Research Highlights 1986

International Maize and Wheat Improvement Center

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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). The CGIAR consists of 40 donor countries, international and regional organizations, and private foundations.

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Preface

The spectrum of agricultural research is a broad one, ranging from basic to adaptive research, from ''new biology's'' pursuit of transgenosis to the refining of existing technologies so as to meet the needs of specific groups of farmers. CIMMYT does little basic research and not much more that can be classified as adaptive. The bulk of our efforts lies between those extremes, in the areas of strategic and applied research

This issue of *CIMMYT Research Highlights* presents a selection of the Center's research activities. Most of the articles contained in this edition discuss research that is part of the applied dimension of our work. Some focus on activities whose ultimate goal is the development of research procedures, and others deal with adaptive research aimed specifically at technology generation. One, the article on the maize seed industry, is derived from the Center's work in commodity sector analysis. (A more panoramic view of CIMMYT's research is given in Appendix V of the *1986 CIMMYT Annual Report*, which provides a listing of journal articles, book chapters, and conference presentations published by the Center's staff.)

The Center's research agenda reflects purposeful decision making in response to a broad range of client needs. Most of CIMMYT's work is organized within the context of five interrelated categories of investigation. First, a high proportion of our energies are concentrated on research designed to deliver products directly to national program clients. Improved germplasm is the primary example. Our clients then refine and adapt such products to their specific circumstances. The articles about bread wheat shuttle breeding and the development of Altar 84 durum wheat exemplify this category of research.

A second set of activities is one step removed from the first and actually serves to generate products (germplasm and information) that can be used as inputs into the germplasm improvement research found in category one. These efforts are sometimes referred to as germplasm ''enhancement'' and focus on the incorporation of desirable traits into useful agronomic types that can then serve as source populations. CIMMYT's work in intergeneric and interspecific crosses (known commonly as ''wide crosses'') reflects this set of activities, and will be featured in future publications.

The third category of CIMMYT research is aimed at acquiring a better understanding of underlying mechanisms (e.g., crop physiology) so as to improve the efficiency and effectiveness of our work in categories one and two. The three articles on maize research contained herein provide good examples of these efforts. This class of work frequently involves Ph.D. thesis candidates, Postdoctoral Fellows, and collaborative relationships with institutions focusing on basic and strategic research. The Center is currently engaged in about 90 such collaborative ventures (most divided roughly evenly between European and North American institutions).

A fourth category of work lies along the frontier between research and training, and involves plant breeders, agronomists, and economists working alongside national program colleagues to enhance the effectiveness of research in their countries. The reports in this year's *Highlights* that focus on Indonesia, Ghana, and Chile emerged from this kind of work. Notice that two sorts of products result from such efforts: the research results themselves, and improved skills of the participants.

Finally, CIMMYT staff frequently engage in joint research with national program colleagues aimed, in part, at developing research procedures that can be applied to similar problems encountered elsewhere. Such work comprises a fifth category of research in CIMMYT, and is illustrated by the report discussing some of our experiences in Haiti.

Since CIMMYT's strategic research efforts are not really represented in this year's collection of highlights, let me comment briefly on them here, particularly on our expanding role in the area of biotechnology. We currently use several standard biotechnology tools, especially in our work on wide crosses. Some of these applications are made through collaborative work, and some are made in CIMMYT's own laboratories. In the near future, we expect to add facilities and staff that will allow us to use some specialized tools of a somewhat more exotic nature (gene probes, e.g., restricted fragment length polymorphisms). Through collaborative research linkages, we now have others apply these tools for us and subsequently provide the results; however, our plans call for developing an in-house capacity. We are adding that capacity to reduce costs as well as to widen our window on new possibilities in biotechnology. In the arena of new biological research techniques, CIMMYT sees itself as a tool user rather than a tool developer. We are readying ourselves to apply appropriate new techniques fashioned in basic research laboratories and anticipate serving as a conduit for their wider use in the developing world.

The articles contained in this issue of *CIMMYT Research Highlights* represent but a portion of the broad array of the Center's investigative work. Much of our research aims at finding near-term solutions to important problems. Some is designed to develop more effective research procedures (for use both by national programs and by CIMMYT), and some serves as a vehicle for training. Beyond that, a growing portion of our research is oriented toward finding ways to make our primary activities more efficient.

My colleagues join me in hoping that you find CIMMYT Research Highlights 1986 both interesting and informative. We welcome comments and questions.

Donald L. Winkelmann
Director General

Maize Research

The Maize Program's breeding strategy differs in important ways from that of other sizable maize improvement programs, particularly ones in developed countries that are catering to national germplasm needs and even some commercial enterprises with significant international markets. In general, those organizations develop improved germplasm for specific locations within a country and afterwards investigate the possibility that the superior materials might be used more widely—in other regions of the same country or in different countries altogether

CIMMYT's own approach has to be somewhat different because of its global mission and the diverse needs and circumstances of its clients. In general, the Center's Maize Program develops what we refer to as *intermediate* maize germplasm products and distributes them to national maize programs for testing. Those products are fairly refined elite materials but are still sufficiently variable that breeders can select within them to develop final products for specific locations, a process in which CIMMYT scientists often assist. That approach enables us to help attend to the germplasm needs of numerous Third World countries and provides national maize breeders with some of the means for strengthening their crop improvement capacity (see diagram on the following page showing the Maize Program's structure)

This Year's Highlights

The articles in this year's *Research Highlights* describe and give some results of three major activities that are central to the Maize Program's breeding strategy, namely 1) the characterization of maize production environments in Third World countries, 2) development of germplasm that performs well in those environments, and 3) provision of information about germplasm products.

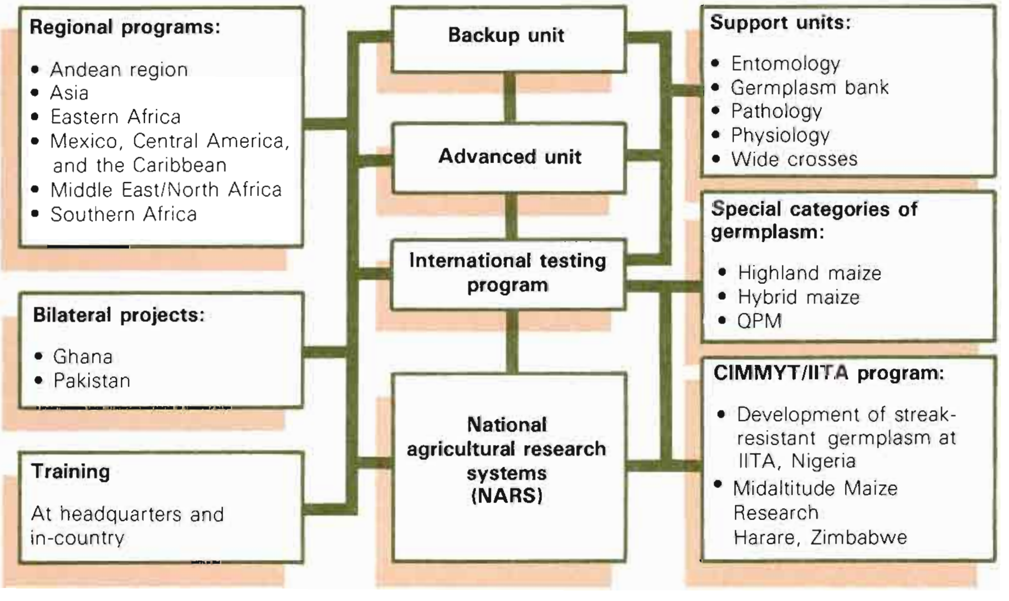
To carry out our breeding strategy effectively, it is important that we have as much detailed information as possible about the types of germplasm and particular combinations of traits required for maize production in the Third World Throughout much of the Maize Program's 20-year history, such information was derived informally from the experience of Program staff and that of CIMMYT's predecessor organization, a project established by the Rockefeller Foundation. Their first-hand knowledge served the Program well as a guide to the development of a fairly complete array of maize germplasm.

During 1985 we initiated a more formal effort to augment current knowledge about germplasm needs with a study whose purpose is to delineate and characterize the entire range of maize production environments in approximately 70 developing countries. In the first article Hiep Ngoc Pham, breeder, and Gregory Edmeades, physiologist, present some of the findings of that study and explain how researchers can use them to determine and adjust the priorities of their maize improvement programs.

Our assessment of the maize improvement situation in developing countries is that a growing number of national programs have the capacity to provide, and that farmers are much in need of, elite materials that possess high levels of tolerance or resistance to various abiotic and biotic stresses. One contribution the CIMMYT Maize Program can make in helping meet that need is to provide readily usable sources of stress tolerance or resistance. As Gregory Edmeades and H. Renée Lafitte, associate scientist, explain in the second article, the increased emphasis on stresses encountered in marginal production environments implies greater involvement by specialists such as crop physiologists in maize improvement.

In addition to developing new germplasm products, Maize Program staff are increasingly expected to provide information about them, particularly as national programs become more skilled at employing these materials in more complex ways. Much new data are being generated by our hybrid program, which was established in part to provide information on hybrids for developing country environments. In the third report, Surinder K. Vasal, breeder; David L. Beck, postdoctoral fellow; and José Crossa, associate scientist, summarize the results of a study conducted over the last 2 years to determine the potential utility of a wide range of CIMMYT materials in hybrid development.

Structure of the CIMMYT Maize Program



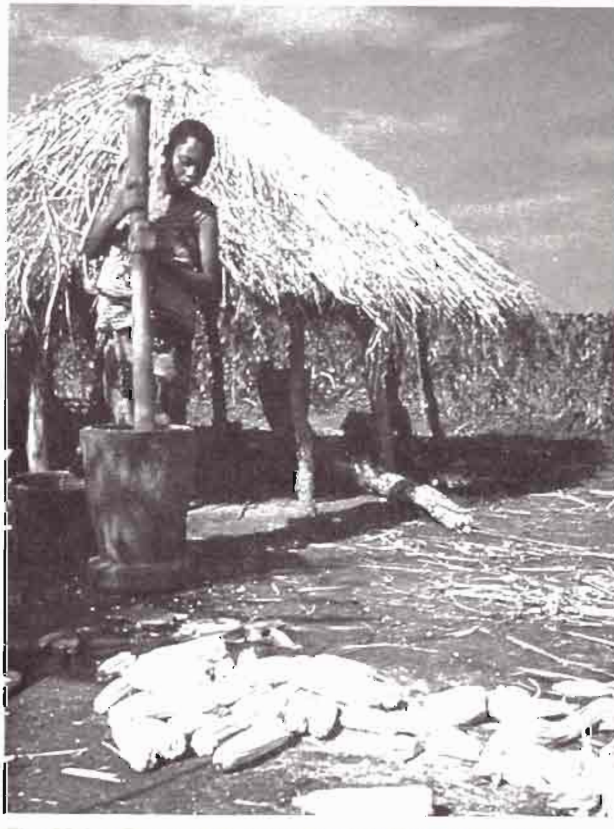
Delineating Maize Production Environments in Developing Countries

H.N. Pham and G.O. Edmeades[1]

When the Maize Program first began developing germplasm for maize production environments in the Third World, it defined them rather generally. Each environment was characterized by a particular combination of factors that determine whether specific maize genotypes can perform adequately and are likely to be adopted by farmers. One environment, for example, required genotypes with tropical adaptation, late maturity, and white dent grains

The general definition sufficed for many years, supplemented by observations from our own staff and other scientists in developing countries about details such as the relative importance of major disease problems On that basis the Maize Program created a wide array of gene pools and populations and through various breeding approaches improved these materials for resistances and other traits that seemed necessary within the various environments In doing so the Program assumed that some improved maize germplasm should be made available for each of the Third World's important maize production environments. By the mid-1980s that goal had in large part been accomplished, and the sizable number of materials developed had undergone numerous cycles of improvement.

As a next logical step in the improvement program, it was decided that CIMMYT maize scientists should begin assigning priorities to the materials and taking various steps to increase the utility of the most important ones, chiefly by raising their levels of resistance to diseases and insects and their tolerance to abiotic stresses. Our staff had already gathered information about the relative importance of the various pools and



The Maize Program is defining with greater precision than before the germplasm requirements of maize-production environments throughout the Third World.

[1] Hiep Ngoc Pham and Gregory Edmeades are breeder and physiologist, respectively, in the CIMMYT Maize Program

populations from the level of demand for them among plant breeders in developing countries and from the performance of the materials in different environments. But we lacked more detailed and reliable information on which to base decisions about the degree of emphasis that ought to be placed on particular categories of germplasm and on the resistances or tolerances required in these materials to make them better adapted to various production conditions.

It was primarily this need for information that gave rise to the study on what we have come to term *mega-environments*, the purpose of which was to delineate and characterize the entire range of maize production environments in approximately 70 developing countries. We anticipate that this effort is only the beginning of a series of more narrowly focused studies, the results of which will give us an even more complete picture of future challenges in maize germplasm development. This report describes why and how the initial study was undertaken, what results have been obtained so far, and how they can be put to use. It also speculates about additional steps that can be taken toward verifying and amplifying the information collected so far

The Concept of Mega-Environments

Our existing general definitions of maize production regions were the point of departure for the mega-environments study, the aim of which was to determine the approximate extent of the regions and add several new elements to their definitions. Thus, in addition to specifying climatic adaptation, length of growing season, and grain color and type, study cooperators were asked to estimate the frequency of water stress, incidence of specific diseases and insects, and importance of special soil factors such as aluminum toxicity. Having distinguished various regions in their countries according to those criteria, study participants estimated the extent of each mega-environment with respect to area planted to maize. That information was gathered through a survey of national maize program staff, who reported their estimates in the form of tables and country maps indicating the rough boundaries of each mega-environment and the location of experiment stations within them where maize is tested.

The mega-environments are not to be confused with political boundaries or with broad geographical constructs (forest, savanna, and so forth), although they may correspond roughly to the latter and have been delineated on a country-by-country basis. Rather, the mega-environments are intended to be superimposed on such descriptions to obtain a quite specific representation of maize germplasm requirements in the Third World.

It appears from the data we have so far (from about 80% of the countries surveyed) that the Third World's total maize producing area comprises some 20 different regions. One of those, for example, comprising nearly 5 million ha of maize, consists of lowland tropical areas where late-maturing, white dent maize is cultivated with only occasional moisture stress but some pressure from virus diseases, borers, and armyworm. That and the other mega-environments are each fairly uniform in their germplasm requirements and may be found on more than one continent.

Those two characteristics—the relative uniformity and wide distribution—of the mega-environments have important implications for maize breeding. They suggest that germplasm developed at one location within a mega-environment is likely to perform well at others within the same mega-environment, though probably with minor modifications. If a variety shows promise within a particular mega-environment in Central America, for example, it will probably also perform well at locations representing that same mega-environment in West Africa, given the addition of resistance to maize streak virus. Likewise, the variety should perform well at suitable locations in Southeast Asia, assuming that downy mildew

Maize that performs well in the lowland tropics of Central America or Asia might also show promise within the same type of environment in Africa. To prevent the outcome shown in the foreground of this photograph, however, resistance to maize streak virus would have to be incorporated into that material.

resistance is incorporated into it. The existence of fairly uniform mega-environments found on various continents enables the CIMMYT Maize Program to conduct a global breeding program at a few representative sites and provides a firm basis for international exchange of germplasm and test results. Progress made in Latin America or Asia can thus benefit scientists in Africa and vice versa.

In synthesizing the country reports to show regional patterns in mega-environments, we decided to concentrate first on sub-Saharan

Table 1. Mega-environments of sub-Saharan Africa

	Mega-environment								
	1	**2**	**3**	**3A**	**4**	**5**	**6**	**7**	**8**
Area (000 ha)	1461	1882	3587[a]	1200	1925	1305	3624[b]	249	71
Ecology	HT	ST	ST	ST	LT	LT	LT	LT	LT
Grain type	WD	WD	WD/F	WD/F	WD/F	WD/F	WD/F	YD/F	YD/F
Maturity	LXL	I	LXL	L	XEE	I	L	E	L[c]
Moisture	A	CD	AB	C	CD	B[d]	B[e]	C	AB[f]
Biotic stresses:									
Helminthosporium maydis	0.7	0.1	0.4	0.7	1.3	2.2	1.9	1.4	1.4
H. turcicum	2.8	1.1	1.6	3.3	0.3	0.8	0.5	0.2	0.7
Puccinia sorghi	1.5	1.0	1.3	1.0	0.1	0.4	0.1	0.0	0.0
P. polysora	0.0	0.0	0.0	0.0	0.6	0.0	1.5	1.4	0.7
Streak	0.2	1.2	1.2	0.7	2.9	1.7	2.0	1.9	1.6
Stalk rot	0.5	0.3	0.1	0.7	1.0	0.8	1.8	0.6	0.7
Mildew	0.0	0.1	0.2	0.0	1.1	0.5	0.6	0.1	0.7
Ear rot	3.0	1.3	1.6	1.3	1.3	1.6	2.4	0.4	0.0
Borers	2.7	1.7	1.8	3.0	1.6	2.1	2.9	2.2	3.0
Armyworm	0.2	0.9	0.0	0.0	0.0	0.5	0.0	0.1	0.0
Rootworm	0.5	0.5	0.5	1.0	0.2	0.1	0.0	0.0	0.0
Termites	0.2	0.0	0.9	0.0	0.4	0.5	0.4	0.8	0.0
Striga	0.2	0.0	0.6	0.0	0.6	0.5	0.3	0.6	0.0

Note: Abbreviations used in the table are as follows. For ecology HT = highland tropics, ST = subtropics, and LT = lowland tropics. For grain type W = white, Y = yellow, D = dent, and F = flint. For maturity E = early, I = intermediate, L = late, and X = extra. For moisture status A = rarely stressed, B = sometimes stressed, C = frequently stressed, and D = usually under some stress. Biotic stresses are rated on a scale of 0 to 5, in which 0 indicates that the problem is not present and 5 that maize cannot be grown in the environment unless resistant varieties are available. Ratings listed in the tables are combined estimates for individual regions of each country, weighted by area.

[a] Includes 520,000 ha of maize grown on acid soils.
[b] Includes an estimated 200,000 ha on low pH soils.
[c] Includes small areas of intermediate-maturity maize.
[d] Includes small areas of moisture classes A and C.
[e] Roughly 300,000 ha are in moisture classes A and C.
[f] Includes 120,000 ha in moisture class C.

Africa since our data set for this region is the most complete. Within our classification scheme, the continent has three principal types of climatic conditions—tropical, subtropical (including midaltitude environments in which subtropical germplasm is adapted), and highland—which together encompass nine mega-environments. The salient features of those environments (along with their estimated extent in sub-Saharan Africa) are indicated in Table 1, and some of the environments are shown on the map of West Africa in Figure 1.

Application of the Study Results

Much of the information gathered in the course of this study is based on researchers' experience and knowledge rather than quantitative studies of the sort that ought to be conducted in the future. Even so, the data we have now are far more detailed and comprehensive than

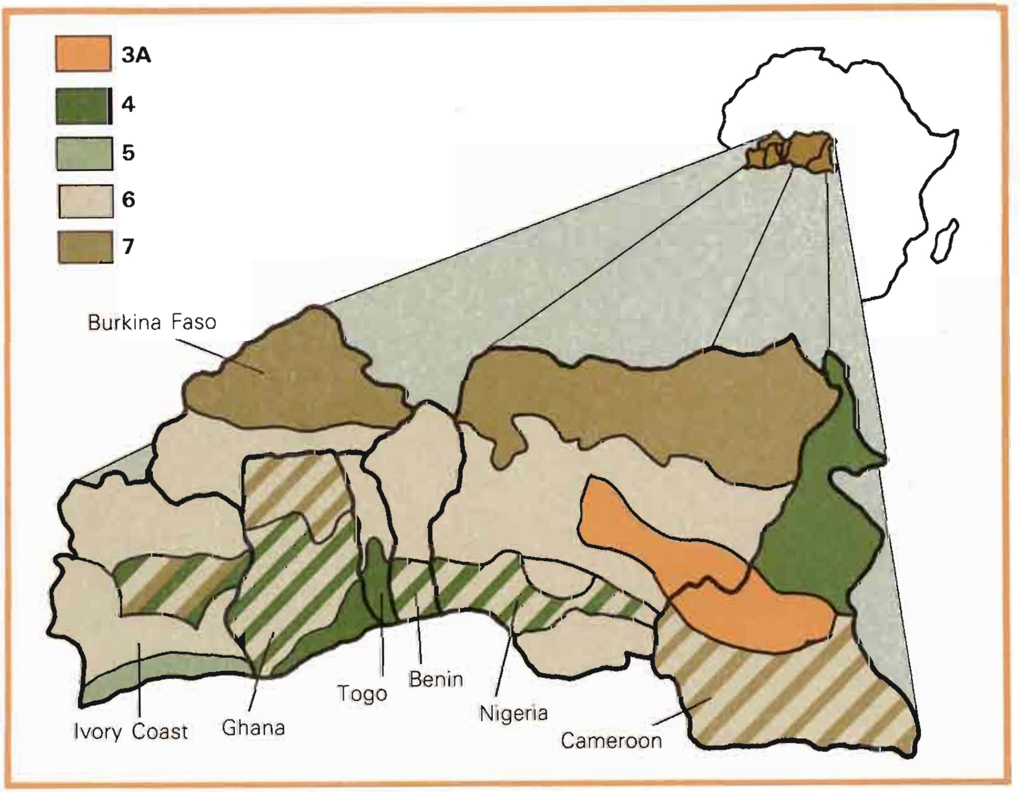


Figure 1. Maize mega-environments of selected countries in West Africa (See Table 1 for descriptions of mega-environmnets 3A-7).

the previously available information, they have enabled us to define production environments more precisely, and they are accurate enough to serve as a guide to priority setting in maize improvement programs.

Various units in CIMMYT's own maize program have already begun using the information precisely for that purpose. The backup unit, for example, has drawn on study results in determining top-priority germplasm types for development of new pools and in choosing traits that need to be included in its special-purpose pools. In addition to creating those new materials, the backup and advanced units have retired a few others for which the need in developing countries now seems fairly minimal The highland maize program and physiology unit have made similar decisions about the importance of particular traits in their germplasm development efforts.

We expect that scientists in developing countries will employ the data in much the same way It should be apparent, for example, from estimates of the extent of the mega-environments and incidence of certain stresses whether there are any discrepancies between the current priorities of a breeding program and the germplasm requirements of the main production areas it serves (too much or too little attention being given to certain germplasm types or characteristics). Should it prove necessary to make adjustments in priorities, a national program may then elect to modify its requests for CIMMYT trials and reallocate its research resources accordingly

Information collected through the mega-environments study on the incidence of various biotic and abiotic stresses in developing countries serves as a guide to the Maize Program's work on special-purpose pools. Shown here is the fall armyworm (*Spodoptera frugiperda*) resistance reaction in one of the materials of which the multiple-borer resistance pool is composed.

