principal facteur de propagation et les pratiques visant à éviter le passage de l'eau qui a servi à arroser les cultures infectées sont fort importantes. De plus larges informations sont nécessaires quant à la survivance des bactéries en tant que parasites ou épiphytes dans les mauvaises herbes ou dans d'autres cultures, de riz par exemple, afin de mettre au point des stratégies de lutte dans le cadre de systèmes agricoles tropicaux. La résistance est appelée à être un élément essentiel dans la lutte contre la maladie.*

Tolérance du blé tendre à la sécheresse: Analyse de l'augmentation du rendement des ressources génétiques du CIMMYT au cours des années

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Résumé
L'auteur analyse les données relatives du rendement correspondant à des milieux de faible rendement, exempts de maladies, mais où sévit la sécheresse, données obtenues au cours des Essais internationaux sur le rendement du blé tendre de printemps, ainsi que les données d'un essai comparatif du rendement avec risque complet (600 mm) et risque réduit (300 mm) effectué à Ciudad Obregon, au nord du Mexique. Le rendement des anciens témoins Siete Cerros 66 et Inia 66 affectés par la sécheresse au cours des années pendant lesquelles se sont poursuivis les ISWYN est comparé:

- *au rendement moyen de toutes les lignées incluses dans les ISWYN;*
- *au rendement des variétés produites par le CIMMYT et mises plus récemment à l'essai;*
- *au rendement de variétés de haute taille, tolérantes à la sécheresse, cultivées dans diverses localités.*

Les résultats témoignent d'une progression constante du potentiel de rendement au cours des deux dernières décennies dans des milieux affectés par la sécheresse, grâce à l'emploi de variétés semi-naines sélectionnées dans des conditions presque optimales. Les deux variétés-témoins ont fait preuve d'une grande stabilité de rendement temporaire et spatiale dans ces milieux et leurs rendements ont été supérieurs à ceux des variétés de haute taille cultivées dans les diverses localités. Les variétés obtenues plus récemment et qui constituent la meilleure sélection de blés de haut rendement et aussi les plus adaptables du CIMMYT se sont comportées de façon plus satisfaisante que les variétés témoins et que les variétés plus anciennes dans toutes les conditions, et même en conditions de sécheresse.

D'après ces résultats, il apparaît possible de combiner le potentiel de rendement élevé et la capacité de réponse aux divers facteurs de production dans des variétés résistantes à la sécheresse.

Les résultats ainsi obtenus sont analysés dans le contexte de diverses méthodes d'amélioration appliquées dans des conditions de sécheresse, y compris la méthode d'amélioration du CIMMYT visant à obtenir la tolérance à la sécheresse.

Progrès réalisés au Brésil dans la production de blés tolérant mieux la toxicité de l'aluminium

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Résumé
Les sols brésiliens sur lesquels s'étendent les cultures de blé présentent, en majorité, un pH peu élevé, un haut degré de toxicité due à la présence d'aluminium et une faible concentration de phosphore. L'aluminium a une influence négative sur le dévelopemment des plantes et provoque une anomalie physiologique ("crestamento"). Toutes les variétés brésiliennes de blé cultivées dans ce type de sol (latosol) se montrent tolérantes à la toxicité de l'aluminium. La nature du sol et l'incidence des maladies sont autant de facteurs qui limitent la production de blé, mais l'application de chaux en éliminant la toxicité de l'aluminium augmente la productivité. Diverses institutions brésiliennes sont aujourd'hui engagées dans la réalisation de programmes dynamiques d'amélioration et contribuent de la sorte à élever la productivité et la stabilité des cultures de blé. L'évolution des blés brésiliens s'est faite en plusieurs étapes parmi lesquelles l'introduction de blés mexicains a eu une grande importance. Les nouvelles variétés améliorées ont permis, ces dernières années, d'obtenir des rendements pouvant atteindre 5 000 kg/ha dans des conditions expérimentales en sols acides. Dans les conditions ordinaires des cultures, les rendements se sont élevés à 2 500 kg/ha à la faveur des technologies recommandées. Sur les terres traitées à la chaux les blés mexicains ont fourni jusqu'à 7 000 kg/ha.