Some national programs will also find opportunities for more efficient use of resources by examining maps showing the mega-environments in neighboring countries. Suppose, for example, that a certain mega-environment is relatively minor in country A but quite extensive in several other countries. Rather than carry out extensive breeding and experiment station testing of germplasm for that mega-environment, the maize program in country A could choose the lower cost option of studying the results of CIMMYT trials conducted within the mega-environment in other countries, requesting seed of germplasm that performed well in those similar environments, possibly refining the germplasm so that it would meet farmers' requirements more closely, and introducing it into on-farm testing.

Refining the Definition of Mega-Environments

Additional applications of the mega-environments concept (particularly those calling for more precise and accurate knowledge) will have to await the results of more detailed studies that we have already begun or hope to initiate in the future. Some of those studies are described in the following paragraphs.

Maturity prediction and environmental classification—In 1987 we will begin a study on the response of maize to photoperiod and temperature. A better understanding of that relationship should enable us to fit maize genotypes more closely to marginal environments, which are frequently characterized either by short rainy seasons of variable length or by cool temperatures in locations at higher altitudes or latitudes.

There is some evidence from trials conducted with landraces in Mexico (see *Research Highlights 1984*, pages 45-46) that the base and optimum temperatures for calculating heat units and perhaps the slope of development rate versus temperature vary with genotype according to the temperature regime of the genotype's area of origin. Little is known, however, about the interaction between temperature and photoperiod in maize, especially in tropical materials.

Over the next 3 or 4 years, therefore, we will be examining the photoperiod-temperature responses of 30-50 synthetics, experimental varieties, and hybrids representing the mainstream of our improvement program for highland, temperate, midaltitude tropical, and lowland tropical germplasm For that purpose a field facility has been installed at Tlaltizapan, Mexico, that allows artificial lengthening of natural photoperiods in a plot whose total area is 480 m^2 and which can be subdivided into three photoperiod regimes. Data generated in this study will be used to verify phenology models developed under controlled environmental conditions at the Plant Environment Laboratory, University of Reading, UK.

Classification of trial sites—In a study being conducted in cooperation with Iowa State University, USA, we are attempting to identify *environmental analogs* (groups of locations that are highly uniform in climate and other environmental conditions), with the aim of improving the efficiency of the Maize Program's international testing system.

The current approach in progeny testing is to distribute trials widely at the request of cooperators. The testing environments and quality of data received vary over the different locations where any particular trial is grown. Moreover, progeny from subsequent cycles of improvement of CIMMYT populations are generally tested at different sets of locations (in accordance with cooperators' trial requests during any given year), making it difficult to compare performance over cycles of selection. Although this approach has proved to be effective in disseminating germplasm to maize breeders in developing countries (the testing network's primary objective), it is not the most efficient way of assessing progress in our breeding program.

One alternative would be to employ the same test sites year after year, but to do so would place an unfair burden on a few national programs. A better option would be to classify testing environments in such a way that we can test the progeny, not at the same few sites, but at various sites chosen from a group of locations in the same mega-environment that have very similar growing conditions. This scheme would permit continued participation by numerous national programs in the population improvement process but would reduce considerably the variation due to genotype x environment interactions in the data collected. That outcome, in turn, should improve the quality of selections based on international trial data

The first step in grouping test sites was to distribute questionnaires to key experiment stations throughout the Third World soliciting long-term average data on climatic and agronomic conditions. When more responses have been received (we have 120 so far), the stations will be grouped, using cluster analysis. With those groupings we will be better able to direct trials of progeny from the population improvement program to test locations that accurately represent their respective mega-environments and in which it is possible to distinguish superior genotypes consistently. In addition to resulting in better products for national programs, this grouping of test locations will better enable them to use data from trial sites in other countries (as described in the example given above) where the same mega-environments are represented.

Quantified definitions of agricultural environments—Other studies that we hope to undertake will be intended to overcome limitations in our current definitions of the mega-environments. One of those is that they are derived from general observations about germplasm performance and lack a solid quantitative basis. Ideally, our definitions would be based on means and standard deviations of temperature, length of growing season, rainfall, radiation, and soil characteristics. Without such data we cannot distinguish among locations within a mega-environment, or even between mega-environments, with a high degree of precision and certainty.

A related problem is that our information on disease incidence is subjective, being based on estimates rather than on trials conducted to assess crop loss in particular regions. Moreover, some of our estimates may not take into account widespread use in some regions of resistant maize germplasm, which could mask the true risk from certain diseases. Unless we can obtain a more accurate assessment of the disease threat through trials that include susceptible checks, there will always be some risk of introducing susceptible germplasm into a region where disease pressure is high. Much the same task needs to be performed for other important parameters of the mega-environments, such as insects and various abiotic stresses.

To compile a database comprising disease incidence and many other agroecological, crop performance, and socioeconomic variables would be a large undertaking, requiring the participation of specialists from many disciplines and close cooperation among various groups that already have extensive meteorological and land resource databases. The costs, however, would be far outweighed by the potential benefits of that effort, which would place our attempts to characterize maize production environments at a higher level of precision. Building a quantitative foundation for our definitions of those environments would enable us to perform tasks already mentioned (setting priorities and allocating resources for research) with much greater accuracy and would create some new opportunities as well. It might even be possible to predict the outcome of introducing technologies into certain regions, resulting in a considerable savings of scarce funds for agricultural research.

Crop Physiology and Maize Improvement

G.O. Edmeades and H.R. Lafitte[1]

During the approximately 15 years since crop physiologists first became directly involved in plant breeding programs within the international agricultural research centers, their influence has waxed and waned with shifts in opinion about their discipline's potential contribution to crop improvement. That it can be substantial is now a widely shared opinion among most of the centers that have crop improvement programs.

Physiologists perform a wide range of tasks in the centers but are especially active in research on crops, such as sorghum and millet, that are widely grown in difficult marginal environments. In view of the centers' increasing emphasis on such environments, it is important to examine the involvement of crop physiologists in developing germplasm (not only of the above-mentioned crops, but of others as well) that performs well under high levels of abiotic stress. This report examines the role of physiologists in the CIMMYT Maize Program, outlines their strategies for developing sources of stress tolerance, and describes some of their current work.

The Role of Crop Physiology at CIMMYT

CIMMYT physiologists became involved in the improvement of maize for stress tolerance during the mid-1970s after having explored several other avenues of research. Among the most important of their early efforts were studies of the influence of radiation and temperature on the growth of highland and lowland maize (5, 6), which showed that the limited productivity of tropical maize is partly related to its low harvest index and excessive leafiness. In subsequent investigations various ways of increasing harvest index were identified (selection for reduced plant height, tassel size, and leaf area), resulting in more efficient distribution of dry matter in tropical maize (4, 8) This fundamental alteration of the structure of the tropical maize plant was an important step toward raising its potential productivity in developing countries.

By the mid-1970s it was apparent that other steps needed to be taken as well before the greater efficiency of the improved maize genotypes could be realized. One of those was to come to terms with the wide range of stresses under which improved maize would be expected to perform, especially in Africa. It was recognized that development of germplasm with stress tolerances would require research on various aspects of stress physiology

Work on drought tolerance was initiated during 1975 in a population that was later designated Tuxpeño Drought and led to several important observations about improvement of this trait. Researchers found, for example, that tolerance to drought stress is increased significantly by reduced tassel size and plant height and that it is also associated with reduced anthesis-to-silking delay under

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stress, a trait connected with density tolerance (2) The latter finding suggests the existence of a common mechanism that imparts tolerance to reduced photosynthesis per plant arising from a whole range of stresses It also appears from data gathered so far that, as Blum (1) has suggested, unidentified stress-adaptive alleles exist at relatively high frequency in elite maize populations.

The current role of crop physiology, which has grown out of the work on drought tolerance and the research that preceded it, is not to deliver stress-tolerant germplasm in finished form. Rather, it is to offer guidance to breeders in obtaining stress tolerance within their own germplasm and to supply them with sources of specific stress tolerance for use in backcrossing programs The support provided by physiologists takes several forms, including rapid, accurate screening tools that can augment selection for yield alone, stress-management techniques that maximize expression of genetic variability for stress tolerance (but which create a level of stress that corresponds to conditions in developing country production environments), and conceptual models (*ideotypes*) of

Physiologists in the Maize Program are attempting to determine whether it is possible to select for improved maize performance under N stress without sacrificing responsiveness to high levels of N. Here associate scientist Renée Lafitte uses a portable photometer to measure chlorophyll content, which is an indicator of nitrogen status.

stress-tolerant crops as well as process-oriented models that simulate crop behavior under stress. Developing those products requires investigation of the environmental and genetic controls on crop phenology and development and of the effects exerted by inter- and intraplant competition on crop performance. Those effects are especially important when selections are made under environmental stress, which causes soil variability to become more pronounced, yields to fall, and heritability for yield to be reduced. Additional services provided by crop physiologists are to catalog CIMMYT's maize germplasm for particular traits, help breeders fit genotypes to environments with greater precision, and assist in agroecological zonation.

A Strategy for Developing Sources of Specific Stress Tolerance

Within the last several years, the Maize Program's physiology unit has devised and begun to implement a five-step strategy for developing sources of specific stress tolerance.

The first step is to determine the distribution and importance of the stresses that occur and types of germplasm grown in developing countries. We have made an initial attempt at assessing the relative importance of abiotic stresses, based on results from a study aimed at characterizing Third World maize production environments (described in the first article of this section) and on the experience of CIMMYT staff and other researchers. The resulting inventory of stresses given in Table 2 serves as a guide to priorities in our current program.

The second major step consists of the following procedures: screen a wide range of germplasm to determine which populations, pools, landraces, and other materials have the highest levels of specific stress tolerance; develop screening techniques; identify secondary traits

Table 2. Abiotic stresses affecting tropical maize production

Stresses (in order of importance)	Areas affected	Comments
1. Radiation	Lowland tropics	High temperatures accelerate crop development more than crop growth rate, so that the radiation intercepted per heat unit (or quantity of photosynthate available per growth stage) may be only 50% of that at high-yielding locations in the temperate zone.

Table 2. (continued)

Stresses (in order of importance)	Areas affected	Comments
2. Nutrient	Sub-Saharan Africa	Deficiencies of N and sometimes P are especially severe where soils are overcropped, aged, or eroded or when crops are weedy. S and Zn are also deficient at many sites.
3. Moisture	Sub-Saharan Africa and Central America	Drastic yield reductions can occur if dry periods of 2-4 weeks coincide with crop establishment or flowering. Drought is more severe with poor weed control and shallow alfisols having low water-holding capacity.
4. Aluminum toxicity	South America, Asia, and Central Africa	Approximately 1.8 million km^2 of Brazil's high-rainfall soils are affected by low pH and Al saturation averaging 59% (twice that reported as being sufficient to reduce maize growth). Worldwide, a total of 10 million km^2 is reported to be affected by Al toxicity (9).
5. Temperature[a]	Lowland tropics (high temperature) and highlands (low temperature)	High temperatures affect establishment of maize at the onset of rains and may damage tassels and leaves. They are often associated with drought in the lowland tropics. Low temperatures affect establishment at the latter part of grain filling in the highlands and temperate zone.
6. Flooding[a]	Asia and the Middle East	Restricted root growth resulting from anoxia in flooded soils causes considerable but undocumented losses in marginally drained and irrigated land. Salinity commonly occurs in arid, irrigated areas.

[a] Temperature and flooding stress are of roughly equal importance.

that can serve as indicators of tolerance to stresses; and devise a selection index.

The third and fourth steps are to initiate short- and long-term breeding approaches aimed at developing stress-tolerant germplasm. The former involves recurrent S_1 or full-sib selection with high selection intensity in agronomically superior populations to improve general or specific stress tolerance. Selections are made in such a way as to maintain yield under favorable growing conditions while improving performance under stress. That approach should give rapid progress in a short time, although gains may then plateau as variability for stress tolerance is exhausted. The long-term approach is to assemble all known sources of tolerance (materials from CIMMYT's maize germplasm bank and other breeding programs as well as local varieties) to form a pool that possesses unique stress tolerance but that initially may have undesirable agronomic characteristics. Selections are made under stress, and the poor agronomic type of the pool is gradually improved. Progress is slow, but the pool's genetic variability for the trait being sought should be greater than that of the elite populations. The final step (which, like the others, will be an ongoing activity) is to supply breeders in our Advanced Unit and in national maize programs with agronomically acceptable stress-tolerant populations for direct use or stress-tolerant pools for backcrossing.

The Current Physiology Research Program

Of the six stresses listed in Table 2, the physiology unit is currently focusing on two (drought and nutrient deficiency), in addition to improving germplasm for general stress tolerance.

General stress tolerance—Sources of general stress tolerance are being developed that should help plant breeders establish a stronger base on which to build specific stress tolerances in elite materials. Plant density, since it is easy to manipulate, is the mechanism we are using to induce stress. Under different plant densities, we are selecting for prolificacy, which, according to some studies, is associated with density tolerance (10), although stalk strength is often lessened when the second ears of prolific plants deplete stem sugar reserves.

During 1985 many lowland tropical and subtropical materials were screened for prolificacy at normal plant densities, and 3-11% of the families observed were selected. Remnant seed was grown under high and low densities, so that we could evaluate the materials for both prolificacy and density tolerance, and families were intercrossed in a half-sib block. Each half-sib family is being grown at two densities, one well below the optimum to allow expression of prolificacy and the other well above to allow expression of barrenness and lodging tolerance. Second ears are selected at low density from the same families that show, at high density, good synchrony between silking of first and second ears, little barrenness, lodging resistance, reduced tillering, and minimal stem etiolation. Correlations between those traits and number of second ears show that yield and number of second ears are positively associated and that a reduced interval between silking of first and second ears is associated with second ear formation (Table 3).

The germplasm has been stratified to form two lowland tropical pools with white grain (one late and the other early maturing) and a midaltitude tropical pool of intermediate maturity. A fourth maize pool has been formed from a cross made between maize (B73) x tripsacum (obtained from the USA) That cross has a high level of prolificacy but little resistance to lodging and diseases and relatively low yields. It has been backcrossed three times to lowland tropical maize that has an above-average level of prolificacy. As new sources of prolificacy are identified, they will be added to the appropriate pool

Recurrent selection for drought tolerance—In the work on drought tolerance, we are pursuing both the short- and long-term breeding approaches outlined above. Under the former recurrent S_1 or full-sib selection is being carried out in four elite populations (listed in Table 4) at two locations over a 2-year cycle. Pool 16 is grown in Burkina Faso before being sent to Mexico, while 1000 S_1 families of the other populations are planted at Ciudad Obregon, Mexico, both under irrigation and severe drought and heat stress. The best 250 S_1 families are then grown in replicated yield trials during the winter cycle at our station in Tlaltizapan, Mexico, under three irrigation regimes: 1) normal irrigation to monitor yield potential, 2) withdrawal of irrigation

Table 3. Correlations between number of second ears per plant at low density and other traits of 327 half-sib families of Pool STDRSP, Tlaltizapan, Mexico, 1987A

	Mean	Range	Correlation
Second ears per plant	0.43	0.06-0.88	1.00
Silk delay (days)			
Primary to secondary ear[a]	2.6	0-8	-0.22**
Primary ear, low to high density	2.9	-3-12	NS
Lodging (percent)[b]	14.7	0-84	NS
Yield (t/ha)[b]	8.51	3.52-13.12	0.19**
Total ears per plant[b]	1.00	0.55-1.40	0.30**

** Significant at the 1% probability level.
NS Not significant.
a Evaluated at low density (40,000 plants/ha).
b Evaluated at high density (106,000 plants/ha).

2 weeks before flowering to create grain-filling stress, and 3) withdrawal of irrigation at tassel initiation to induce flowering and grain-filling stress. The trial design is an alpha (0, 1) lattice (11) with two replications, and individual plot size is small because of restricted land and seed supplies.

Selections are made (with a selection intensity of 5% in the S_1 scheme) for lines that have high relative leaf and stem elongation, short anthesis-to-silking interval, cool canopy temperatures (as determined with an infrared thermometer), slow rate of leaf death, high grain yield under drought, and a yield under irrigation equal to the mean of the population. We also consider lines desirable that have low chlorophyll photooxidation, small tassels, and a low degree of leaf rolling under drought stress. Selections for drought tolerance were made previously among full-sib families of the population Tuxpeño Drought. It appears that a given stress treatment that was appropriate for full-sib families in previous selections is normally too severe for S_1 families and that the correlations among selected traits differ according to the level of inbreeding in the families being tested (Table 5). Correlations between grain yield and other traits, with the exception of anthesis-to-silking interval, are weaker for S_1 than for full-sib families.

After three cycles of selection, a major evaluation of the cycles will be conducted. We anticipate that much of the populations' variability for drought tolerance will have been

Table 4. Maize populations currently being selected for drought tolerance at CIMMYT

Name	Maturity	Grain type	Recurrent selection scheme
La Posta	Late	White Dent	S_1
Pool 26	Late	Yellow Flint/dent	S_1
Pool 16	Early	White Dent	Full sib
Pool 18	Early	Yellow Flint/dent	S_1

Note: La Posta is streak resistant and Pool 16, which is handled in conjunction with the Semi-Arid Food Grains Research and Development (SAFGRAD) Project in Burkina Faso, is partially resistant to the disease. All of the materials listed here have undergone one cycle of selection for drought tolerance.

extracted, and it will then be possible to identify new drought-tolerant materials for improvement.

Creation of a drought-tolerant pool—In 1986 we initiated a long-term approach to combating drought stress by identifying foundation components for a drought-tolerant pool. In including cycle 8 of Tuxpeño Drought as one of the major components, we have capitalized on the advances made in this population through recurrent selection. A US Corn Belt x latente selection and the original source of the latente character (Michoacan 21) were also used to form the pool. (*Latente* is the term used to describe the performance under drought that is characteristic of a collection of maize from the state of Michoacan, Mexico, in which developmental events can apparently be deferred until drought is lifted.) A fourth important source was the Thai hybrid KSX 2301, which is characterized by slow, early leaf development. Those and several less important components have been crossed in a diallel and sown in a half-sib recombination block.

The pool will be maintained in an open structure, with additional sources continually being introgressed into it. Screening and

Table 5. Correlations between grain yields under drought stress and other characters for which selections were made in full-sib families of Tuxpeño Drought (cycle 3) during 1979 and in S_1 families of La Posta (cycle 1) during 1986

Variable	Full-sib families of Tuxpeño Drought	S_1 families of La Posta	Stress level
Relative leaf and stem extension rate	0.39**	NS	
Anthesis-to-silking interval			
Under stress	-0.36**	-0.50**	Interm
Under irrigation	NS	-0.44**	
Leaf death score	-0.48**	-0.20**	Interm.
Canopy temperature during grain filling	-0.65**	-0.27**	Severe

Source: (3)
Note: The full-sib family correlations were observed under severe stress, and those for S_1 families were obtained under either intermediate or severe stress. Both materials were grown at Tlaltizapan.
** Significant at the 1% probability level.
NS Not significant.

selection of new source materials will take place at Tlaltizapan each winter cycle. They will include entries in CIMMYT's maize germplasm bank that were collected at arid locations, elite materials supplied by Center outreach staff, and entries from other breeding programs that have concentrated on maize performance under limited water supply Our criteria for selecting sources of unique drought tolerance will include capacity to adjust osmotically, aggressive rooting behavior, high dawn leaf-water potential, and low chlorophyll photooxidation.

Nitrogen use efficiency—Maize yield is very responsive to natural variations in the supply of nitrogen. This element is frequently deficient in the tropics, where many countries cannot import and distribute enough fertilizers to exert any significant effect on production Nevertheless, most plant breeding institutions, CIMMYT included, develop varieties under high levels of N Their strategy is based on the assumption that, if there is any N x genotype interaction, it is not of the crossover type; that is, a variety found to be superior at high N levels should continue to stand out among other materials under low N supply, though by a reduced margin.

In 1985 the physiology unit embarked on a study to test that assumption We hope to show whether it is possible to select for improved performance of maize under N stress without sacrificing its responsiveness to high levels of N In selecting for more efficient use of N, one must consider the various components of this trait.

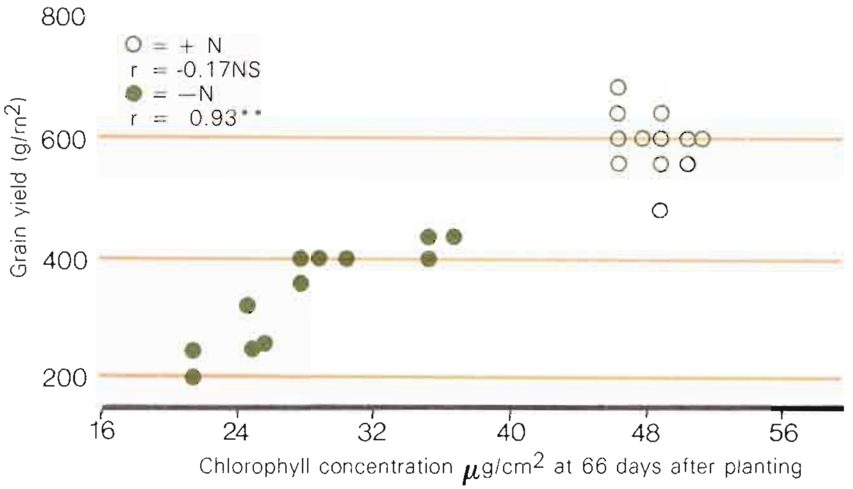
- Total N uptake: A genotype's overall efficiency in absorbing N from a limited pool of soil N, which may be depleted by leaching and volatilization
- N/CHO ratio: Efficiency with which a genotype utilizes absorbed N to produce carbohydrate
- Nitrogen harvest index, grain protein percentage, and grain yield Efficiency with which a genotype translocates N to grain.

It is also important in our judgment that at the test site grain yield under reduced N supply should be 50% or less of that under high N To meet this requirement, we established a permanent low-N block of land at our station in Poza Rica, Mexico, and reduced the N supply in the block by cutting and removing two succeeding green crops of maize.

During 1986 a trial containing 18 genotypes of contrasting maturities (12 late and 6 early) and levels of improvement (16 improved and 2 landraces) was grown with five replications. At flowering and during grain filling, chlorophyll concentration (a trait that is highly correlated with leaf N concentration) was measured with a chlorophyll photometer (7), which distinguishes variations in greenness that the eye cannot detect. Each measurement takes only about 10 seconds to complete. Although there was no relationship between grain yield and leaf chlorophyll concentration under high N, the chlorophyll readings taken at flowering on plants under N stress did show differences between high-and low-yielding materials (Figure 2). The genotype x N level interaction for grain yield was significant at the 8% probability level within maturity classes and was statistically significant both for total N recovered and for the weight of grain produced per unit of N absorbed by the plant. Those results indicate that selection under N stress might be justified.

A selection index was developed that comprises high grain yield under N stress and without N stress, high ear-leaf chlorophyll content during grain filling under N stress, short anthesis-to-silking interval under N stress, and large ear-leaf area under N stress. Correlations between grain yield under N stress and the other traits that make up the index show the tight positive association between chlorophyll content at flowering and grain yield when both were measured under limited N (Table 6).

To determine whether progress can be made in selecting for improved performance under N stress without sacrificing responsiveness to high levels of N, we are using the variety that showed the highest level of N-use efficiency in the exploratory trial described above. Progeny of that variety—Across 8328, a tropical, late-maturing material with yellow dent grains—are being grown under two levels of N (0 and 200 kg/ha) in plots consisting of single 5-m rows. The trial has an alpha (0, 1) lattice design with three replications. Selections are being made according to the index described previously, with a



NS Nonsignificant
** Significant at the 1% probability level.

Figure 2. Relationship between grain yield at harvest and ear leaf chlorophyll concentation in 12 late-maturing genotypes grown under two nitrogen regimes, Poza Rica, Mexico, 1986A.

selection intensity of 20%. The method of population improvement being employed is full-sib recurrent selection, in which a new set of 250 full-sib families is made in the recombination step. In the first cycle of selection, the correlations between traits observed for the full-sib families were similar to those measured in the variety trial (Table 6). Families that yielded well under limited N also retained their lower leaves in a functional state for a longer time and had a shorter anthesis-to-silking interval.

Laboratory analyses are being kept to a minimum, both because they are time-consuming and because we want the selection index to be readily usable in developing country maize programs, which often do not have the necessary laboratory facilities. In evaluating changes that arise from selection, however, we will rely heavily on laboratory analyses.

Future Crop Physiology Research

The work on general stress tolerance, drought, and nitrogen use efficiency will continue, and we hope also to initiate research on some of the other problems listed in Table 2. Phosphorus deficiency, for example, is common in the tropics (though less problematic than nitrogen), so it would be useful to

Table 6. Correlations between grain yield at low N and other variables at low (-N) and high (+N) levels of N in an evaluation of 11 late-maturing varieties (1986A) and of 250 full-sib families of Across 8328 (1986B)

Variable	Varieties	Full-sib families
Grain yield (+N)	0.25	0.46**
Chlorophyll at flowering (-N)	0.88**	0.80**
Chlorophyll 3 weeks after flowering (-N)	0.88**	0.80**
Ear leaf area (-N)	0.75**	0.61**
Anthesis-to-silking interval (-N)	-0.67*	-0.58**
Total plant N (-N)[a]	0.79**	0.74**
Nitrogen harvest index (-N)[a]	0.76**	0.74**
Total biomass (-N)[a]	0.97**	0.78**
Green leaves below the ear		
69 days after planting (-N)	+	0.75**
82 days after planting (-N)	+	0.74**

a Measured on a subset of 73 full-sib families.
* Significant at the 5% probability level.
** Significant at the 1% probability level.
\+ Not measured in the evaluation of varieties.

select for more efficient uptake and use of this nutrient when it is in short supply. We also plan to begin selection for more efficient conversion of intercepted radiation into biomass and screening of lines for tolerance to soil aluminum in cooperation with CIMMYT staff based at the International Center of Tropical Agriculture (CIAT). Among the other services we expect to provide are maturity prediction and environmental classification (a study has already been started and is discussed in the above-mentioned report on maize production environments) and evaluation of the Maize Program's germplasm for forage qualities

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Studies on the Combining Ability of CIMMYT Maize Germplasm

S.K. Vasal, D.L. Beck, and J. Crossa[1]

Over the past 20 years, the Center's Maize Program has contributed substantially to the body of maize germplasm available by developing and improving a large number of gene pools, populations, and experimental varieties and distributing them to some 80 countries through an international testing network. That germplasm is currently being grown on 5-6 million ha across the Third World largely in the form of open-pollinated varieties but also in various types of hybrids developed by national programs and private seed companies.

Because of growing interest among maize breeders in the development of hybrids for Third World countries, the CIMMYT Maize Program has initiated its own hybrid program (under the direction of Surinder K. Vasal), which will provide various products and services, including early generation inbreds, nonconventional hybrids, information, and training.

During recent years use of hybrids seems to have increased in developing countries, particularly the ones (such as Argentina, Brazil, China, El Salvador, Guatemala, Kenya, and Zimbabwe) that are quite advanced in their research and seed production capabilities According to a study conducted by the CIMMYT Economics Program in 1986 (summarized in the Commodity and Policy Analysis section of this *Research Highlights*), hybrids now occupy about 36% of the Third World's total maize area, if we count the three major producers Argentina, Brazil, and China, and about 12% if they are excluded. In the various developing countries where hybrids are being adopted, their use is generally concentrated in the more favorable growing areas where farmers are at less risk and have a better chance of getting an adequate return from their investment in seed and other inputs.

The growing number of farmers whose circumstances permit them to adopt hybrids has stimulated greater interest in hybrid development among certain national maize programs. Since a number of those programs have begun devoting a significant share of their resources to such work, the CIMMYT Maize Program has followed suit by initiating its own hybrid program. The broad objectives of the program are to

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develop new germplasm products for hybrid development and to accumulate and publish information about the utility for hybrid development of the tropical and subtropical materials we already have.

At its inception the program could have given highest priority to any number of urgent tasks. But we decided that collecting data on the combining ability of our tropical and subtropical maize germplasm was the most pressing task and the most likely to be of immediate benefit to national programs. Up to that time little had been done at CIMMYT or in other institutions to characterize the combining ability of the Center's germplasm, yet it was an essential step toward enabling plant breeders to tap this potentially valuable resource for hybrid development. The information was also urgently needed as a guide to our own hybrid program in its germplasm work.

The combining ability studies were initiated in 1985 with the division of various pools and populations into eight groups. Diallel crosses were made within each group, and the F_1 progeny and parents evaluated in 1985 and 1986. From the results of those evaluations, we now have a general idea as to which materials combine well This report presents a summary of our findings, to be followed by more detailed reports in the near future.

Uses of the Study Results

In conducting the eight combining ability studies, we had various objectives in mind, the overall one being to identify combinations of materials that show heterosis. That and other information generated by the studies should provide national programs and other groups with a better basis for making decisions about germplasm available from CIMMYT. The information on heterotic patterns should be particularly useful to national programs that are just now at the point of selecting materials with which to initiate hybrid breeding. Those data will also facilitate choices of appropriate noninbred testers for further evaluating the combining ability of the germplasm and help in identifying good candidates for interpopulation improvement schemes designed to further boost the combining ability of the material and improve its tolerance to inbreeding stress. In addition, it should be apparent from the study results which materials are divergent and which similar (the divergent ones giving the best heterotic responses), and on the basis of those patterns it will be possible to further group the materials for more efficient handling in hybrid development.

With other more specific objectives in mind, we included particular features in the diallel studies. Diallels 1 and 2, for example, contained, in addition to subtropical materials, a number of temperate materials, the performance of which will be of special interest to public and private sector breeding programs in the USA and other countries, whose work impinges on that of CIMMYT and some national maize programs in the Third World. Both tropical and subtropical germplasm was included in diallel 3 to give an indication of the potential heterosis of hybrid combinations between these two types of materials. Finally, for programs that have a specific interest in quality protein maize (QPM), we included diallels 7 and 8 among the studies to gather information on the stability in crosses of the genetic modifiers responsible for giving opaque-2 maize a more normal-looking endosperm.

Formation of the Diallels

Grouping the germplasm to form various diallels was made necessary by two circumstances. First, the only other possibility was to cross each genotype with every other genotype, which would have been a monumental task considering the size of CIMMYT's collection of improved maize germplasm. Second, many combinations showing potential heterosis might not have turned out to be very useful in breeding programs because of differences among the materials in certain key characteristics.

Four of those traits—climatic adaptation, time to maturity, grain color, and protein quality—were our primary criteria in grouping the germplasm, although we also knew from experience that there are genetic similarities between certain pools and populations and where that was the case included the one that best represented the germplasm. Tropical and subtropical materials were included in different diallel studies, with the exception of diallel 3, which, as mentioned previously, was composed of both types so that we could evaluate hybrid combinations between them. The diallels were further distinguished by the germplasm's maturity. With respect to grain color and texture, we followed no hard and fast rule. For some categories of germplasm, we placed white- and yellow-grain materials in different diallels, while in other cases we put them in the same diallel. Taking all those factors into account, we formed eight groups of pools and populations (their

Table 7. Composition of eight diallels developed in Mexico and evaluated internationally

Parent code	1	2	3	4
P1	Pop. 46	Pop. 33	Pop. 22	Pop. 27
P2	Pop. 48	Pop. 34	Pop. 43	Pop. 28
P3	Pool 27	Pop. 42	Pop. 25	Pop. 36
P4	Pool 28	Pop. 45	Pop. 27	Pop. 24
P5	Pool 30	Pop. 47	Pop. 28	Pool 25
P6	Pool 40	Pool 31	Pop. 32	Pool 26
P7	Pool 42	Pool 34	Pop. 42	Suwan-1
P8	—	Pool 39	Pop. 45	—
P9	—	Pool 41	Pop. 44	—
P10	—	—	Pop. 47	—
P11	—	—	Pop. 34	—

composition is indicated in Table 7), with diallels 1 and 2 consisting of all the subtropical germplasm (early maturing materials in 1 and intermediate maturity in 2, each including both white- and yellow-grain types), diallels 4 and 5 the tropical, late-maturing genotypes (the yellow-grain materials in 4 the white ones in 5), and diallel 6 the tropical, early and intermediate-maturity materials of both grain colors. Diallels 7 and 8 were made up of QPM germplasm, the former containing subtropical materials and the latter tropical germplasm of both grain colors.

All the diallels were developed during the 1985A cycle at our experiment stations in Mexico, the tropical materials at Poza Rica and the subtropical ones at Tlaltizapan. Each diallel cross was made in a paired-plot system, reciprocal crosses were made, and the ears were bulked and shelled together as one entry or cross. The parents in each diallel were increased by sib mating. In diallel 3 crosses were made only between tropical and subtropical germplasm, using the design-2 mating system.

Evaluation of the Diallels

The diallels were tested at locations in Mexico, the USA, and various countries in Central and South America and Asia. Although most of the materials were evaluated at six or more sites, some were tested much more widely, specifically diallels 1 and 2, which were of special interest to US maize breeders. In general, we received enough data from trial cooperators to interpret the results and draw reliable conclusions from them. What follows are brief summaries of our conclusions about four major categories of germplasm.

Subtropical germplasm—Among the subtropical, early maturing genotypes of which diallel 1 was composed, the two materials that showed the best general combining ability (GCA), or average performance in the crosses, were P2 (Population 48) and P5 (Pool

5	6	7	8
Pop. 21	Pop. 30	Pool 27QPM	Pool 23QPM
Pop. 22	Pop. 31	Pool 29QPM	Pool 24QPM
Pop. 25	Pop. 49	Pool 31QPM	Pool 25QPM
Pop. 29	Pop. 23	Pool 32QPM	Pool 26QPM
Pop. 32	Pop. 26	Pool 33QPM	Pop. 62
Pop. 43	Pool 16	Pool 34QPM	Pop. 63
Pool 24	Pool 18	Pop. 67	Pop. 64
—	Pool 20	Pop. 68	Pop. 65
—	Pool 21	Pop. 69	Pop. 66
—	Pool 22	Pop. 70	PR 7737
—	—	—	—

30), as indicated in Table 8 (here we present data only on grain yield, although we discuss results for other traits; data on GCA for those traits will be reported in subsequent publications). Both P2 and P5, which are based largely on temperate germplasm, exhibited positive and significant GCA effects. Parents P6 (Pool 40) and P7 (Pool 42), which also contain temperate germplasm, showed significant but negative GCA effects for yield, flowering, plant height, and ear height. Those effects, with the exception of the one for yield, can be considered desirable since they contribute to earlier maturity and reduced plant and ear height.

In addition to determining the general combining ability of the parents in the diallels, we have listed the five most heterotic crosses. In diallel 1 the maximum best-parent heterosis for those crosses ranged from 102 to 104% (Table 9). Population 48 in particular performed well in crosses with Pools 27, 28, and 30 and with Population 46. Pool 30 also combined well with Population 46. Only two crosses, however, can be considered of much practical importance, namely Population 46 x Pool 30 and Population 46 x Population 48, since all three of the parents in these two flint x dent crosses have the same grain color. The former showed significant, positive specific combining ability (SCA) effects.

In diallel 2 (containing germplasm of intermediate maturity), P3 (Population 42), P4 (Population 45), P5 (Population 47), P7 (Pool 34), and P9 (Pool 41) showed positive GCA effects, but only those of Population 42 were significant (Table 8). The pattern changes slightly, however, if we consider results from the USA and Mexican test locations separately (Table 8

Table 8. Estimates of general combining ability effects for grain yield across locations in seven diallels

Parent code	1	2	4	5	6	7	8
P1	-0.07	-0.06	-0.08	0.15	-0.26**	-0.13	0.03
P2	0.39**	-0.06	-0.07	0.09	-0.28**	-0.31*	0.05
P3	0.01	0.30**	-0.13	-0.22**	0.17**	-0.03	-0.31**
P4	0.09	0.12	0.39**	-0.04	0.27**	0.06	-0.19**
P5	0.31**	0.13	-0.29**	0.06	0.20**	-0.03	0.13*
P6	-0.31**	-0.27**	-0.21**	0.20*	-0.36**	-0.05	0.27**
P7	-0.43**	0.03	0.39**	-0.24**	-0.41**	0.05	0.08
P8	—	-0.20	—	—	0.14*	0.17	-0.10
P9	—	0.07	—	—	0.17**	0.13	-0.14*
P10	—	—	—	—	0.37**	0.14	0.18**

* Significant at the 5% probability level.
** Significant at the 1% probability level.

gives only the across-location data) At the former only, P9 (Pool 41) appeared to be a good combiner, judging from its GCA effects for yield, but the pool had significant negative effects for yield at the Mexican locations, as did P8 (Pool 39). Those two materials showed negative significant GCA effects for other characters as well, while those of P2, P3, and P5 were positive.

Of the five most heterotic crosses in diallel 2, Population 42 and Pool 41 were involved in three and Population 47 in two (Table 9). Among white-grain materials, Population 42 x Population 47 and Population 34 x Population 42 should prove to be useful. Population 33 x Population 45 is the only cross between yellow-grain materials that will be of any interest to breeders at non-US locations.

Tropical germplasm—In diallel 4, which comprised the late-maturing, yellow-grain genotypes, parents P4 (Population 24) and P7 (Suwan-1) showed highly significant positive GCA effects for yield (Table 8). All of the other parents exhibited negative effects for yield, but these were significant only in the cases of P5 (Pool 25) and P6 (Pool 26). Population 24 also had significant, positive GCA effects for flowering time and plant and ear height, which would contribute to later maturity and increased height. Parents P3 (Population 36) and Pool 25, on the other hand, showed significant negative GCA effects for

Table 9. Most heterotic crosses in diallels of CIMMYT's subtropical maize germplasm

	Grain yield (t/ha)	Best parent heterosis (%)	SCA effect (t/ha)	Grain color[a]	Grain texture[b]
Diallel 1 (early)					
Pop. 48 x Pool 28	5.08	104	0.11	Y x W	D x D
Pop. 46 x Pool 30	4.95	103	0.22**	Y x Y	F x D
Pop. 48 x Pop. 46	4.96	102	0.15	Y x Y	D x F
Pop. 48 x Pool 27	4.96	102	0.07	Y x W	D x F
Pop. 48 x Pool 30	4.95	102	-0.24**	Y x Y	D x D
Diallel 2 (intermediate)					
Pop. 34 x Pool 41	4.76	119	0.28**	W x Y	F x D
Pop. 42 x Pool 41	4.94	114	0.11	W x Y	D x D
Pop. 47 x Pool 41	4.88	114	0.22*	W x Y	D x D
Pop. 42 x Pop. 47	4.86	113	0.00	W x W	D x D
Pop. 42 x Pop. 45	5.03	111	0.15	W x Y	D x D

a Y = yellow and W = white.
b D = dent and F = flint.
* Significant at the 5% probability level.
** Significant at the 1% probability level.

all characters other than yield and might therefore be useful for acquiring early maturity and reduced plant and ear height.

Of the five best crosses in Diallel 4, the two best were Population 27 x Suwan-1 and Population 27 x Pool 25, both of which involved only flint-grain genotypes and exhibited positive, though nonsignificant, SCA effects (Table 10). Among the other three crosses, all involving flint x dent or dent x dent combinations, Population 24 x Population 36 showed highly significant, positive SCA effects. Populations 24 and 27 occurred twice in the five most heterotic crosses and Suwan-1 three times.

Four of the parents in diallel 5 (late maturing, white-grain materials)—P1 (Tuxpeño-1), P2 (Population 22), P5 (Population 32), and P6 (Population 43)—had positive GCA effects for yield, but they were significant only for Population 43 (Table 8). P3 (Population 25) and P7 (Pool 24) showed significant negative GCA effects for yield. Only the parents P1, P6, and P7 exhibited positive GCA effects for all the other characters.

Table 10. Most heterotic crosses in diallels of CIMMYT's tropical maize germplasm

	Grain yield (t/ha)	Best parent heterosis (%)	SCA effect (t/ha)	Grain color[a]	Grain texture[b]
Diallel 4 (late, yellow)					
Pop. 27 x Suwan-1	6.55	113	0.13	—	F x F
Pop. 27 x Pool 25	5.95	113	0.21	—	F x F
Pop. 36 x Pop. 24	6.78	112	0.42**	—	D x D
Pop. 24 x Suwan-1	6.67	110	-0.21	—	D x F
Pool 26 x Suwan-1	6.29	109	0.00	—	D x F
Diallel 5 (late, white)					
Pop. 29 x Pop. 32	7.20	113	0.32*	—	D x F
Pop. 21 x Pop. 25	7.16	112	0.38**	—	D x F
Pop. 21 x Pop. 32	6.94	108	-0.13	—	D x F
Pop. 22 x Pop. 32	7.33	107	0.32*	—	D x F
Pop. 32 x Pool 24	6.41	107	-0.26*	—	F x D
Diallel 6 (early-intermediate)					
Pop. 49 x Pop. 26	6.14	110	0.12	W x Y	D x F
Pop. 49 x Pool 21	6.13	109	0.14	W x Y	D x F
Pop. 23 x Pool 20	6.28	107	0.22*	W x W	F x D
Pop. 26 x Pool 21	6.05	107	0.02	Y x Y	F x F
Pop. 23 x Pop. 26	6.24	106	0.11	W x Y	F x F

a W = white and Y = yellow.
b F = flint and D = dent.

* Significant at the 5% probability level.
** Significant at the 1% probability level.

Two striking features of the five most heterotic crosses in diallel 5 were that four of them were flint x dent combinations and that an equal number contained Population 32 (Table 10) Only for three crosses, however, were the SCA effects significant and positive.

In diallel 6, which included yellow- and white-grain genotypes of early to intermediate maturity, the parents showing significant, positive GCA effects were P3 (Population 49), P4 (Population 23), P5 (Population 26), P8 (Pool 20), P9 (Pool 21), and P10 (Pool 22), as indicated in Table 8. With the exception of Population 49, those materials also had positive GCA effects for other characters. The rest of the parents exhibited negative effects for all characters, including yield, except Population 30, which had positive effects for plant and ear height.

Of the five most heterotic crosses in diallel 6, two—Population 26 x Pool 21 and Population 23 and Pool 20—can be considered of greatest importance to breeders, since both parents in the former are yellow-grain materials and in the latter white grain (Table 10). The other three crosses involve combinations of yellow- with white-grain parents. The only cross that showed significant, positive SCA effects for yield was Population 23 x Pool 20.

Tropical x subtropical combinations—Population 44 was a parent in four of the five highest yielding crosses between these two types of germplasm, the other parents being Populations 32, 43, 27, and 25. The fifth cross—Population 43 x Population 42—also gave a good heterotic response (Table 11)

QPM germplasm—All of the subtropical QPM populations serving as parents in diallel 7—P7 (Population 67), P8 (Population 68), P9 (Population 69), and P10 (Population 70)—showed positive, but nonsignificant, GCA effects for yield (Table 8). Conversely, all of the subtropical QPM pools, with the exception of P4 (Pool 32 QPM), had

Table 11. Most heterotic crosses in diallel 3 (tropical x subtropical maize populations)

	Grain yield (t/ha)	Best parent heterosis (%)	Grain color[a]	Grain texture[b]
Pop. 32 x Pop. 44	6.65	113	W x W	F x D
Pop. 43 x Pop. 42	6.85	111	W x W	D x D
Pop. 43 x Pop. 44	6.71	109	W x W	D x D
Pop. 27 x Pop. 44	6.33	107	Y x W	F x D
Pop. 25 x Pop. 44	6.23	106	W x W	F x D

a W = white and Y = yellow.
b F = flint and D = dent.

negative effects for that trait, those of the early maturing parent P2 (Pool 29 QPM) being the greatest and significant. That and another early maturing QPM pool (Pool 27 QPM) also exhibited significant negative effects for days to silk and for plant and ear height. They had positive GCA effects for kernel modification, however, implying that they had an undesirable influence on this trait in the crosses. Other parents, P3 (Pool 31 QPM), P5 (Pool 33 QPM), and P9 (Population 69), showed negative GCA effects for kernel modification and can be considered favorable in their influence on that trait. Populations 68 and 70 also had negative GCA effects for kernel modification, but they were nonsignificant. The worst parent with respect to kernel modification (showing significant, positive GCA effects) was P6 (Pool 34 QPM). Even so, that pool was a parent in two of the four most heterotic crosses in diallel 7, the other parents being Pool 33 (QPM) and Populations 67, 69, and 70 (Table 12) Only three of the crosses, though, had positive SCA effects.

In diallel 8 no clearcut patterns emerged in the heterotic responses of the tropical, hard-endosperm QPM genotypes. Moreover, none of the three most heterotic crosses will be of much interest to plant breeders since all are combinations of soft- with hard-endosperm parents.