Obtention de blés aptes à assimiler plus efficacement les éléments nutritifs: Progrès et potentiel

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Résumé
L'aptitude à assimiler efficacement un élément nutritif se définit comme la capacité d'un génotype de se développer dans un sol où la quantité de cet élément, requise par un génotype normal, est insuffisante. Le blé présente une diversité génétique considérable en ce qui concerne son aptitude à assimiler aussi bien le cuivre que le zinc et le manganèse et il semble possible, grâce aux efforts d'amélioration, d'obtenir ces caractéristiques et de les combiner en un seul génotype. Le seigle, pour sa part, est particulièrement apte à opérer cette assimilation et apparemment cette caractéristique pourrait être transmise au blé par translocation de chromosomes. Le triticale a hérité de son progéniteur, le seigle, cette faculté d'assimilation. Faute de connaissance des facteurs biochimiques qui interviennent dans ce procéssus et faute de méthodes efficaces de sélection, l'assimilation du phosphore n'a guère progressé. Mais les chercheurs affirment que l'assimilation d'azote par le blé a atteint le niveau requis. Une bonne assimilation des éléments nutritifs est de nature à rendre la plante plus résistante aux maladies et à la sécheresse, à favoriser un enracinement plus profond et à accroître sa capacité de réponse à d'autres engrais, azotés notamment.

Pratiques de contrôle intégré des maladies dans les milieux tropicaux de culture du blé

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Résumé
Une stratégie de contrôle intégré des maladies (CIM) implique l'emploi de multiples tactiques visant à maintenir les populations pathogènes à des niveaux inférieurs à ceux qui provoquent des pertes économiques. Cette stratégie comporte en même temps la minimisation de la sélection directionnelle de ces populations et l'attenuation de leurs effets nocifs dans le milieu de cultures. Ainsi conçu, le CIM s'avère une mesure pertinente et applicable dans les cultures de blé introduites dans les systèmes traditionnels de culture des zones tropicales. La production et la diffusion de variétés résistantes aux maladies, les pratiques culturales, les tactiques de lutte biologique et l'application des pesticides à la semence sont autant des mesures importantes dans la culture du blé en zones tropicales. Pour être exercé efficacement, le CIM requiert la réalisation de recherches sur les systèmes locaux de culture et l'existence d'un réseau de vulgarisation.

Perspectives de recherches nécessaires concernant les zones tropicales non irriguées

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Résumé
La nécessité de faire des recherches portant sur les zones tropicales non irriguées où est cultivé le blé - en prenant pour exemple le Cône sud - est ici analysée. Dans cette région, l'option la plus économique, et la seule, consiste à cultiver du blé en rotation avec du soja ou du maïs.

Les auteurs passent en revue les facteurs défavorables que constituent un climat imprévisible, une radiation solaire peu abondante, des températures élevées et la sécheresse et examinent l'importance à leur accorder dans un programme d'amélioration. De plus, sont envisagées les répercussions des problèmes du sol, de la germination avant la récolte, des maladies et les invasions d'insectes dans l'élaboration de matériel génétique stable et de haut rendement pour cette région. L'analyse révèle la necessité d'assurer à ce matériel génétique une large capacité d'adaptation associée aux caractéristiques requises et les avantages du système d'essais dans de nombreuses localités.

En ce qui concerne la culture elle-même, le manque d'humidité au cours du développement du blé est considéré comme le facteur limitatif le plus important et diverses mesures seraient à recommander, dont la culture minimale, afin de conserver l'humidité du sol, un roulage superficiel et l'érosion. Il est essentiel d'éliminer les éléments chimiques que contient le sol en pourvoyant à son amélioration, afin de favoriser la pénétration des racines et de mettre plus efficacement à profit l'eau qu'il contient.

Intégration des recherches sur le blé et la production de céréales au Bangladesh

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Résumé
Le labeur accompli par l'équipe de chercheurs du Centre du blé de l'Institut de recherches agricoles du Bangladesh a favorisé une expansion spectaculaire des cultures de blé dans ce pays entre 1974 et 1983. Ces chercheurs se sont donné pour tâche d'élever la production de blé dans un milieu socio-économique toujours plus instable pour la culture de cette céréale. A cette fin ils ont communiqué le résultat de leurs travaux aux agriculteurs auxquels ils ont fait connaître de nouvelles variétés et démontré, les appliquant en milieu réel, des techniques de production peu coûteuses, comme la culture minimale. Enfin, des activités dans le cadre de la formation pratique ont favorisé la collaboration entre chercheurs et agriculteurs.

Stockage de la semence de blé en milieux tropicaux

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Résumé
Les problèmes que pose le stockage de semence de blé dans les conditions qui sont celles des zones tropicales diffèrent de ceux dont s'accompagne le stockage dans les régions où le blé est une culture traditionnelle. Les températures et l'humidité élevées ne permettent pas d'appliquer des méthodes de stockage efficaces et peu coûteuses. Les agriculteurs se sont très bien adaptés aux problèmes relatifs à la production de semence de blé mais, le manque de conteneurs ne leur permet d'élever ni la qualité ni la quantité de semence stockée dans les exploitations agricoles. De plus, les agriculteurs doivent pouvoir disposer de certaines quantités de grain pour leur alimentation et aussi d'argent liquide et ne peuvent donc pas distraire une partie de leur récolte pour la conserver comme semence.

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