Conclusion

From the results of the diallels, we can draw some conclusions about the GCA effects of the materials

Table 12. Most heterotic crosses in diallels of CIMMYT's quality protein maize germplasm

	Grain yield (t/ha)	Best parent heterosis (%)	SCA effect (t/ha)	Grain color[a]	Grain texture[b]
Diallel 7 (subtropical)					
Pool 34 x Pop. 67	5.80	107	0.25*	Y x W	D x F
Pop. 69 x Pop. 70	5.81	106	0.00	Y x Y	F x D
Pool 27 x Pop. 67	5.71	106	0.26*	W x W	F x F
Pool 33 x Pop. 69	5.76	105	0.12	Y x W	F x F
Diallel 8 (tropical)					
Pop. 65 x PR 7737[c]	6.58	116	0.32**	Y x W	F x D
Pool 23 x PR 7737	6.40	105	0.02	W x W	F x D
Pop. 66 x PR 7737	6.26	105	0.05	Y x W	D x D
Pop. 62 x Pop. 66	6.44	104	0.29**	W x Y	F x D

a Y = yellow and W = white.
b D = dent and F = flint.
c Soft-endosperm material.

* Significant at the 5% probability level.
** Significant at the 1% probability level.

included and about possible heterotic patterns between them The parents showing good GCA effects for yield are as follows:

Diallel 1—Pool 30 and Population 48

Diallel 2—Populations 42 and 47

Diallel 3—Populations 43 and 44

Diallel 4—Population 24 and Suwan-1

Diallel 5—Population 43

Diallel 6—Populations 23, 26, and 49 and Pools 20, 21, and 22

Diallel 7—Populations 67, 68, 69, and 70

Diallel 8—PR 7737

Possible heterotic combinations are listed in Table 13. That information should be useful in identifying germplasm for interpopulation improvement programs, in addition to indicating likely matches primarily between CIMMYT populations and pools used in hybrid development.

Table 13. Possible heterotic combinations with CIMMYT populations

Population	Diallel	Possible heterotic partner
21	5	Pops. 32 and 25 and Pool 23
22	5,3	Pop. 32
23	6	Pool 20
24	4	Pop. 36 and Suwan-1
25	5,3	Pop. 21
26	6	Pool 21
27	4,3	Pool 25, Suwan-1, and Pop. 44*
28	4	Pop. 24 and Suwan-1
29	5	Pop. 32
31	6	Pop. 49*
32	5,3	Pops. 21, 22, 29, and 44
33	2	Pop. 45
34	2	Pop. 42 and Pool 34*
36	4	Pop. 24
42	2,3	Pops. 34, 43, 45*, and 47
47	2,3	Pop. 42
43	5,3	Pops. 42 and 44
44	3	Pops. 32, 25, 27*, and 43
45	2,3	Pop. 33 and Pool 33
46	1	Pop. 48 and Pool 30
48	1	Pop. 46 and Pools 27* and 28*
49	6	Pops. 26* and 31* and Pool 21*

* Indicates that the material is of a different grain color from the matching population in the column at far left.

The research projects highlighted in 1986 are but a cross section of some of the main thrusts in the CIMMYT Wheat Program (See diagram of the Program's structure on the following page). They illustrate the Program's involvement in the two major enterprises of CIMMYT—namely research (of which wheat germplasm improvement is an element) and strengthening national programs (of which giving assistance to develop technology is an element).

The first two articles are on germplasm improvement. One relates to a specific methodology utilized within the Program and the other discusses improvement in general, where we see the fruits of the breeding effort. The third article discusses the Program's commitment to assist national agricultural research systems (NARS) in developing technologies which will help them increase productivity as well as production.

Germplasm Improvement

A successful breeding methodology—The first article highlights a specific breeding methodology, namely shuttle breeding, that has proven to be very successful and has had tremendous impact on wheat germplasm development within CIMMYT

Some 30 years before this methodology was coined "shuttle breeding" in the late 1970s, Norman E. Borlaug and his colleagues were already using the concept within Mexico and reaping germplasm improvement rewards. International shuttle breeding has been utilized in the last 10-15 years and will receive a great deal more emphasis in the future. Although this methodology has become a key element in our international disease screening approach, Sanjaya Rajaram, head of the bread wheat improvement program, and two Brazilian colleagues present an article on one of our oldest—and probably most successful—international shuttle programs that has to do with an abiotic stress—namely aluminum toxicity in the soil.

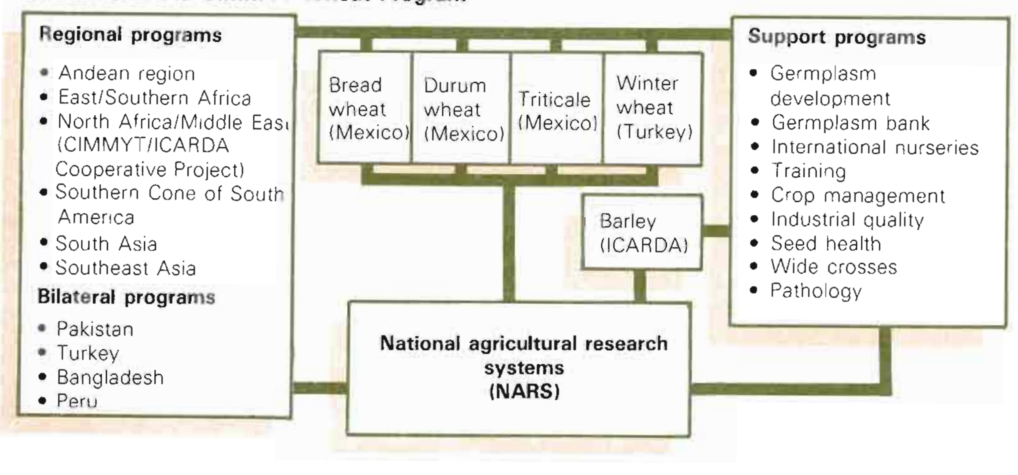
Shuttle breeding is a methodology that will be receiving more attention in the future as we attack other specific problems. This is CIMMYT's move towards developing wheats with the basic characteristics, plus more specific adaptation for particular regions. Recently, we have initiated preliminary shuttle programs with Ethiopia (septoria leaf blotch tolerance and stem rust resistance for durum wheat), Nepal (to enhance resistance to tan spot), and Ecuador and Kenya (to develop wheat adapted to tropical highland conditions). CIMMYT and China will soon formalize a shuttle partnership program to assist the Chinese in developing more productive wheats with better scab resistance. A winter wheat shuttle is also being planned between our program in Turkey and Texas A&M and Kansas State Universities in the US.

Development of superior durum wheat germplasm—In the second article, Pedro Brajcich, head of the durum wheat improvement program, and his colleagues chronicle the development of superior germplasm. Altar 84 is a cultivar that is making a significant impact and that we suspect will have an even greater impact in the future as it is released by national programs around the world. It is a definite step in the right direction because it combines additional yield potential with higher quality. This is important because the quality has been increased significantly as yield potential was increased—which is not an easy thing to do. It also appears that because of Altar 84's good adaptation, it should be released by several countries that are interested in growing durum wheat.

Strengthening National Programs

Finally, Matthew McMahon, head of the wheat agronomy program, summarizes 4 years of research in the Secano Interior of Chile on the rotation of wheat with a legume forage plant. This is only an example of the type of work that CIMMYT becomes involved with in cooperation with NARSs' programs. It is important to point out that the results of this work came about due to the interaction of national program staff and CIMMYT staff working together to solve a specific production problem in a collaborating country.

Structure of the CIMMYT Wheat Program



Developing Bread Wheats for Acid Soils through Shuttle Breeding

S. Rajaram, R. Matzenbacher, and O. de Sousa Rosa[1]

Shuttle breeding in Mexico—the driving force of CIMMYT's bread wheat, durum wheat, and triticale improvement programs—is a well known success story In this scheme, the F_2 is grown in one environment and selected progeny (F_3) are planted in a different location. Successive generations are alternated (shuttled) between the two locations. The underlying philosophy is to incorporate adaptation and resistance to all the pathogens and stresses encountered in two distinct locations. It was in the mid-1970s that the late Glenn Anderson, associate director of the CIMMYT wheat program at the time, coined the term "shuttle breeding", long after Norman E. Borlaug began using the methodology itself.

In the late 1940s, Borlaug began crossing, screening, and selecting germplasm during winter and summer cycles each year at two diverse locations, Cd. Obregon and Toluca, Mexico. A breeding cycle still takes place at the Mexican government's Northwestern Agricultural Research Station (CIANO) during the winter (November to May) This location is an irrigated desert environment near Cd Obregon in the state of Sonora at 27.2°N latitude, 39 m elevation. Seed harvested at CIANO is "shuttled" for May and June planting at the beginning of the summer cycle at CIMMYT's research station in the central highlands near Toluca (elevation 2640 m and 19°N latitude) and at El Batan (elevation 2240 m and 19°N latitude).

At Cd. Obregon, breeding materials are crossed and resulting progenies are evaluated for their yield potential under high fertility and well watered conditions. Progeny are also screened for resistance to leaf and stem rusts.

At Toluca, breeding materials are also crossed and the germplasm is screened for resistance to stem, leaf, and stripe rusts as well as to septoria tritici blotch, septoria nodorum blotch, fusarium head scab, bacteria such as *Xanthomonas campestris* pv *translucens*, and barley yellow dwarf virus (BYDV).

One generation a year at each of these locations enables the breeders to eliminate daylength-sensitive germplasm Only materials that are insensitive to the daylength variation are selected.

In addition to Cd Obregon, Toluca, and El Batan, CIMMYT uses a number of "off-station" sites in Mexico to screen for resistance to septoria tritici blotch, septoria nodorum blotch, fusarium head scab, helminthosporium leaf blotch, stripe rust, and stem rust and tolerance to heat and drought.

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The use of contrasting locations for generation advancement and selection of germplasm in Mexico has resulted in many widely adapted bread wheat cultivars with high genetic yield potential. Broadly adapted cultivars such as Siete Cerros, Anza, Nacozari 76, Pavon 76, and the Veery sibs were produced in this fashion and have been released in many countries.

Shuttle breeding has proven to be very effective in Mexico and can also work well on an international basis. The best example is CIMMYT's 13-year collaboration with Brazilian scientists. The goal in this project has been to develop high-yielding wheat cultivars with tolerance to aluminum/acid soil conditions. With shuttle breeding, dramatic results have been derived through the combination of the early work of Brazilian organizations (which developed aluminum-tolerant wheat cultivars) and the work of CIMMYT (which developed high-yielding cultivars with better agronomic type). A number of high-yielding, aluminum-tolerant wheat cultivars have been released or recommended for release in several Brazilian states, and promising cultivars have been developed for other countries with soil aluminum problems. This article discusses some historical background, what has been accomplished, and plans for the future regarding the development of bread wheats for the problems associated with soils that have toxic levels of aluminum.

The Acid Soil Problem

Soil acidity is a major growth limiting factor for plants in many parts of the world. Approximately 1 billion hectares in the tropics and subtropics are acidic (6). This includes large areas of Brazil, the Andes of South America, China, Southeast Asia, the Himalayas of the Indian Subcontinent, and Central Africa. Currently, many of these areas are either undeveloped for agriculture, or, where cultivated, are of very low productivity. To meet the rapidly growing demand for food for the next century, these problem soils must be developed and productivity on them improved. This can be done by a combination of plant improvement, corrective chemical amelioration and fertilization, and improved management practices.

Growth limiting factors that have been associated with the acid soil complex include toxicities of aluminum and manganese and deficiencies of calcium, magnesium—and especially phosphorus and molybdenum These acid soil factors may act somewhat independently, or more often together, to negatively affect plant growth.

Aluminum and manganese toxicities are the two most important factors limiting the growth of crop plants in many acid soils of the world. Aluminum toxicity is particularly severe below pH 5.5. Agronomists' current approach to this problem is to change the pH by adding lime to the soil. This is not always economically or physically feasible, particularly in strongly acidic subsoils.

Calcium has to be leached into the subsoil (4). The Ca ion cannot leach alone. To maintain electro-neutrality, an ion must move with it. The rate at which calcium is leached is dependent on the mobility of the accompanying anion. 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 calcium which is almost entirely sorbed on the exchange complex. Calcium added as calcium chloride leaches most rapidly and calcium sulphate (gypsum) is 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 leads 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 (4).

Aluminum toxicity severely inhibits root growth by preventing cell division in the root apical meristem. The restricted root system makes the plant vulnerable to moisture stress and unable to utilize normal

Co-author Ricardo Matzenbacher, wheat breeder at FECOTRIGO's Center for Experiment and Research, checks advanced lines in the aluminum screening plots at Cruz Alta, Rio Grande do Sul. At left is CEP 8530, an aluminum tolerant line, compared with Suzhoe F3 # 1, a highly aluminum-susceptible line at lower right.

levels of available essential plant nutrients. Aluminum toxicity symptoms are not easily identified as the foliar symptoms often resemble those of some nutrient deficiencies.

Current Situation in Brazil

Even though Brazil is currently producing significant amounts of wheat (about half of the 5-6 million tons it consumed in 1986), wheat production in the country still has many problems. About 70% of the 2.83 million ha under wheat cultivation in Brazil have a low pH (between 4.0 and 5.5), high levels of aluminum and manganese, and low levels of available phosphorus, potassium, and other micro-elements. Some areas of Paraná and Sao Paulo states have been cleared of forest only during the past 20 years or so and have many problems, including acidity with its associated toxicities, infertility, and shallowness of soil that is highly subject to erosion from heavy rainfall. Average Brazilian wheat productivity has fluctuated between 300 and 1600 kg/ha between 1963 and 1986 (Figure 1). High regional incidence of fungal, viral, and bacterial diseases; drought; and frosts are generally responsible for the dips in productivity. It is important to note that many millions of additional hectares in the Cerrados area which are otherwise suitable for wheat production also have many of the problems listed above (5).

The situation in Brazil exemplifies some of the problems of moving wheat production into the warmer nontraditional areas, an objective of a number of national programs cooperating with the CIMMYT Wheat Program. A long-term and

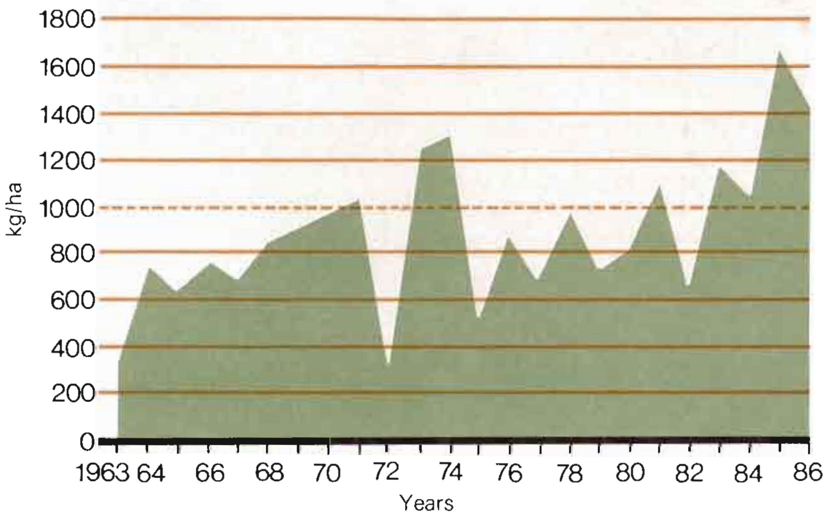

Figure 1. Average Brazilian wheat productivity from 1963 to 1986. Source: (5).

continuous research effort will be necessary to develop crop production methodologies to stabilize production. Development of cultivars better adapted to the acid soils will continue to be a part of the overall crop improvement programs in Brazil and CIMMYT.

Historical Background of the Brazilian Acid Soil Problem

Brazilian scientists first observed differences among wheat cultivars planted in acid soils in the 1920s, although it had not yet been determined that the acid soils themselves were causing these differences. Due to the yellowing and poor growth of the plants, the problem was given the name "crestamento," which in Portuguese means "burning" or "toasting." In 1925, crosses made between the crestamento-tolerant Alfredo Chaves cultivars and the cultivar Polyssu gave rise to new crestamento-tolerant Brazilian cultivars, such as Fronteira, Surpresa, Minuano, Jesuita, and Guarany (5).

By 1942, Brazilian scientists were able to attribute crestamento to the high acidity present in the soil. Later in the decade, they determined that it was caused by the presence of toxic levels of soil aluminum (1, 2). In 1954, it was found that tolerance to aluminum was a heritable characteristic (3). Brazilian studies showed that tolerance was a dominant effect and possibly controlled by a pair of genes. In 1980, it was found that tolerance is differentiated by two independent genes.

As the Brazilian breeding programs developed, the cultivars Preludio and Carazinho were released in 1956 and 1957. Because they averaged 1 t/ha and showed resistance to leaf rust and tolerance to aluminum toxicity, these cultivars became very popular with farmers. In the 1960s, cultivars such as IAS 20 showed a yield potential of up to 1.4 t/ha in soils with toxic aluminum.

The increase in soybean production starting in 1968 brought about two new practices (5) Lime was applied to enhance soybean production and as a result wheat production increased also. In addition, because of the new wheat-soybean doublecrop system, late-maturing wheat cultivars were abandoned and only early-maturing cultivars have been used since. Liming did not eliminate the need to maintain varietal tolerance to aluminum toxicity. Because lime usually is applied only to the plow layer (top 20 cm of soil), susceptible cultivars planted in limed soil develop their root systems only in this superficial layer, causing inadequate nutrient uptake and vulnerability to moisture stress.

Era of CIMMYT Collaboration

By the late 1960s, although Brazilian cultivars had been improved through the years, they were still low-yielding, too tall, and deficient in agronomic characteristics such spike fertility and straw strength. In 1969, John W. Gibler, then technical director of the Federation of Wheat and Soya Cooperatives for the state of Rio Grande do Sul (FECOTRIGO), first initiated genetic material exchange with CIMMYT. The main objective was to combine the Brazilian wheats' tolerance to toxic levels of aluminum with the high yield potential of the Mexican wheats.

By 1974 N.E. Borlaug had informally arranged a shuttle breeding program between CIMMYT's Mexican bread wheat program and FECOTRIGO's newly organized Experiment and Research Center (CEP) at Cruz Alta and the National Research Center for Wheat (CNPT) of the Brazilian Agricultural Research Corporation (EMBRAPA) at Passo Fundo. By 1977 the shuttle program was intensified and expanded to include the Organization of Cooperatives of the State of Paraná (OCEPAR) at Cascavel. The Paraná State

Figure 2. Mexican and Brazilian locations involved in the shuttle breeding scheme.

Agricultural Research Institute (IAPAR) at Londrina, the Sao Paulo Agricultural Institute (IAC) at Campinas, and the Agricultural Research Center for the Cerrados (CPAC) of EMBRAPA at Brasilia also now cooperate with CIMMYT to various degrees although they are not exactly involved in shuttle breeding. See Figure 2 for the Brazilian locations.

The exchange of genetic material between Brazil and CIMMYT permits the introduction of thousands of lines and segregating populations for all the collaborating breeding programs. The genetic combinations of high-yielding Mexican wheats with semidwarf characteristics and Brazilian wheats with aluminum tolerance are made in Cd. Obregon, Toluca, Cascavel, Passo Fundo, and Cruz Alta (Figure 2).

The laboratory screening procedure adopted by CIMMYT for detecting tolerance to soluble aluminum in the segregating wheat populations involves a visual evaluation of the growth of the primary root in seedlings (Figure 3) after exposure to an aluminum concentration of 46 ppm. Seedling roots are then immersed in a solution of hematoxylin, which stains the root tips black. The seedling roots are then placed in aerated distilled water for 24 hours in which only the roots of tolerant seedlings will continue to grow (Figure 3).

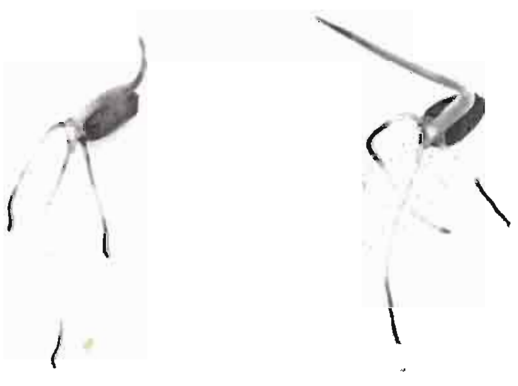

Figure 3. The roots of the wheat seedling at right have continued to grow (new growth beyond black-stained region) after being exposed to an aluminum concentration of 46 ppm, indicating that the seedling is aluminum tolerant. The roots of the seedling at left show no growth beyond the stained region, thus the seedling is aluminum susceptible.

Promising segregating materials identified by the lab screening procedure are sent to several Brazilian states to be tested in acid soils and to Toluca and Cd. Obregon in Mexico for testing in nonacid soils. In Mexico, selections are made mainly for agronomic characters and resistance to stem, leaf, and stripe rusts. In Brazil, besides selecting for aluminum tolerance, selections are also made for the local disease complex of leaf rust, stem rust, helminthosporium spot blotch, septoria tritici blotch, septoria nodorum blotch, fusarium head scab, barley yellow dwarf virus, and bacterial stripe. In Brazil, when plants reach the full tillering stage (late August in Passo Fundo and Cruz Alta), visual evaluations are made for ''crestamento'' tolerance and the results are immediately telexed to CIMMYT for use during the selection process in Toluca, Mexico.

Until the material breeds true to type and becomes essentially homozyotic, selection is done in both Brazil and Mexico.

Results in Brazil

Much of the tested material is discarded because of its susceptibility to aluminum toxicity and diseases. However, Brazilian scientists are highly enthusiastic about the gains in yield potential that have been incorporated into their aluminum-tolerant wheat germplasm.

In 1980, Alondra was released for general cultivation in primarily nonacid soils as a multiline cultivar in Paraná state. However, Alondra also often yields well in acid soils and yet it is susceptible to high levels of soluble aluminum. Derived from the cross D6301/Nainari 60//Weique-Red Mace/3/Ciano-Chris (CM11683), Alondra's performance in Brazil's acid soils may be partly due to its ability to efficiently extract and utilize phosphorus when phosphorus is present in low levels. Since acid soils also tend to have low levels of available phosphorus, it is important that this characteristic be incorporated into germplasm intended for such soils. Brazilian scientists have identified progeny from Alondra that have higher levels of tolerance to toxic levels of aluminum and have been using them further in crossing programs.

In recent years, a number of cultivars obtained from the shuttle breeding cooperation have been recommended for cultivation in several Brazilian states (Table 1). Alondra is in the pedigree of several of these new cultivars. In one of these cultivars, Thornbird (BR14), increased phosphorus uptake efficiency has been combined with true tolerance to aluminum. Although Thornbird is still moderately tall, it is the first of the new generation of early, aluminum-tolerant, and high-yielding wheats emanating from this cooperative shuttle breeding effort. Thornbird and the other cultivars listed in Table 1 have increased yield potential over the current commercial Brazilian cultivars by at least 25% In field experiments, the new high-yielding, aluminum-tolerant cultivars are producing yields higher than 4 t/ha—in some cases higher than 5 t/ha Several advanced lines are emerging from the breeding pipeline with even higher yield potential.

In addition to high-yield potential, additional major specific traits improved in the Brazilian germplasm include.

- Disease resistance to leaf and stem rusts and powdery mildew.
- Better agronomic type with regard to plant type, shorter and stronger straw, and larger, more fertile spikes.
- Better heat and drought tolerance.

Table 1. Cultivars obtained through alternate selection at Brazil and Mexico and recommended for cultivation in several Brazilian states

Cultivar	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-700Y
OCEPAR 8-MACUCO	IAS 64/''S'' CM 47207-6M-103PR-2T-0T
OCEPAR9-PERDIZ	IAS58/BJY''S''//BNQ CM47971-A-4M-105PR-2T-OT
OCEPAR 10-GARCA	IAC 5/ALDAN''S'' CM 46961-16M-109PR-1T-0T
OCEPAR 11-JURITI	IAC 5/ALDAN''S'' CM 46961-16M-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 14402-0M-1T-2T-0T
TRIGO BR 14	IAS 63/ALONDRA''S''//GABOTO/LAGOA VERMELHA Mixture of the lines PF 79765, PF 79767, PF 79780, PF 79782, and PF 79791 = THORNBIRD''S''
TRIGO BR 16-RIO VERDE	PF 70402/ALONDRA''S''//PAT 72160/ALONDRA''S'' B 19789-H-508M-1Y-10F-701Y-1F-700Y

Results at CIMMYT and in Mexico

CIMMYT is equally enthusiastic about the gains made by crossing Mexican wheats with Brazilian wheats and selecting under both Mexican and Brazilian conditions. These major gains in CIMMYT germplasm include:

- Aluminum tolerance.
- Phosphorus uptake efficiency.
- Resistance or tolerance to the leaf spotting diseases, such as *Septoria*, *Helminthosporium*, and *Fusarium* spp.
- Longer leaf duration (stay-green effect).

In the high-altitude regions of Mexico in the states of Michoacan and Jalisco, soils are highly leached and acidic with a high phosphorus fixation problem. In these soils, the aluminum-tolerant cultivars selected through the Mexican/Brazilian shuttle have shown a yield advantage superior to the traditional cultivars such as Anahuac 75 and Pavon 76. A cultivar recently released in Michoacan is Curinda M-87 (IAS58/4/KAL/BB//CJ/3/ALD ''S''; CM50464-12Y-4M-1Y-1M-0Y)

Progress in Other Countries

CIMMYT assembles outstanding advanced lines emanating from this shuttle project into the Aluminum Tolerance Screening Nursery (ATSN) and is currently sending this nursery to 50 locations worldwide. Thus, outstanding lines for yield, aluminum toxicity tolerance, and agronomic type are fed back into the crossing program to further pyramid favorable genes into better cultivars.

The cooperative shuttle program and distribution of the resulting materials through the ATSN is beginning to provide benefits to other countries such as Madagascar, Zambia, Rwanda, Cameroon, and Ecuador. Shuttle breeding with these countries may commence in the near future as well.

The Future

The Cooperative shuttle program has provided tremendous benefits to the CIMMYT and Brazilian bread wheat breeding programs. CIMMYT and Brazilian scientists agree that the current cooperative effort should be continued and enlarged to place greater emphasis on some problems currently under investigation and to consider other problems as well. These problems include:

- Bacteria (*Xanthomonas* spp., *Pseudomonas* spp., etc.).
- Fusarium head scab.
- Barley Yellow Dwarf and other viruses, including vectors.
- Greenbug (*Schizaphis graminum*).
- Phosphorus uptake efficiency.
- Sprouting.
- Midterm drought and early heat stress.
- Maintaining the current level of tolerance to aluminum toxicity.
- Improving quality characteristics.

We see what has been accomplished through 1986 as Phase 1 of this cooperative program. We believe two more phases of 5 years duration each are needed to help solve the problems listed above. Phase 2 would emphasize the broadening of disease resistance. Phase 3 would emphasize increasing yield potential.

Acknowledgements

The authors are grateful to their colleagues in Brazil and Mexico for their participation in this project. We recognize there are many more scientists and technicians involved than the three authors of this article. We would like to acknowledge the excellent collaboration of IAPAR and OCEPAR in Paraná, CPAC in Brasilia, IAC in Sao Paulo, CIMMYT regional staff in the Southern Cone, and the staff of CIMMYT's aluminum laboratory at El Batan.

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Development of Superior Durum Wheat Germplasm—Altar 84

P. Brajcich, J.M. Prescott, T.C. Barker, A. Amaya C., and J.R. Peña B.[1]

The CIMMYT durum wheat improvement program has traditionally responded to the needs of national breeding programs and ultimately to farmers in cooperating countries by providing high yielding, stable, and widely adapted germplasm. Advances made in durum wheat improvement in Mexico demonstrate not only steady improvement in yield potential, good agronomic type, and disease resistance, but also steady improvement in yield stability and good industrial quality.

The pasta industry in Mexico basically uses bread wheats to make semolina-type products. However, in the early 1980s, the industry became interested in using durum wheats to improve the quality of its pasta products. At the same time, farmers were asking for higher yielding durum wheat cultivars. The cultivar Altar 84 was released in 1984 by the National Institute of Forestry, Agriculture and Animal Science Research (INIFAP) to meet the demands of industry and farmers.

Development and Attributes of Altar 84

Altar 84 was derived from the pedigree shown in Figure 4. The name "Altar" comes from a desert area in Sonora, Mexico, near Cd. Obregon where CIMMYT grows its spring nurseries during the winter-spring season.

The cultivar Altar 84, formerly known as the breeding line Gallareta"S", was derived from the cross RUFF"S"/FG"S"//MEXICALI 75 and SHEARWATER"S" made in 1976 (The "S" refers to a sister selection of a given breeding line such as Ruff). Between 1977 and 1980, plants from this cross were selected in segregating generations at Toluca station in the State of Mexico and Cd. Obregon, based on their disease resistance, plant type, high tillering capacity, spike fertility, good seed quality, and high semolina quality.

In preliminary yield tests at the CIANO station at Cd. Obregon in 1981, Gallareta"S" was found to be one of the highest yielding lines. This superior yield potential combined with other desirable traits, such as rust resistance and industrial quality, resulted in its inclusion in the International Durum Screening Nursery (IDSN), and ultimately in elite yield nurseries. This cultivar gave outstanding performance in the 16th International Durum Wheat Yield Nursery (IDYN) and 14th Elite Durum Yield Trial (EDYT), sent to more than 50 locations in 30 countries in 1983-84. In 1984, Gallareta"S" was released as Altar 84 in Mexico. It is currently being yield tested in Spain and Turkey.

Yield potential and adaptation—As shown in Figure 5, the yield potential of Altar 84 under the well watered conditions of CIMMYT's research site at Cd. Obregon is approximately 8.2 t/ha. Other locations where Altar 84 has had high yield, approaching 10 t/ha,

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include Guanajuato, Mexico; Cordoba, Spain; and La Platina, Chile. Under high-input experimental conditions, Altar 84 yielded up to 11 t/ha at Cd. Obregon.

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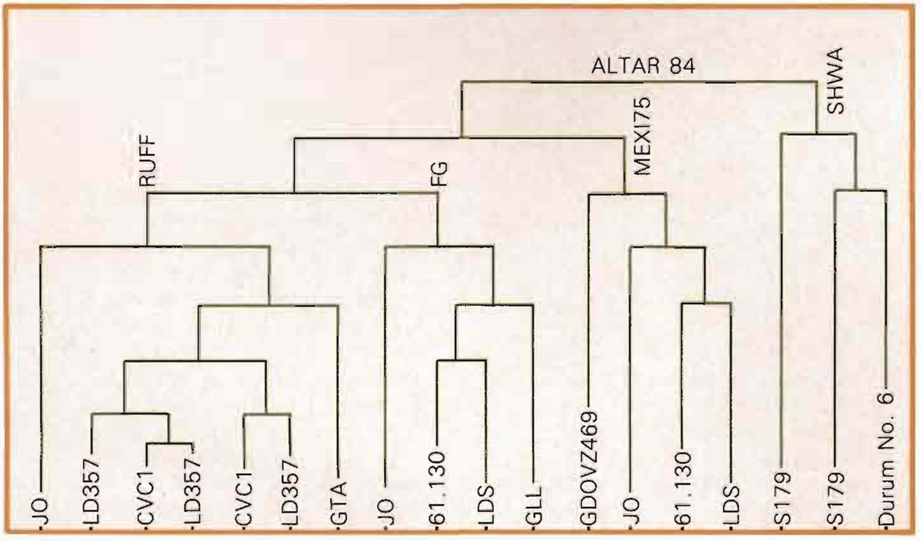

Figure 4. Altar 84 Pedigree.

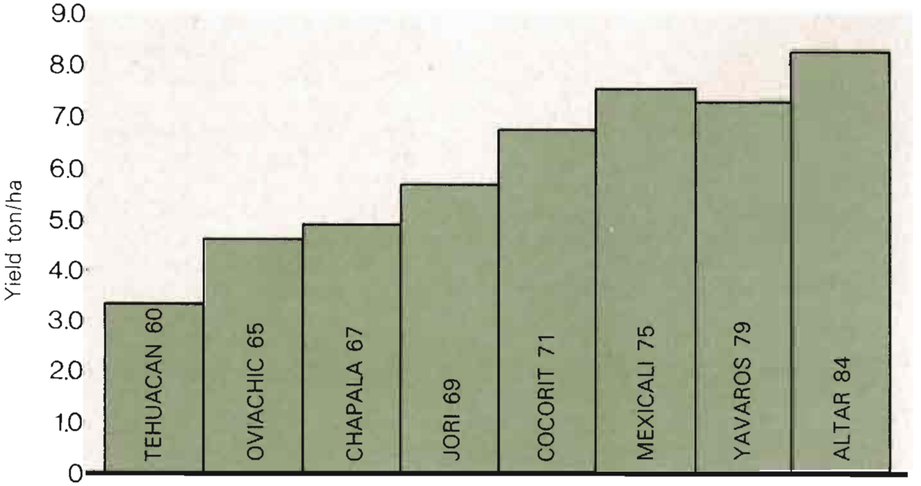

Figure 5. Yield potential of the durum wheat varieties released in Mexico from 1960 to 1984. Three-year means obtained from the Agronomy program in trials conducted at the CIANO station during the 1983-84, 1984-85, and 1985-86 crop cycles.

History of Durum Wheat Improvement at CIMMYT in Mexico

Twenty years ago when CIMMYT's durum wheat improvement program was established, major goals were to incorporate dwarfing genes, photoperiod insensitivity, enhanced spike fertility, and better disease resistance. These goals have all been accomplished. Today's breeding strategy requires developing high-yielding, management-responsive, and input-efficient germplasm that is broadly adapted, stable with good quality traits, and resistant to biotic and abiotic stresses.

In the late 1950s, the first crosses were made between tall durum wheats and wheats bread carrying the Rht1 and Rht2 dwarfing genes. Through intensive backcrossing of progenies to the tall durum wheats, it was possible to select semidwarf durum wheats.

To date, 10 improved durum wheat cultivars have been released in Mexico. The first of these, Tehuacan 60, was named and released by the National Agricultural Research Institute (INIA) in Mexico in 1960. It is a tall cultivar with a yield potential of about 3.3 t/ha (Figure 5). Oviachic 65 was the first semidwarf cultivar released in Mexico. As shown in Figure 5, it has a yield potential of about 4.6 t/ha, almost 40% higher than the yield of tall Tehuacan 60, released 5 years earlier.

By the late 1960s, many outstanding durum wheat advanced lines had been identified with yield potentials superior to that of Oviachic 65. In 1967, the year after CIMMYT was officially established, Mexico released three durum wheat cultivars: Chapala 67, Tehuacan 67, and Pabellon 67. These cultivars further raised the yield potential to about 4.9 t/ha.

1st IDYN

In 1969 an important event in the history of durum wheat improvement in Mexico and worldwide occurred. The International Durum Yield Nursery (IDYN) was assembled and distributed for the first time. The first IDYN consisted of 12 entries, from five countries, including four advanced semidwarf lines from CIMMYT. Inia 66, a semidwarf bread wheat cultivar known to be high yielding and widely adapted, was included as a check. The nursery was grown at 32 locations, most of which were in the durum wheat producing areas of North Africa and the Middle East.

Results of the 1st IDYN provided convincing evidence that the new semidwarf, daylength-insensitive durum wheats were quite widely adapted and demonstrated increased yield potential versus the tall, daylength-sensitive durum wheats grown by farmers at that time.

Another important event in 1969 was the release by Mexico of the cultivar Jori 69. The new semidwarf durum wheats were now showing that they could challenge and, at times, exceed the yields of the semidwarf bread wheats. For example, Jori 69 yielded 10% more than the bread wheat cultivar, Inia 66, in the 1st IDYN.

Advances during the 1970s

In 1971, a CIMMYT-developed durum wheat advanced line was named and released by Mexico as Cocorit 71. This was the first durum wheat cultivar released in which the linkage between sterility and the dwarfing genes was broken. This higher spike fertility increased the yield potential of the durum wheats to 6.7 t/ha (Figure 5), 1.0 t/ha higher than the yield of Jori 69. Both cultivars tended to be somewhat late in maturity and did not have an acceptable level of quality, but they had high yield potential and wide adaptation.

The maturity and quality problems of Jori 69 and Cocorit 71 were solved with the release of Mexicali 75 by Mexico in 1975. Its yield potential is 7.5 t/ha, an increase of 12.0% over Cocorit 71 (Figure 5). Mexicali 75 also matures 7 days earlier than Cocorit 71 and it has good quality for semolina products.

There was a need in some areas for a medium-maturing, high-yielding, semidwarf durum wheat cultivar, so the national program of Mexico named and released Yavaros 79 in 1979. This cultivar is similar to Mexicali 75 in yield potential and with acceptable quality, but slightly later in maturity (similar to Cocorit 71). Yavaros 79 has proven to be widely adapted and highly stable in terms of yield potential across environments and years. Thus Yavaros 79 is currently used as the long-term durum check in CIMMYT's international nurseries.

By the time Yavaros 79 was released, the development of Altar 84 was already in process.

Farmer's field of Altar 84 in the Yaqui Valley in northwestern Mexico.

More important to local breeders, and ultimately farmers, is the relative performance of a given line vs. other lines tested at a particular location To evaluate the relative yield potential of Altar 84, we graphed the mean yield of Altar 84 vs the mean yield of each other entry of the 14th EDYT, 16th IDYN, and the 1st National Durum Wheat Yield Trial, Mexico (ENTDUR)

For example, Figure 6 shows the yields of Altar 84 plotted against the yields of Yavaros 79 for each location of the 16th IDYN Each point on the graph represents the yield of Altar 84 vs. the yield of Yavaros 79 at a specific site. The yield equality line shows where the points would fall if the yield of Altar 84 exactly equaled the yield of Yavaros 79 at each site Thus, points lying above the equality line indicate Altar 84 to be higher yielding, and points below the line indicate Yavaros 79 superiority

The number of sites where Altar 84 was clearly superior (as shown in the example of Figure 6) to the compared entry (i.e , Altar 84 against entry 1, 2, 3,...30) is tabulated in Table 2 Points falling on the line were assessed in favor of the compared entry such as Yavaros 79 When analyzed over all locations, 67% of the 1st ENTDUR, 71% of the 16th IDYN, and 56% of the 14th EDYT favored Altar 84 In other words, breeders evaluating these nurseries would have selected Altar 84 as superior yielding in 64% of the comparisons against competing entries. These competing entries included the best CIMMYT advanced lines and durum wheat entries from cooperating breeders as well as a local durum wheat

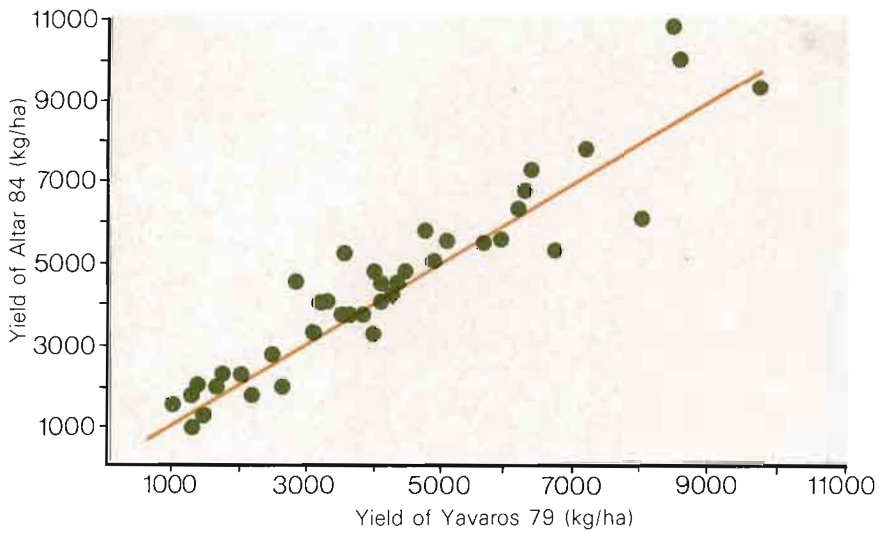

Figure 6. Relative yield of Altar 84 vs. Yavaros 79 across all locations of the 16th IDYN.

check and bread wheat and triticale checks (Seri 82 and Alamos 84, respectively). Thus, the yield potential of Altar 84 is clearly high in many environments, and compares well with many newer CIMMYT advanced lines as well as cultivars entered from cooperating breeders and check cultivars.

An alternative means of assessing yield potential and adaptability of genotypes across environments is the "stability analysis" model developed by Eberhart and Russell (1). Fifty-two locations of the 16th IDYN and the 14th EDYT were classified as stress or nonstress environments according to 4-year

Table 2. Number of sites where Altar 84 was clearly superior to the compared entry in 1st ENTDUR, 16th IDYN, and the 14th EDYT

Entry	14 sites 1st ENTDUR	40 sites 16th IDYN	39 sites 14th EDYT
1	14	25	23
2	12	28	19
3	11	33	26
4	9	23	19
5	13	29	16
6	10	31	19
7	11	31	17
8	10	26	17
9	6	33	17
10	6	39	24
11	12	38	21
12	8	32	26
13	11	36	23
14	11	33	20
15	5	34	21
16	8	28	27
17	8	33	24
18	7	28	29
19	8	32	23
20	9	28	22
21	9	25	24
22	8	18	30
23	9	20	20
24	11	23	21
25	9	30	28
26	5	26	27
27	—	—	—
28	11	16	14
29	12	26	18
30	10	21	18
Total	273/406 = 67.2%	825/1160 = 71.1%	633/1131 = 56.0%

mean rainfall averages recorded in CIMMYT international nursery reports. The 34 stress environments received less than 400 mm of rainfall during the growing season and the 18 nonstress locations received 400 mm or more of precipitation during the growing season or were under irrigation.

The results of performing Eberhart and Russell's stability analysis on Altar 84 across all environments, across the nonstress environments, and across the stress environments are summarized in Table 3. The symbols $\hat{b}$ and S_d^2 denote the slope of the regression line and the sum of the square deviations from the regression line, respectively. $\hat{b}$ is the slope of the regression line of Altar 84 mean yields over the site mean yields (Fig. 7). S_d^2 is a measure of the dispersion of the actual data points around the estimated regression line. The mean yield of Altar 84 at a given site is the average yield from three replicated plots. The site mean yield is the overall average of all cultivars entered in the trial at that site (excluding the local check variety which changes among sites) For example, in Figure 7 the upper line ($\hat{b}$ = 1.25) is the regression of Altar 84 yield vs. the site mean yield of all entries. This slope represents the yield response performance of Altar 84 across all environments. The line through the origin with a slope equal to 1.00 is a hypothetical line of equality between Altar 84 and the site mean.

In the analysis of Figure 7, the slope is equal to 1.25, which is significantly greater than 1 (unit slope). If the scatter of points about the regression line is small enough to be considered stable, such as for the 14th EDYT nonstress analysis in Table 3, it is denoted by "S". The S_d^2 value in Figure 7, however, is 0.53 which is statistically greater than zero, indicating "instability" of yield according to Eberhart and Russell. However, a common criticism of the linear regression methods of studying yield stability is the fact that a few extreme data points may greatly affect stability parameters (2). For example, by removing the four data points in Figure 7 which lie well above the regression line, the subsequent

Table 3. Performance of Altar 84 across all environments in the 14th EDYT and the 16th IDYN. Graph of overall site analysis shown in Figure 7

	Over all sites				
	$\bar{X}$	$\bar{X}_A$	$\hat{b}$	S_d^2	Stability
14th EDYT	4526	4811	1.01	0.35**	H
16th IDYN	4077	4840	1.25*	0.53**	H

X Environment mean yield (kg/ha).
X_A Mean yield of Altar 84 (kg/ha).
* Statistically significant at the 0.05 level of probability.

analysis showed a slope statistically equal to 1.00 and was classified as stable in the overall analysis, nonstress analysis, and stress analysis. Inspecting the position of deviations from regression in Figure 7, it becomes apparent that the large deviations (in the areas of 3000 and 7500 kg/ha site mean yield) are toward higher yield of Altar 84. We have designated this type of deviation "H" in Table 3, for deviations on the high yield side of 1 (unit slope), to differentiate deviations in favor of high yield (which is desirable and an indication of good adaptation) from deviations toward low yield (which is undesirable and an indication of poor adaptation). If Altar 84 had been eliminated as an "unstable" line, ignoring the fact that four high-yield points heavily influenced the deviation from regression

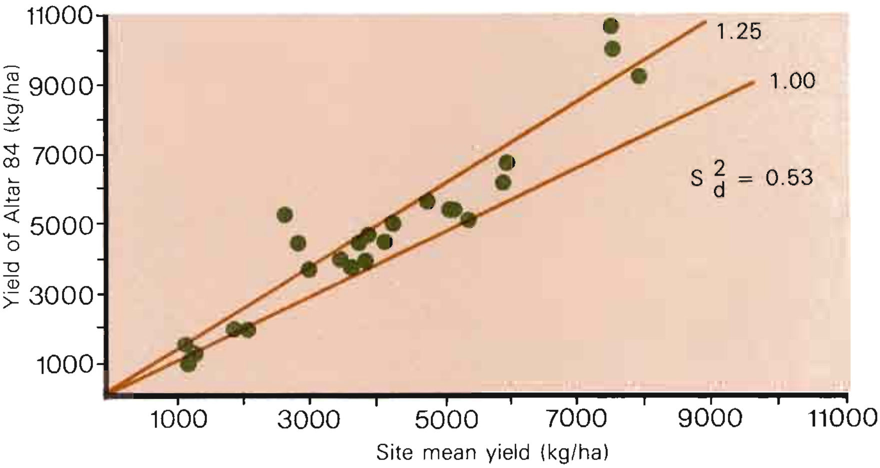

Figure 7. Regression of Altar 84 mean yields over site mean yields for all locations of the 16th IDYN.

Nonstress					Stress				
$\bar{X}$	$\bar{X}_A$	$\hat{b}$	S_d^2	Stability	$\bar{X}$	$\bar{X}_A$	$\hat{b}$	S_d^2	Stability
6112	6319	1.06	0.09	S	3200	3620	1.10	0.73**	H
5388	6424	1.38*	0.44**	H	2866	3382	1.14	0.73**	H

** Statistically significant at the 0.01 level of probability.
Note: For explanation of $\hat{b}$, S_d^2, S, and H, see text.

parameter, we would have eliminated a cultivar which showed 4- to 5-t yield potential in a 2.5-t mean yield environment and 10-t yield potential in a 7.5-t mean yield environment. Furthermore, stability analysis by the Westcott Method (2) showed Altar 84 to be stable in all environments. Thus, broad adaptation, in terms of high yield potential and ability to respond to improved management for Altar 84, is evident in both stress and nonstress environments as shown in Table 3.

Disease resistance—Compared to its predecessors in Mexico, such as Mexicali 75 and Yavaros 79, Altar 84 has excellent resistance to the major rust diseases. As shown in Table 4, the level of resistance in Altar 84, as measured by the average coefficient of infection and the average foliar index, is usually equal to or better than that of Yavaros 79 and Mexicali 75 for the three rusts as well as for head scab, septoria tritici blotch and septoria nodorum blotch, leaf spot, bacterial leaf stripe, and barley yellow dwarf. These data represent

Table 4. Summary of Disease Data from 16th IDYN

Variety	Stripe Rust Leaf[a]	Stripe Rust Head[a]	Leaf Rust[a]	Stem Rust[a]
Altar 84	2.0	8.0	2.0	18.0
Yavaros 79	6.0	23.0	15.0	22.0
Mexicali 75	8.0	3.0	40.0	15.0
Nursery Mean	7.2	12.3	23.1	24.3
No. of observations for each variable	15	5	7	13

a ACI (Average Coefficient of Infection).
b AFI (Average Foliar Index).

Table 5. Industrial quality of durum wheat cultivars Altar 84, Yavaros 79 and Mexicali 75

Variety	Test weight (kg/hl)	1000-grain weight (g)	Yellow Berry (%)	Semolina yield (%)	Semolina protein (%)
Altar 84	84.4	50.07	3.0	57.5	10.3
Yavaros 79	82.4	54.87	2.9	57.5	9.9
Mexicali 75	81.1	56.84	2.8	57.5	10.1

a Residual, solids in water used to cook spaghetti (% based on uncooked spaghetti).
b R = regular; G = good.
c A scale of 1-10, where 1 is the lowest quality and 10 is the highest.

a wide range of environments and pathogen virulence and support the information available from artificially inoculated experiments conducted in Mexico prior to release by the national program.

Quality—One of the primary reasons for the release of Altar 84 in Mexico, and its consideration for release in other countries, is its excellent industrial quality. Grain samples of Mexicali 75, Yavaros 79, and Altar 84 grown in Sonora, Mexico, in 1985-86 were compared for quality characteristics. Overall, Altar 84 was found to combine better quality attributes than the other two cultivars. The results are shown in Table 5.

Altar 84 has a higher test weight and lower 1000-grain weight than Mexicali 75 and Yavaros 79. The higher test weight of Altar 84 is due to its smaller grains. The presence of yellow berry in durum wheat, which increases the percentage of grains with starchy areas and subsequently decreases semolina yield, can lower milling quality. However, this appears to be a

Scab %	Powdery Mildew[b]	*Septoria tritici* [b]	*Septoria nodorum*[b]	*Helm.* spp.[b]	Bacterial Stripe[b]	BYDV[b]
40.0	2.0	5.0	4.0	2.0	5.0	2.0
70.0	4.0	3.0	3.0	2.0	4.0	4.0
70.0	2.0	6.0	4.0	4.0	6.0	3.0
62.7	3.3	4.1	2.9	3.5	4.8	3.8
1	10	10	3	3	3	8

Pigments (ppm)			Sedimentation SDS(cc)		Cooking quality		
Grain	Semolina	Pasta	Grain	Semolina	Solids[a] (%)	Consistency[b]	Grade[c]
5.9	6.0	4.8	9.5	8.0	6.8	G	8
5.6	5.4	4.1	8.0	7.5	6.8	G	8
5.9	6.6	5.6	9.0	7.0	6.5	R	6

minor problem for these three cultivars as their yellow berry percentage (Table 5) is quite low. The three cultivars showed similar semolina milling potential, under the experimental milling conditions used. However, it is likely that in commercial milling, Altar 84 could be slightly better since it has more rounded grains which make it easier to separate the bran from the endosperm resulting in a greater semolina yield. Spaghetti from Mexicali 75 showed some surface stickiness and therefore its quality was estimated as only fair. Altar 84 and Yavaros 79 have good spaghetti cooking characteristics.

Future of Durum Wheat in Mexico

Land area devoted to the production of durum wheat is increasing in Mexico, and the production of Altar 84 in such areas as the Yaqui Valley of northwestern Mexico is growing at a tremendous rate. Part of the increased planting in this region is due to durum wheat's inherent resistance to the disease Karnal bunt which is a problem with local bread wheat cultivars. While this increase is a sign of success for the Mexican and CIMMYT cooperative durum research programs, the breeders are aware that large-scale planting of a single genotype can result in genetic vulnerability caused by pathogens. In response, the CIMMYT durum wheat program is producing many advanced lines with even better quality than Altar 84, and with different genetic backgrounds.

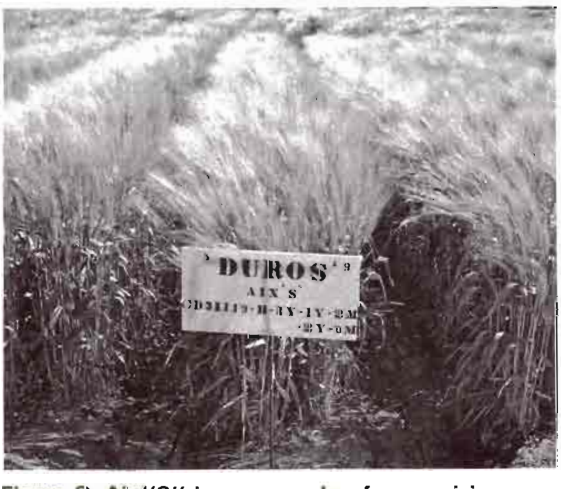

Figure 8. Aix''S'' is an example of a promising advanced line under consideration for release in Mexico that, like Altar 84, has superior yield potential, wide adaptation, good disease resistance, and acceptable industrial quality.

Four promising advanced lines under consideration for release in Mexico are Aix''S'' (Figure 8), CARC''S''/AUK''S'', CHEN''S''/ALTAR 84, and FG''S''/ATO''S''//HUI''S''/3/ROK ''S''. Like Altar 84, these advanced lines have superior yield potential, wide adaptation, good disease resistance, and acceptable industrial quality.

Soon farmers in Mexico and other countries will have a number of durum wheat cultivars to choose from that will enable them to supply a high quality product that will meet the standards of their countries' pasta industries.

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Rotation of Wheat and *Medicago* spp. in Chile's Secano Interior

M.A. McMahon and P. del Canto S.[1]

Most of Chile's wheat is produced under rainfed conditions. One of the rainfed areas is known locally as the Secano Interior. Historically, this area was an important wheat producer, but it is now regarded as a depressed region compared to other regions of the country. This is generally believed to be due to a lack of adequate crop production technology.

The Secano Interior is very similar to other subsistence farming areas of the world. It has infertile soils, poorly distributed rainfall, resource-poor farmers, and a lack of applied research. However, a well focused research program replicated over a 4-year period has produced results that can be transferred directly to Chilean farmers and put into practice by them

In the wheat-*Medicago* spp. (medic) rotation study discussed in this article, the research program was carried out by personnel from both the Chilean National Institute of Agricultural Research (INIA) and CIMMYT The work started with the gathering of information from farmers and with a crop survey. When the information was analyzed and the limiting factors determined, the apparent relevant data from the station research programs were analyzed to design the trials aimed at alleviating these limiting factors. A flow of information between farmers and researchers was maintained all through the project duration. As time went on, new problems were diagnosed (such as sulfur and potassium deficiencies) and addressed; this is a continuous process of field experimentation. As technology adoption and pasture and wheat yields increase, new problems will be identified and dealt with.

This article summarizes research replicated over 4 years on the rotation of wheat with a legume forage plant (*Medicago* spp.) conducted by INIA and CIMMYT. The Information was generated in the southern part of the Secano Interior (Figure 9).

Description of the Secano Interior

This area, located on the eastern side of the coastal mountain range, has no maritime influence (Figure 9). Within Regions VII and VIII, there are 158,855 ha (15% of the Secano interior's total area) that are suitable for wheat production.

The soils range from slightly sloping to slopes of more than 20%. They are derived from granite with topsoils of sandy clay loams while the subsoils are sandy clays. Due to generations of cultivation and poor management, most of the area is highly eroded with a subsequent loss of soil fertility. Soil analyses show NO_3-N levels to range from 2 to 8 ppm, Bray 1 p from 3 to 5 ppm, and exchangeable potassium from 40 to 120 ppm. Organic matter fluctuates between 1 and 2%, depending on the cropping intensity; pH is generally in the range of 5.8 to 6.0.

The area has a Mediterranean-type climate. Seventy to eighty percent of the rainfall (560 mm) occurs

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between May and August. The coldest months are June and July with average temperatures of 8 to 9°C. Occasional frosts occur. The hottest months have average temperatures of 20 to 21°C. The October-April period is dry and soil moisture reserves are inadequate for plant growth (Figure 10).

The present natural vegetation consists of a brush layer where the species *Acacia caven* dominates and a lower layer composed mainly of grasses and legumes.

Cropping in this area involves a very low level of technology and actual yields are far below their potential. Present wheat yields fluctuate between 500 and 700 kg/ha. The higher yields are usually obtained when spring rainfall is high. Cattle production is entirely based on natural pastures of extremely low quality and are normally overgrazed. These pastures are rotated with wheat and grain legumes. These crops are generally unfertilized and cultivation leads to further degradation of the soil resource.

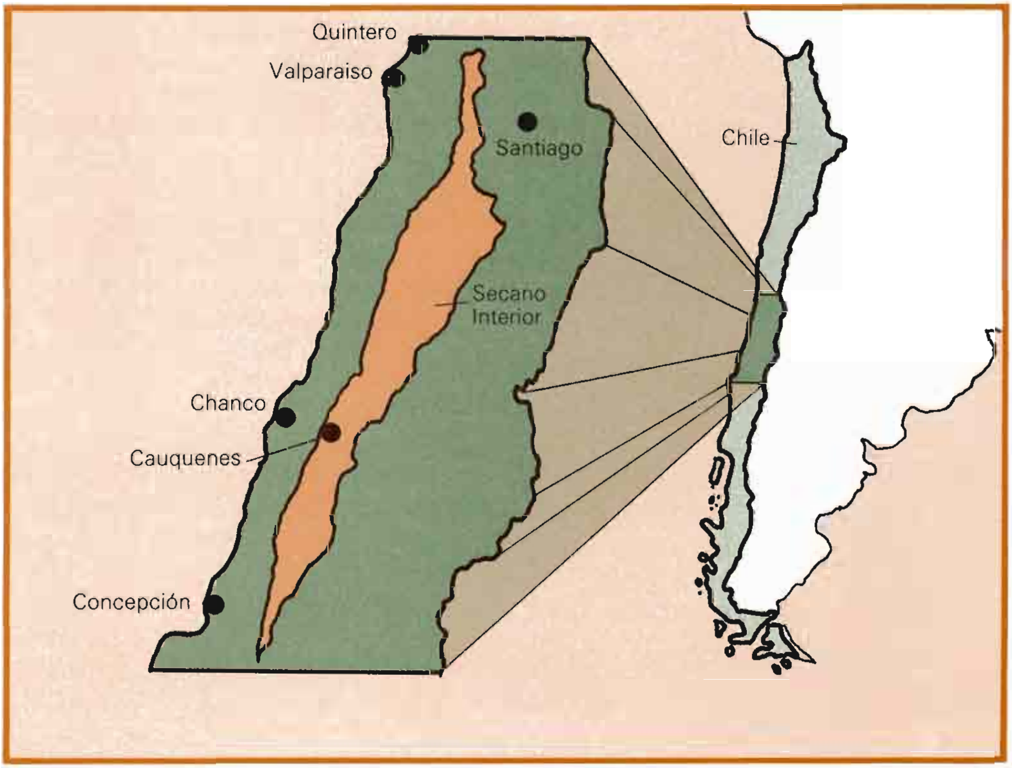

Figure 9. Secano Interior, Chile.

Traditional Pasture-Wheat System

The traditional rotational system of native pasture and wheat has been practiced for generations in the area. The productivity of this system has deteriorated due to overgrazing and the exhaustion of soil fertility through unfertilized cropping. The best pastures are found where an association of brush (*Acacia caven*) and grass have been maintained As can be seen in Table 6, native pasture without fertilization yields an extremely low 1.4 t of dry matter/ha. Fertilization raises production to 2.4 t of dry matter/ha. However, not even these production levels are common in the area and the brush layer is normally absent due to wheat cultivation.

In pastures that are established after wheat, dry matter production is very low but increases with time after the wheat crop. For example, in the first year after wheat there is little or no pasture production. Production reaches its maximum about 15 years after wheat cultivation. These low production levels can be seen in Table 6, where a successional pasture without fertilizer yielded only 0.9 t/ha of dry matter; fertilization increased yield to only 1.8 t/ha.

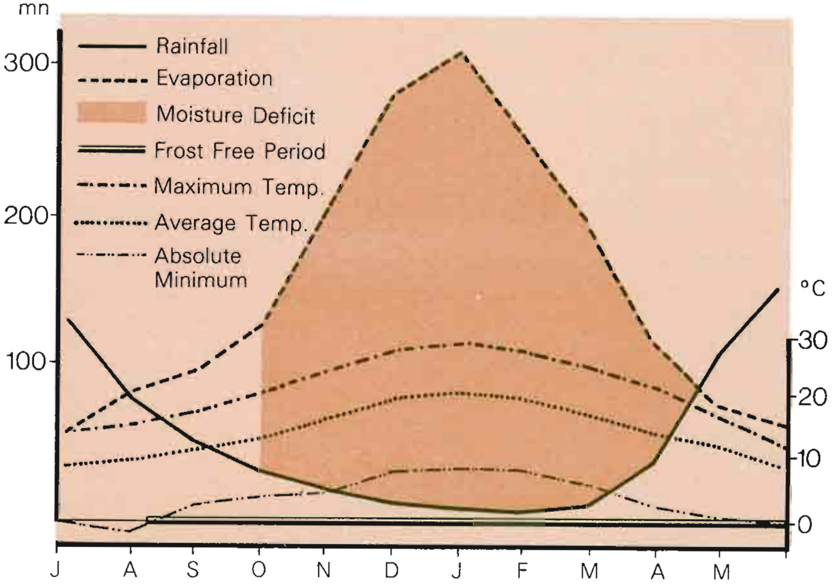

Figure 10. Climodiagram, Cauquenes, Chile (25 years).

Medicago Spp. in Chile

The legume forage plants, *Medicago* spp. (medic), are native to the Mediterranean basin and were probably brought to Chile as forage by the early Spanish colonizers. Today, there are at least two naturalized species in Chile. *Medicago arabica* and *Medicago polimorpha*. They are found from Quintero to Chanco on the coastal terraces and also in the Secano Interior. *M. arabica* is mostly found on the coastal terraces. These species have disappeared from most fields due to deep plowing, but they can be easily seen along roadsides, and in orchards and vineyards where fertility is adequate. Research results indicate that well managed medics in rotation with wheat in this area will increase wheat and meat production by increasing soil fertility and water holding capacity of the soil, reducing weed populations, and controlling erosion.

Wheat-Medic Rotational System

Because of the low productivity of the traditional system, INIA and CIMMYT have been working on a wheat-medicago rotation system for the area. Basically in the cropping pattern, a farmer grows wheat 1 year in a field and then medic the next. In any given year, half the farmer's land is in wheat and the other half in medic. However, there can be many variations to this basic pattern. For example, there can be several years of medic pasture to 1 year of wheat on a specific site. If there is a sufficient amount of medic seed reserve in the soil, wheat can be grown more than 1 year in succession. Cereal legumes such as lentils and chickpeas can also be inserted into the rotation.

The crop year begins in autumn (April-May in Chile) when the first rains come. The land that was previously in medic is sown to wheat while on the land that was in

Table 6. Dry matter yield of different pastures in the Secano Interior[a]

Pasture	Yield without[b] fertilizer (t/ha)	Fertilization (kg N-P-K/ha)	Yield[b] (t/ha)
Phalaris	2.1	50- 75-50-S-B[c]	3.0
Subterranean Clover	2.0	32-100-50-S-B	3.3
Phalaris + Subterranean Clover + Ryegrass	2.9	32-100-50-S-B	2.9
Successional	0.9	90- 75- 0	1.8
Native	1.4	50- 75- 0	2.4

[a] Source: Contreras, D.: Caviedes, E.; Ovalle, C.; Informe Técnico Area de Producción Animal, E.E. Quilamapu.
[b] Average values over 5 years (1979-1983).
[c] Sulfur (S) and Boron (B) in trace amounts.

wheat the previous year phosphorus is broadcast. This is an important step because the applied phosphorus stimulates the medic growth and assures adequate ground coverage. During the year, the medic is grazed and may be eventually cut for hay. In any case, the medic is grazed or cut close to the ground before the next season.

There are a number of key management tools that have to be used to ensure the success of the system:

Hard seed—The hard seed of the medic is the key to the whole system. Medic varieties must produce a high proportion of viable seeds that are dormant for long periods. Fortunately, this is a characteristic of the species naturalized to Chile. The impermeable seed coat becomes permeable to moisture through the action of daily temperature changes throughout the year. These temperature changes cause the seed coat to expand and contract until it cracks exposing the embryo to the moisture necessary for germination.

Most of the seeds from a medic crop must remain "hard" from the time they are shed in the spring, through the long, hot and dry summer, through the next wheat crop and another summer, to the following autumn when the rotation enters into its pasture phase. The perfect situation would be if 85 to 90% of the seed has that degree of "hardness."

Phosphorus—The application of phosphorus throughout the rotation is another key element. This is especially true in the Secano Interior of Chile where soil phosphorus levels are low. Without an adequate phosphorus level in the soil, medic will not be aggressive and will lose its dominance as a species in the pasture phase. The application of 30 to 40 kg P_2O_5/ha each year on both medic and wheat is currently recommended.

Shallow tillage—Deep tillage is the greatest enemy of medic. If the seed is buried too deeply then it is lost to the system. This is the main reason in Chile for the low population of medic in natural pastures. Tillage for wheat should be no deeper than 8 to 10 cm and should be done in the autumn after the first rains. Because the medic improves soil structure and the tillage is shallow, the land can be prepared faster.

Grazing—It is difficult to give blanket recommendations for grazing because management of this factor depends to a great extent on the weather of a particular year. However, some general principles must be observed:

- During the establishment year, grazing should be reduced during flowering. If it is not, seed set will be reduced. Once the pods have formed and begin falling on the ground, grazing causes no problem.

- The wheat stubble should be grazed very closely to the ground.

- Early-season grazing of medic will eliminate weeds and leave the medic without competition.

- With proper stocking rates, medic pastures will produce more forage during the peak season than the animals can eat. Hay can then be cut and can be used when there is little medic to be grazed.

Results of the Study

The rotation of wheat and medic was started in 1983 at Cauquenes (Figure 9). The site selected for this trial was a degraded pasture that has medic (*M. polimorpha*) as a constituent. A rotation of 4 years was planned (3 years of medic and 1 year of wheat). The 4-ha area was divided into four 1-ha treatment plots. The first plot was sown with wheat during the autumn of 1983 and the other three plots were sown with wheat in the autumns of 1984, 1985, and 1986 respectively. The annual fertilization of the medic pasture was 36 kg P_2O_5/ha. Wheat was fertilized at the rate of 30-36-20 kg N-P-K/ha. A summary of the results is presented in Figure 11.

In the first year (1983-84) of the experiment, the wheat cultivar Lucero sown after the degraded pasture yielded 3.50 t/ha. The degraded medic fertilized with 36 kg P_2O_5/ha yielded 4 t dry matter/ha, far more than the best natural or artificial pastures recommended for the area as shown in Table 6.

In 1984-85 the wheat cultivar Onda yielded 4.50 t/ha, while the renovated (first year after wheat) medic pasture yielded 5.16 t/ha of dry matter (Figure 11). In 1985-86 Onda yielded 3.60 t/ha, while the renovated medic pasture (first year after wheat) yielded 5.24 t/ha. The second-year medic also maintained high levels of dry matter production at 5.33 t/ha. In 1986-87 when the cycle was completed, first-year

Plot	1983	1984	1985	1986
1	Wheat[a] 3.50 T/ha	Medic 1st Year 5.16 T/ha	Medic 2nd Year 5.33 T/ha	Medic 3rd Year 5.10 T/ha
2	Medic 4.00 T/ha	Wheat[b] 4.50 T/ha	Medic 1st Year 5.24 T/ha	Medic 2nd Year 6.90 T/ha
3	Medic 4.00 T/ha	Medic[c]	Wheat[b] 3.60 T/ha	Medic 1st Year 6.05 T/ha
4	Medic 4.00 T/ha	Medic[c]	Medic[c]	Wheat[b,d] 2.20 T/ha

a Cultivar Lucero. c No yield data.
b Cultivar Onda. d Yield low due to late planting.

Figure 11. Wheat-medic rotation, Cauquenes, Secano Interior, 1983-86.

medic yielded 6.05 t/ha, second-year medic, 6.90 t/ha; and third-year medic 5.10 t/ha. The wheat cultivar Onda yielded a low 2.20 t/ha due to late planting.

As can be seen from these data, improved medic pastures over the 4 years yielded an average of 5.63 t/ha of dry matter, far above the typical pasture of the area as shown in Table 6. Wheat averaged 3.45 t/ha.

Conclusion

This 4-year project has shown that a highly productive new system can be introduced into a resource-poor area and made to function. Some farmers in the area have already adopted the system

The INIA has already initiated further research on the pasture side of the system. Because this system will lead to higher soil fertility, new high-yielding wheat cultivars will also be an important system component. This has already become obvious to area farmers and they have notably increased their adoption of high-yielding wheat cutivars over the past 4 years.

The total success of this system will depend on its integrated management. High yielding, disease-resistant wheat cultivars coupled with adequate fertilization and proper management of the pasture phase are the keys to success. On-going research on these aspects will be the basis for this management. This system promises to be highly productive and at the same time will contribute to the sustainability of production in this resource-poor area.

Medic pasture after wheat, Cauquenes, Chile, 1984. Such pastures produce dry matter in quantities far above those of the traditional, unimproved pastures.

Crop Management Research

In cooperation with colleagues from national programs, CIMMYT agronomists and economists focus much of their attention on issues related to technology generation in maize and wheat production. They participate in collaborative work to develop and demonstrate procedures for on-farm research (OFR), in addition to offering training in those procedures and providing advisory services at the national program level. Responsibility for the actual research lies with the collaborating national programs.

Over the past decade, the collective experience of CIMMYT and national program staff in OFR has been valuable in formulating a comprehensive set of research procedures that may be used in widely varying situations. That methodology, its application, and its results in two distinct study areas are presented in this year's *Research Highlights*.

Larry Harrington, CIMMYT outreach economist based in Southeast Asia, with colleagues in the Indonesian national program and cooperators from the Netherlands, describes the early stages of developing and testing recommendations for farmers in East Java. Rob Tripp, acting director of the CIMMYT Economics Program, Michael Read, outreach staffer for the CIMMYT Maize Program's bilateral program in Ghana, and colleagues in the Ghanaian national program focus on a later stage in the research process in their article about the adoption of recommended maize production practices in Ghana's Brong-Ahafo region.

Both articles emphasize that OFR is not a linear, assembly-line process that moves from start to finish with mechanical assurance. Instead, the authors show how the planning of each stage in OFR is influenced by a careful consideration of farmers' needs and interests, by possible changes in farmers' circumstances, as well as by experimental results. The results obtained by the OFR teams in East Java and Brong-Ahafo certainly demonstrate the practicability of the research methods. But even more important, they emphasize the inherent advantages of strong cooperation among researchers, farmers, and extension agents working to improve the productivity of small-scale farmers.

Maize Production Research in East Java, Indonesia

M. Dahlan, Heriyanto, Sunarsedyono, S. Wahyuni, C.E. Van Santen, J.Ph. Van Staveren, and L.W. Harrington[1]

Indonesia's leading province with respect to maize production is East Java, where annual production is around 1.5 million tons, or about 40% of the national total. About 70% of the maize grown in East Java is used for direct human consumption, and for many farm families it is a major staple food that is more important than rice.

The crop is typically grown on very small farms of less than 1 ha on a variety of land types, both irrigated and rainfed It is grown on the slopes of volcanoes, in paddy fields after rice, and on limestone hills in the southern part of the province. Although it is occasionally monocropped, maize is more commonly grown in complex cropping patterns that may also include cassava, upland rice, soybean, and peanut.

Continued growth in the productivity of resources devoted to maize production is essential for four reasons:

- To provide food for the expanding rural population.
- To meet rapidly growing demand for maize as livestock feed
- To increase farmers' incomes and, indirectly, contribute to rural development.
- To free scarce land and other resources for alternative uses.

In view of these needs, the Malang Agricultural Research Institute for Food Crops (MARIF)—which has primary responsibility for research on *palawija* crops (nonrice food crops), including maize—and the CIMMYT Economics and Maize Programs initiated an on-farm research (OFR) program in January 1984 (1). Another cooperator in this venture is the ATA-272 project (Agricultural Technical Cooperation between Indonesia and the Netherlands).

The OFR program started with two major objectives. The first was to try OFR procedures and ascertain their proper role in MARIF's activities. The second was to develop recommendations that could be rapidly adopted by farmers in a single study area.

The OFR Study, Malang District

The program's activities were initially restricted to one study area in Malang District, East Java, where crop production systems are heavily influenced by land type, soil type, and elevation (Table 1) *Sawah* fields are bunded wetlands with rice-based cropping systems, in which *palawija* crops are generally grown after rice. *Tegal* fields are rainfed, unbunded fields used for the bulk of *palawija* production.

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1 Marsum Dahlan, Heriyanto, Sunarsedyono, and Sri Wahyuni are connected with the Malang Research Institute for Food Crops, Malang, Indonesia. C.E. Van Santen and J.Ph. Van Staveren are technical cooperators from the Netherlands. Larry W. Harrington is a Thailand-based economist for the CIMMYT Economics Program.

Because it represented a relatively simple production system, the *tegal* system practiced on young volcanic soil (Table 1) was chosen to define the first OFR study area. The area covers 30,000 ha (5%) physical area in Malang or roughly 60,000 ha of annual harvested area (since two crops are grown), and includes an estimated 40,000 farms, each operating around 0.8 ha of *tegal* farmland (Figure 1). The average annual rainfall is 2130 mm, with 5 to 6 wet months (over 200 mm rainfall/month) and 2 to 4 dry months (less than 100 mm rainfall/month). The most common cropping pattern in the study area is maize-maize, though some farmers grow upland rice-maize.

Farmers' Practices

Production practices in the study area are fairly intensive (Table 2), yet maize grain yields are often lower than 2 t/ha Maize fields are usually plowed two to four times, using cattle for draft power, and then harrowed and leveled The rainy season maize crop is planted between September and November, depending on the onset of the rains, and harvested in December-February. Farmers normally like to plant the post-rainy season crop immediately afterwards, but excess rain frequently forces some to delay planting up to several weeks. About half of the farmers in the study area grow upland rice as the rainy season crop and tend to plant post-rainy season maize even later.

Table 1. Major crop production systems, Malang District

System no.	Land type	Soils	Dominant crops	Elevation (+ m)	Physical area (%)
1	*Tegal*	Limestone	Maize, cassava, grain-legumes	<600	43
2	*Tegal*	Young volcanic	Maize, upland rice	400-700	37
3	*Sawah*	Alluvial and young volcanic	Transplanted rice, maize	400-700	15
4	*Tegal*	Young volcanic and volcanic ash	Maize and horticultural crops	400-1500	5

Relatively few farmers (23%) use such recently released improved varieties as Arjuna; 48% use traditional, unimproved varieties, and the remainder use older improved varieties such as Harapan. A very small number are trying commercial hybrids. Farmers indicated that yield and tolerance to insect damage and lodging are important considerations in selecting maize varieties.

Maize is grown at extraordinarily high densities, with initial plant stands of around 150,000 plants/ha for unimproved varieties and 105,000-110,000 plants/ha for improved materials. Most farmers manipulate their plant stands by continuously removing spindly, weak, diseased, or damaged plants. At harvest, densities are often lower than 40,000 plants/ha.

The maize fields in the study area are rarely weedy, as might be expected with very small farms. Apart from the weed control they gain through intensive tillage, farmers normally conduct two additional weedings in each crop cycle.

Virtually all farmers in the study area use nitrogen fertilizer (urea). The average dose is over 160 kg

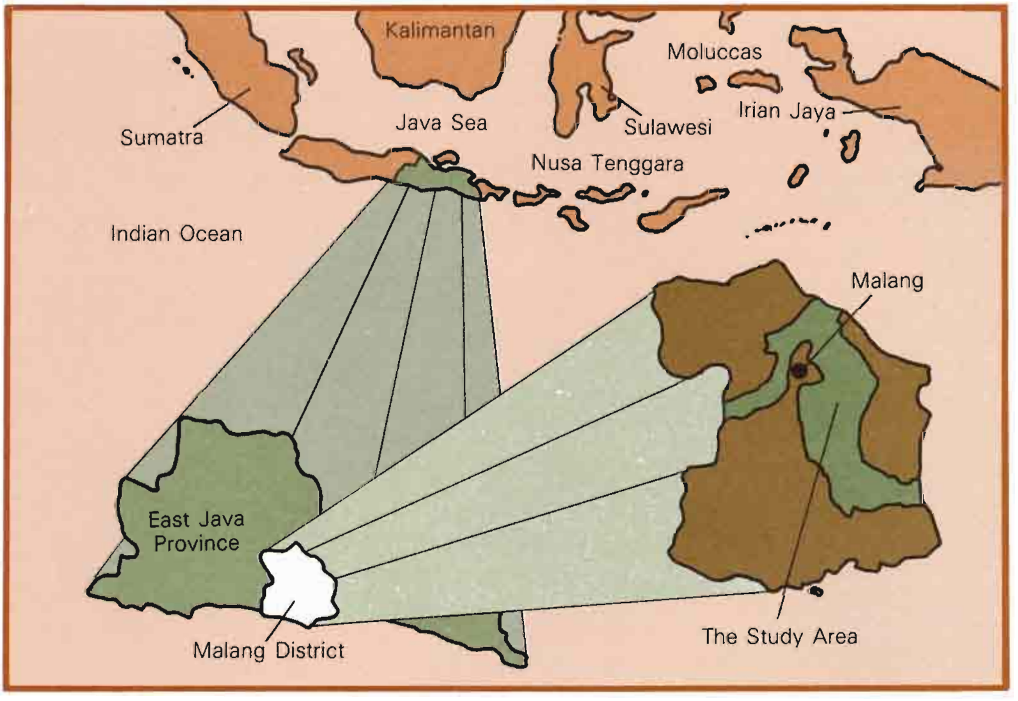

Figure 1. Map of Indonesia and East Java.

N/ha, split in two applications that coincide with the first and second weedings. Few farmers apply more than an insignificant amount of nitrogen at planting, and few apply phosphorus or potassium. The high nitrogen doses are a consequence of urea's ready availability and very low (i.e., highly subsidized) farm-level price.

It should be noted that rainy season maize (October planting) and post-rainy season maize (February planting) are managed in very similar ways. The major exceptions to this rule are that 1) land preparation is usually more intensive for the rainy season crop, and 2) manure, when applied, is normally spread before plowing for the rainy season crop. Throughout the study area, the rainy season crop is planted by most farmers at about the same time, with the onset of the first rains. However, planting time for the post-rainy season crop is much more variable, and may extend over a period of 6 weeks between early and late plantings.

Table 2. Maize production practices in the study area

Percentage of farmers that	
Plant traditional, unimproved varieties	48
Plant older improved varieties	29
Plant new improved varieties	23
Use self-supplied seed	75
Take out bad plants	83
Applied manure last season	57
Applied nitrogen	100
Apply phosphate (only in specific villages)	30
Average	
Density at seeding, unimproved varieties (seeds/ha)	150,000
Nitrogen dose (kg N/ha)	162
Maize yield (t/ha)	1.8

Source: MARIF (1985)

Diagnosis: Problems and Causes

In the first stages of research, the OFR team was faced with what seemed to be a paradox They observed that in spite of intensive management (adequate tillage, row planting, adequate weeding practices, and high nitrogen and manure application rates) maize, regardless of variety, had spindly stalks and discolored leaves Yields were low, averaging 1.8 t/ha of grain, even though research on the experiment station indicated that 5 t/ha could easily be obtained from the variety Arjuna

A farmer examines the maize seed he will plant (his rice crop is in the background).

The OFR team was able to resolve this paradox by paying close attention to the causes of various productivity problems and their respective interactions with farming systems parameters. Three factors—insect damage and poor management of plant population and fertilizer—adversely affected maize productivity

Insect damage—Maize in the study area is often damaged during early growth stages by shootfly (*Euxesta* spp) and other insect pests This is particularly true for post-rainy season maize that is planted a bit late, although rainy season maize can also receive considerable damage. Late planting in the post-rainy season can usually be attributed to a previous upland rice crop (rainy season upland rice is harvested after rainy season maize) or to a delay in tillage operations due to excessive soil moisture. Surveys of shootfly incidence conducted in several research cycles have found up to 80% of the plants in each field infested with that pest.

Plant population management—Farmers in the Malang study commonly overplant maize and then progressively, systematically thin out ''bad plants''—those damaged by insects or diseases, or that appear too spindly. High initial densities lead to interplant competition and, together with high nitrogen doses, contribute to lodging.

From the beginning, it was clear that this problem could not be effectively addressed without a good understanding of its causes. The selection of priority research issues depended heavily on which of three hypotheses was most accurate:

- Overplanting and thinning are done to produce green fodder for livestock.
- Overplanting compensates for poor seedling vigor and low germination rates.
- Overplanting compensates for expected losses to shootfly and other pests and diseases.

Farm surveys provided data that led to the rejection of the fodder production hypothesis; many farmers who thin their maize and also own livestock do not bother to use the thinnings as feed. The second hypothesis—seed quality and germination rates—has not yet been rigorously tested, but is not felt to be critical. The third hypothesis, that farmers overplant to compensate for damage by shootfly and other pests and diseases, was judged most accurate. Thus, research aimed at improving population management practices needed to address pest control problems, but not seed quality, seed storage, or fodder availability.

Fertilizer management—Farmers in the study area use high levels of nitrogen on their maize (an average of 162 kg N/ha) but do not obtain high yields. The efficiency of the applied fertilizer is quite low—at times as low as 3 additional kilograms of maize produced per additional kilogram of nitrogen applied. Working hypotheses to explain low fertilizer efficiency included:

- Farmers' plant population management practices (overplanting and thinning) reduce fertilizer efficiency.
- Farmers' varieties do not respond to fertilizer application (i.e., they have low yield potential).
- Nutrient imbalances cause low fertilizer efficiency. Soil test data from the study area show phosphorus and potassium deficiencies. Perhaps fertilizer efficiency could be increased by substituting phosphorus for some of the nitrogen.
- Fertilizer efficiency is low because nitrogen is applied late. Few farmers apply nitrogen at planting time. Some have tried to mix urea with seed, with unfortunate results. Labor scarcity at planting time does not explain this problem; labor is even more scarce at weeding time, and the additional labor input for applying fertilizer is low.

Each of the hypotheses was found to be fairly accurate, with the possible exception of the hypothesis on variety. Farmers' varieties were found to yield quite well under improved management (pest control and better plant population and fertilizer management).

Evidence from On-Farm Experiments

The problems discussed in the previous section were examined from 1984 to 1986 in five cycles of on-farm experimentation. Some experiments served to further define problems, whereas others were aimed at finding possible solutions. The results of the trials are fairly consistent and tend to support the hypotheses proposed during the diagnostic stage. It appears that farmers' maize yields can be doubled through simple improvements in management practices at a moderate increase in cost.

The OFR team conducted 71 on-farm trials in seven villages during five crop cycles. Twenty-eight farmers participated; some cooperated with only one trial in one season, and other farmers participated during all cycles, but they did not necessarily use the same field each time. The team is currently conducting trial cycle 7.

Plant protection—Evidence of shootfly incidence and yield losses caused by insect attack early in the growing season was obtained in a number of ways, including experiments and surveys. Insect damage early in the growing season might conceivably be reduced if farmers could plant their maize earlier, but rainfall patterns and intensive land use practices prevent most farmers from doing so. A simpler and more effective solution is the use of an appropriate insecticide.

Results of cycle 3 verification trials (Table 3) illustrate the response to plant protection that is often found in the study area. The major insect control treatment tested by researchers was the application of carbofuran 3% granules in the hole at planting time, at the rate of 0.3 kg/ha active ingredient. The economics of carbofuran treatment appear quite favorable: additional costs can be repaid by a yield increment of less than 50 kg/ha grain. (Carbofuran is highly subsidized, but even at unsubsidized prices it would give very good economic returns.) In villages where OFR has been done, there is evidence of farmers' early and spontaneous adoption of this plant protection practice, along with lower seed rates and changes in plant population management.

Plant population—Farmers in the study area overplant and thin largely because they are concerned about insect damage and perhaps because of other factors such as seed quality or the possible recurrence of downy mildew. Virtually all farmers, regardless of which variety they use, remove damaged, diseased, or spindly plants and harvest fewer than 40,000 plants/ha. The alternative plant population management practice that was tested consisted of using lower plant densities (around 90,000 plants/ha) and not thinning (this practice is feasible only in conjunction with pest control measures). A number of OFR studies generated data on plant population, and results of cycle 1 exploratory trials illustrate the effect of lower initial plant stands on maize grain yields (Table 4).

Fertilizer management—It was commonly observed during the exploratory survey and production survey done in 1984 that farmers' maize yields were low despite high levels of nitrogen chemical fertilizer and the use of manure. Discolored leaves during early growth, frequent stem lodging, and spindly plants were noted in field observations. Several alternatives to farmers' fertilizer management were examined (Table 5); during the second cycle of experimentation in the 1984-85 rainy season, an NPK factorial trial was done at four locations. In that trial, observations on the timing of nitrogen application were also made. Soil samples from five locations in the study area were used for chemical analysis and a fertilizer experiment in the greenhouse. During the fourth and

Table 3. Effect of plant protection on maize yield (kg/ha), verification trials, third cycle (post-rainy season, 1985), eight locations

	Crop protection		
Location	No[a]	Yes[b]	Response
Bambang	2049	2295	246
Kamantri	1359	2513	1154
Argosari	2109	3625	1516
Randu Agung 1	2448	3560	1112
Randu Agung 2	2217	2934	717
Pakisjajar	2716	3095	379
Dengkol	3006	2724	-282
Sukoanyar	2666	4618	1952
Average	2321	3171	850

a This is the completely unmodified farmer practice. Yield cuts were made in nonexperimental parts of the trial fields (same harvested area and harvesting technique as the experimental treatments).

b The only difference from the previous treatment is that carbofuran was applied at planting. Planting and all management were done entirely by farmers as in the "no crop protection" treatment.

fifth cycles (the 1985-86 rainy season and 1986 post-rainy season), the response of maize to combinations of nitrogen, phosphorus, and potassium was studied over locations and seasons, and additional greenhouse studies were done.

These studies generally supported the hypotheses generated during the diagnostic stage. No significant yield response to nitrogen beyond 132 kg N/ha was found, but the effects of phosphorus application and earlier nitrogen application were consistently large. Data from 15 verification trials from three cycles (Table 6) provide the most dramatic illustration of the effect of improved fertilizer management on maize yields.

Table 4. Effect of plant population management on maize grain yields (t/ha), exploratory trial, first cycle (post-rainy season, 1984)

Location	Farmer plant population management[a]	Alternative plant population management[b]
1	1.9	2.4
2	3.9	5.1
3	3.9	5.0
4	2.1	2.3

[a] The first treatment was the unmodified farmer practice, except that the improved variety Arjuna was used.

[b] The second treatment also used Arjuna, and employed a lower density (90,000 plants/ha). Plants were thinned to 60,000/ha at 3 weeks. Thinning was dropped in later cycles as it led to excessively low densities at harvest. Thus, these data *underestimate* the effect of improved plant population management on yields.

Table 5. Alternatives to farmers' fertilizer management practices

Factor	Farmers' practices	Alternatives
N dose	162 kg/ha	92-138 kg/ha
N timing	½ at 20 days ½ at 40 days	1/3 at planting 2/3 at 30 days
P dose	(-0-)	60-90 kg/ha

The economics of improved fertilizer management are very attractive. Cost increases are very small, as the increased expense for phosphorus is largely matched by a lower nitrogen cost. The additional costs, including a reasonable return on investment capital, are repaid with a yield response of only 80 kg/ha.

Table 6. Effect of improved fertilizer management on maize yield (kg/ha), verification trials

Location (village) and number of trial	Cycle[a]	Improved practice plus farmer fertilizer management[b]	Improved practice plus improved fertilizer management[c]	Increase in yield
Sukoanyar 1	3	2570	4097	1527
Sukoanyar 2	3	1647	3587	1940
Dengkol 1	3	4796	4942	146
Dengkol 2	3	4007	5612	1604
Pakisjajar 1	3	2463	3493	1030
Pakisjajar 2	3	4772	5617	845
Pakisjajar 3	3	1911	3887	1976
Randu Agung 1	3	3105	4433	1328
Randu Agung 2	3	3897	4860	963
Argosari	3	3933	3696	237
Kemantrin	3	2143	3671	1528
Pakisjajar	4	4405	5445	1040
Pakisjajar 1	5	2783	4002	1219
Pakisjajar 2	5	5283	4876	407
Sumbersekar	5	3504	4165	551
Average		3415	4426	1011

[a] Cycle 3, 1985 post-rainy season; cycle 4, 1985-86 rainy season; cycle 5, 1986 post-rainy season.

[b] Farmer practice, plus Arjuna seed, improved plant population management, and crop protection (carbofuran). The farmers' fertilizer management practice varied from location to location, but typically included high nitrogen doses (in excess of 150 kg/ha) applied in two equal amounts. The first application coincided with the first weeding at about 3 weeks after seeding (without any phosphate) and the second was done about 6 weeks after seeding.

[c] The improved fertilizer management practice was 46 kg/ha nitrogen and 92 kg/ha phosphate applied at seeding and an additional 90 kg/ha nitrogen applied 30 days after seeding. Other practices were the same.

Conclusion

The MARIF OFR program has been operating for only a few years, yet has accomplished a great deal. Surveys have been conducted, a diagnosis made, and a relevant set of trials planted. The diagnosis is recurrent, updated several times each year. Some alternative practices identified by researchers have been spontaneously adopted by farmers. The OFR procedures first used by maize researchers have been taken up by MARIF soybean and cassava researchers, and scientists from different disciplines have found OFR a fruitful way to cooperate.

For the near future, a formal exercise in farmer assessment of the new technology is planned, as well as research on extrapolating research results to other districts of East Java. Diagnostic activities and exploratory experiments have also been initiated in a completely different (and somewhat more complex) study area.

Work continues and new research is planned and implemented in an evolutionary manner, as researchers continuously improve their understanding of farmers' circumstances and problems through OFR.

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Changing Maize Production Practices of Small-Scale Farmers in Ghana

R. Tripp, K. Marfo, A.A. Dankyi, and M. Read[1]

The Ghana Grains Development Project has been active in Ghana since 1979, and involves the Grains and Legumes Development Board, the Crops Research Institute, and the Ministry of Agriculture in developing methods to increase maize and cowpea production. The project, sponsored by the Canadian International Development Agency, receives technical support from CIMMYT and the International Institute of Tropical Agriculture.

The project combines on-station research with an extensive program of on-farm experimentation throughout the country. The results of the experimental program are used to formulate recommendations for farmers, who receive information about new practices through "verification-demonstrations." These demonstrations are planted on farmers' fields and compare farmers' practices with one or two recommended alternatives.

As the verification-demonstrations increased and it became evident that farmers were accepting maize production recommendations, project personnel decided to assess the degree of adoption and obtain information that would be useful in setting priorities for future work. With support from CIMMYT's Economics and Maize Programs, a study to fulfill both of those objectives was undertaken in 1986 in the Brong-Ahafo Region, where maize is an important commercial crop and the extension program is well established.

The Survey

The area selected to begin looking at the adoption of new maize production practices encompasses parts of the Agricultural Districts of Techiman, Nkoranza, Wenchi, and Kintampo (Figure 2) and lies in Ghana's transition zone between the forest and the savanna. In this area most of the maize is planted during March and April, though a substantial amount is also planted in September during the minor rains.

The survey, done in May 1986 in eight villages in Brong-Ahafo, was confined to farmers growing between 0.2 and 8.0 ha of maize in the major season of 1986; these criteria account for the vast majority of maize growers in the area. The farmers averaged about 2.2 ha of maize.

About half of the fields were prepared by hand (slash and burn) and half by tractor. Maize planting may be done by family labor, hired labor, or both; only 15% of the farmers relied exclusively on hired labor, whereas 44% used only family labor. Maize is planted by hand in holes made with the tip of a machete, and weeding is also done manually. Fertilizer is available locally and about half of the farmers use it. Maize may be monocropped or intercropped with some combination of cassava, cocoyam, and plantain. About one-third of the maize fields were intercropped.

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The maize is harvested by hand and may be stored for a variable period of time before sale. Most of it is sold, either to private buyers or to the government Food Distribution Corporation, as root crops are more prominent than maize in the local diet. About 80% of the farmers reported maize to be their most important source of income.

The Ministry of Agriculture sells maize seed and fertilizer; the latter is sold in the district capitals but is frequently unavailable. Sales in the area for 1983-1985 averaged about 1200 t of compound fertilizer (mostly 15:15:15) and about 270 t of ammonium sulphate. In 1986 Grains and Legumes Development Board personnel began selling maize seed at the village level.

The Sample

The survey villages were chosen because of the presence of either a Ministry of Agriculture or Grains and Legumes Development Board representative who had performed a verification-demonstration in 1985. In each of the villages a sample of five farmers was randomly drawn from the list of people who had attended the demonstration, and an additional five farmers were drawn from the general population, using lists developed by the extension agents. This sampling method was

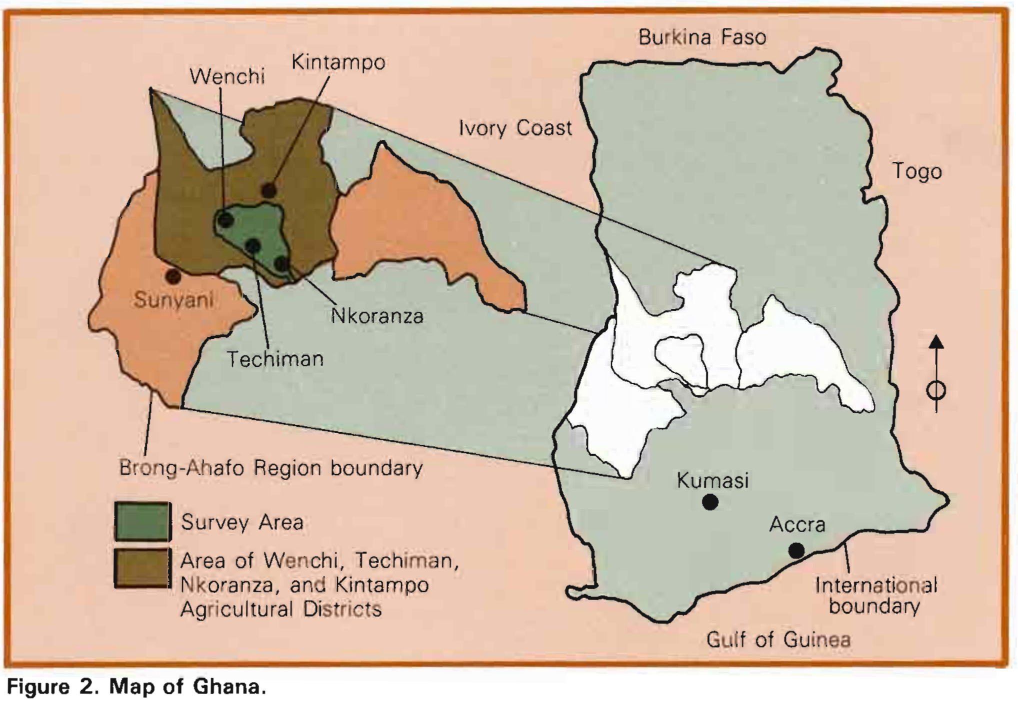

Figure 2. Map of Ghana.

chosen because one of the original objectives of the study was to compare farmers who had attended demonstrations with those who had not. As it turned out, many farmers in the general population had also attended a demonstration in previous years, and there were no significant differences between attendees and those who had never attended. Thus the data from this study fairly represent the practices of maize farmers in villages in the area where extension is rather active.

The Recommendations

The recommendations (Table 7) whose adoption was measured in this study were developed from several years of on-farm experiments throughout Ghana and, beginning in 1980, were included in verification-demonstrations. A verification-demonstration consists of three plots: one represents the farmers' practice and the other two represent recommended options. Farmers were invited to the plots for formal presentations at planting, mid-season, and harvest. At harvest the yields of the plots were calculated and discussed with the farmers in conjunction with information on the costs of the various options.

Staff of the Grains and Legumes Development Board and many extension agents from the Ministry of Agriculture were responsible for using this method, initiated by the Ghana Grains Development Project in 1980, to extend maize recommendations. But in this case the verification-demonstrations were more than a useful extension tool. They became an important source of information for refining the recommendations because the results were analyzed each year.

Table 7. Recommended practices for maize production in the study area

Practice	Recommendation
Variety	Improved variety. La Posta or Dobidi (full season); Aburotia (medium maturity).
Planting	In rows 90 cm apart;[a] 40 cm between hills in the row; 2 seeds/hill.
Fertilizer	2.5 bags of compound fertilizer (15:15:15) per hectare applied on the surface 2 weeks after planting; 2.5 bags of ammonium sulphate per hectare applied on the surface 5 to 6 weeks after planting. Equivalent to 45-19-19 kg N:P_2O_5:K_2O.[b]

[a] 75 cm for medium-maturity varieties.
[b] This recommendation depends on soil fertility. Where soil fertility is very low, twice these rates are recommended. If land is newly cleared, little or no fertilizer may be necessary.

The recommended practices for variety, planting, and fertilization were responsible for an increase of approximately 1 t/ha of maize over the farmers' practice (Table 8) Economic analysis of these trials has shown the recommendation to give an acceptable marginal rate of return (at least 100%) over the farmers' practice, except in 1984 when maize prices collapsed.

The performance of the individual elements of the recommendation can also be examined A number of experiments have shown the improved varieties to be superior to local varieties under virtually all management conditions, and good evidence of fertilizer response over a wide range of maize management practices has been obtained as well. Experimental evidence on plant density and spatial arrangement is a bit more problematic. Farmers used to plant maize randomly, rather than in rows, with relatively large distances between hills and a high number of seeds per hill. Some advantage to improved spacing and a concomitant reduction in the number of seeds per hill has been demonstrated. These changes in planting practices are more likely to give yield increases on fields with adequate fertility.

Adoption Rates

The survey showed quite high rates of adoption of the recommendations for variety, planting method, and fertilization (Table 9). The maize cropping system had a strong influence on adoption; farmers were much more likely to follow the recommendations in monocropped than in intercropped maize fields (Table 10) The gap in the use of the recommended practices in mono- and intercropped fields is greatest for fertilizer and least for variety. It should also be pointed out that, although adoption rates are above 60% for each of the recommendations in monocropped fields, in only 36% of these fields were all three of the recommended practices followed.

The survey results indicate that just about 50% of the maize area in the study villages is planted to improved maize varieties. The newly released varieties Dobidi and Aburotia are found already on many farmers' fields, although the bulk of the

Table 8. Results of verification-demonstrations in transition zone

	Yield (kg/ha)				
Practice	1981	1982	1983	1984	1985
Farmer practice	1780	1880	1580	1950	1680
Recommendation[a]	3150	3200	2500	3050	3450
Difference	1370	1320	920	1100	1770
Number of sites	21	71	77	93	69

[a] 2.5 bags/ha each of 15:15:15 and ammonium sulphate.

improved maize is still the variety La Posta, which has been available for about a decade.

The object of the row planting recommendation was to improve the spatial arrangement and population of maize fields by establishing a higher number of hills but a lower number of seeds per hill. When maize is planted in rows it is also much easier to apply the correct amount of fertilizer. The majority of the farmers space their rows adequately, but the spacing between hills tends to be greater than the recommendation. There is good evidence that farmers who monocrop maize achieve better plant spacing and density when row planting than when random planting. Those who row plant have a higher number of hills per hectare and a lower number of seeds per hill, and come much closer to the recommended practices than do farmers who random plant.

The fertilizer recommendation asks farmers to apply a top dressing of compound fertilizer followed by a

Table 9. Adoption of recommended practices[a]

Practice	Ever used (%)	Used in 1986 (%)	Used on largest maize field in 1986 (%)
Improved variety	88.6	81.0	58.2[b]
Row planting	82.3	68.4	57.0
Fertilizer	83.5	46.8[c]	42.9[c]

a N = 79.
b Farmers who use an improved variety on at least half of their largest maize field.
c N = 77.

Table 10. Adoption of recommendations by cropping system (farmers who followed recommendation on largest maize field, 1986)

Practice	Maize planted as monocrop (%)	Maize planted as intercrop (%)
Improved variety	70.4	32.0
Row planting	74.1	20.0
Fertilizer	60.4	4.2
(N)	(54)[a]	(25)[b]

a N = 53 for fertilizer.
b N = 24 for fertilizer.

side dressing of ammonium sulphate. When farmers are able to obtain both fertilizers, most make two separate applications, although some mix the two and apply them at the same time. Farmers tend to apply both fertilizers later than recommended, and the rate of application varies widely, as might be expected. The amount of fertilizer applied will depend on the availability of fertilizer, the farmer's cash resources, and the fertility of the field. More compound fertilizer is used because it is much more easily available than ammonium sulphate.

The Adoption Sequence

A number of studies have shown that farmers are generally cautious with recommendations, preferring to test them out a bit at a time. Although 53 farmers (67%) in the sample have used improved maize varieties, row planting, and fertilizer, they have not necessarily adopted all of these recommendations at the same time. The evidence shows that farmers prefer a step-by-step approach to adoption.

The survey data (Table 11) not only illustrate this characteristic of adoption behavior, but also provide examples of its logic. About half of the farmers began by adopting only one of the recommendations. The vast majority of them chose to adopt either fertilizer or an improved variety There is good evidence that either one of these simple changes would provide a profitable return to the farmers, even if they did nothing else. This is less true for a simple switch to row planting, and only a few of the farmers began their adoption of recommendations in this way.

Of the farmers who adopted two of the recommendations in the same year, the majority began with a combination of row planting and fertilization, which would enable them to profit from the significant interaction of improved population with improved fertilization. A lower number of farmers began with a combination of the improved variety and fertilization, where an interaction might also be expected, and none of the farmers adopted as their first step a combination of improved variety and row planting, where an interaction is probably the least likely.

Finally, the survey showed that 13 of the farmers adopted all three of the recommendations in the same year. It is significant that this represents only about one-fourth of the population that eventually adopted the entire package, and that the majority of farmers reached this point through a series of steps.

Extension and the Farmers

One of the original purposes of the survey was to test the effectiveness of the verification-demonstrations by comparing the adoption behavior of farmers who had attended them with that of farmers who did not; as it turned out, there is not much difference between the practices of either group. The lack of correlation between attendance at a verification-demonstration and adoption is not surprising, given that verification-demonstrations are only one part of a range of extension activities carried out by the project and by other agencies. People attend demonstrations out of curiosity, interest, and at times to reinforce knowledge that they have already put into practice. When farmers using the recommendations were asked how they first learned of them, their answers illustrated the importance of extension activities in general for spreading information about new practices.

In certain cases, an extension effort may not reach all of the farmers in an area Although women play an important part in agriculture, extension sometimes is not directed toward them. In this study, however, the results indicate that women adopted the recommendations on their maize fields to about the same extent as the men had. In addition, adoption rates were equally high for farmers with no education as for educated farmers.

Farmer Circumstances

Another way of looking at adoption patterns is to consider the relationship between each recommendation and farmer circumstances—the socioeconomic and natural features of the farm. Recommendations stand a good chance of adoption only if they are compatible with the resources and interests of the farm family and with the soils, climate, and biological conditions of the farm.

Variety—Although the vast majority of the farmers now use improved maize varieties to some extent, adoption is certainly not complete. One means of understanding this situation is to study farmers' opinions of the varieties. Farmers rated the improved varieties superior with respect to yield (with or without fertilizer) and resistance to lodging, which helps to explain their high acceptance. In addition, there were no complaints about the quality of the seed

Opinions of storage and cooking quality, however, were lower: local maize was rated superior on both counts. Farmers say that improved maize is more easily infested with weevils (perhaps because it tends to have poorer husk cover than the local maize). In the study area

Table 11. Adoption sequence for farmers who have used all three recommendations

Recommendation adopted first	Number of farmers	Percent
Fertilizer only	13	24.5
Variety only	10	18.9
Row planting only	4	7.5
Row planting and fertilizer	9	17.0
Variety and fertilizer	4	7.5
Variety and row planting	0	0.0
Variety, row planting, and fertilizer	13	24.5
Total	53	99.9

farmers do not depend greatly on maize as a staple food, and their concerns about cooking quality may be linked to market prices. Private traders sometimes express a preference for local maize by buying it first or paying a bit more for it. This preference is said to be based on the superiority of the local maize, especially for making *kenkey* (steamed fermented corn dough), but this subject needs further investigation.

In any case, for most farmers the agronomic qualities of the improved maize varieties would still appear to outweigh any disadvantages in storage, cooking, or marketing.

It has also been pointed out that the improved varieties are less likely to be planted in intercropped fields (32.0%) than in monocropped fields (70.4%). The reason for this is not immediately clear, as the evidence indicates that the improved varieties are superior to the local varieties under any conditions. It may be that farmers prefer to use the improved varieties on their more important maize fields, but there is no indication that farmers see any necessary link between the improved varieties and the other recommended practices.

Row planting—There is a strong relationship between cropping system and row planting of maize. Only 20% of intercropped fields are row planted, whereas 72.2% of monocropped fields are row planted. This is understandable if one considers the problems of row planting maize with several other crops, and the fact that intercropped fields tend to be planted on newly cleared land, where stumps and other obstacles make row planting more difficult.

Planting in rows takes more time than random planting, if only because more holes per hectare are made, but farmers seem to manage this method with little difficulty after some practice. Nevertheless, one indication of the importance of the time element in row planting is the fact that, for monocropped maize, row-planted fields tend to be smaller than random-planted fields. The mean size of row-planted monocropped maize fields is 1.52 ha, whereas the mean for random-planted fields is 2.32 ha.

Fertilizer—Hardly any intercropped maize receives fertilizer, and it is not known if the response of the intercrop to fertilizer would be profitable for farmers. The fact that intercropped fields have usually been continuously cropped for less time and are more fertile complicates the comparison of farmers' fertilizer use on inter- and monocropped fields. Sixty-four percent of intercropped fields were not planted the previous year, and only 16% had been cropped for 2 or more years. Only 15% of monocropped fields, on the other hand, were not planted the previous year, and 77% had been cropped for two or more years. Cropping history makes a big difference in a farmer's decision to use fertilizer: a farmer is much more likely to fertilize an older field than one that has been newly cleared.

Conclusion

The results of the study show that farmers in increasing numbers are taking up the recommendations. It is important to look at this adoption process in several different ways because a single index of adoption can be quite misleading. For example, almost all of the farmers in the study have used at least one of the recommendations, and the vast majority follow at least part of the recommended practices. However, only a minority use all of the recommended practices on all of their fields, and almost none follow the recommendations perfectly (e.g., timing of fertilizer application or planting distance). So, depending on one's criteria, one could defend adoption rates from close to zero to nearly 100%.

The logic of the adoption process is evident from the survey results. Farmers show an ability to test recommendations on their own and adapt them to their particular circumstances. At first they grow new varieties on a small portion of their fields and often use only parts of a package of recommended practices. Those recommendations that are used are compatible with the farmer's resources, marketing practices, and agronomic conditions.

One of the most striking results of the study is the differential adoption of the recommendations on monocropped and intercropped maize fields. The use of row planting and fertilizer, in particular, appears to be much less common on intercropped fields. In Ghana's transition zone, which is the country's single most important maize production area, most maize fields are monocropped. It is reasonable to believe that the high rates of adoption found in this study will be found in many other areas of the transition zone. Closer to the forest, however, intercropping becomes much more prevalent, and the adoption of the recommended practices examined in this study will almost certainly be lower.

The recommended practices described in this study are themselves candidates for further work and refinement. Breeding efforts continue to develop superior maize varieties, suited to various environments. Cooking quality, storage, and marketability have been recognized as important criteria for screening new varieties. Planting methods may be further refined, not only for intercropping maize, but to help farmers achieve good stand establishment by protecting the seed from the pests that lower plant populations. Fertility management will also continue to receive attention so that farmers can be given more precise recommendations for varying conditions.

The increases in maize production already achieved because of the adoption of the current recommendations are an important consequence of work by the Ghana Grains Development Project. But at least equally important is the demonstration of a research methodology that takes farmers' interests and conditions into account, and an extension strategy that allows recommendations to be tested, debated, and assessed by farmers and extension agents. Support for this active partnership between farmers, extension workers, and researchers will contribute a great deal to Ghana's future agricultural development.

Commodity and Policy Analysis

To provide better information to national program decision makers and others, CIMMYT Economics Program staff regularly collect and analyze data on the production, utilization, and trade of maize and wheat. The results of these analyses are reported in alternate years in the *Facts and Trends* series. In 1986, CIMMYT economist James L. Longmire prepared an issue of *Maize Facts and Trends* to provide basic information on current world maize production and utilization, and to present a study of the economics of maize seed production. Results of that study, summarized here, cover seed costs, pricing, and performance. The discussion underscores the great scope for wider dissemination of improved maize seed in developing countries and presents some issues that policymakers must face as they try to promote the growth of effective seed industries in their countries.

The necessity of providing policymakers and others with accurate technical information is reflected in this section's second article, prepared by Michael Yates, Gustavo E. Sain, and Juan Carlos Martinez, CIMMYT economists with responsibilities in the Central America and Caribbean Region. Some policies (on input delivery, marketing systems, credit, or extension, for example) influence the potential acceptability of technologies generated through on-farm research. Using data obtained from on-farm investigations, researchers should be able to supply administrators with information to help them make more effective policy decisions. One example of that use of data is a case study of policies affecting the availability of different types of fertilizers in Les Cayes, Haiti. That work is part of a series of studies that apply findings from on-farm investigations to the implementation of policy at the local level.

The Economics of Commercial Maize Seed Production in Developing Countries

J.L. Longmire[1]

A viable seed industry is a key element of any country's attempt to increase crop productivity, especially for maize As developing countries seek to improve their seed industries, a number of issues arise. What balance of open-pollinated varieties and hybrids is appropriate? What types of hybrids are likely to be most effective? What is the most effective seed industry structure? What levels of prices are needed to provide incentives for seed producers as well as value for money for farmers planting the commercial seed? What is the role of governments in regulating the seed industry? In 1986 staff of CIMMYT's Economics Program conducted a study of the economics of commercial maize seed in developing countries to address some of those issues (1).

Initially, data were gathered on recent use of maize seed throughout the world to place in perspective the challenge that lies ahead for national maize research programs, seed enterprises, and other groups involved in the development and marketing of improved maize seed. Two prominent features of maize seed use were observed: the marked contrast between regions, and the relatively limited spread of improved maize seed in the Third World.

During 1985-86 farmers planted some 3.2 million t of maize seed worldwide, about 1 million in developed and the remainder in developing countries, on almost 140 million ha (Figure 1). At prevailing prices and exchange rates, the global value of that seed (including the value assigned to farmers' own seed) was about US$ 3.2 billion. The seed planted in developed countries had a total value of over US$ 2.4 billion (because of the predominance of high-value hybrid seed in North America, Europe, the USSR, and South Africa), whereas that sold in the Third World was worth just under US$ 800 million. Thus, farmers in developing countries planted almost 70% of the world's maize seed on a tonnage basis, but its US dollar value was less than a quarter of the world total.

About half the maize planted in the Third World during 1985-86 was improved. There is, of course, much regional variation in the proportion planted to improved maize In Africa, for example, only one-third of the maize sown was improved, compared with almost 60% in Asia and Latin America. The overall percentage is much reduced, however, if we exclude large countries with sizable areas planted to improved maize, particularly Argentina, Brazil, and China. In the remaining developing countries, only about one-third of the total maize area is planted to improved materials.

Aside from general patterns in maize seed use, trends in the use of particular seed types were examined. Estimates of area planted, planting rates, quantity of seed planted, seed prices, and seed

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value were compiled for three categories of seed: 1) that grown by farmers for their own use, including the seed they traded among themselves, 2) commercial seed of open-pollinated varieties, and 3) hybrid seed. The first category includes all noncommercial maize seed that farmers planted, and the last two all the commercial seed they bought.

Generally speaking, hybrid maize is concentrated in the more favorable (and therefore less risky) growing areas of developing countries. In developing countries overall, hybrids occupied about 38% of the total maize area, commercial seed of open-pollinated varieties another 7%, and farmers' own seed the remainder. Eliminating Argentina, Brazil, and China, however, alters the picture considerably, reducing the area planted to hybrids to only 16%, and raising that occupied by farmers' own seed to almost three-fourths in other countries of the developing world.

In Thailand, Egypt, Guatemala, and Ecuador, a large share of the maize area is planted to commercial seed of open-pollinated varieties. The widespread adoption of commercial seed in those countries may be accounted for by the successful development of new open-pollinated varieties by national maize research programs and simultaneous growth of viable seed industries. But that combination of events is uncommon, with the result that in many regions of the world commercial seed of open-pollinated varieties is planted to less than one-third of the total maize area.

The Continuum of Maize Seed Types

In studying the variable patterns of seed use and the conditions that shape them, we found it helpful to

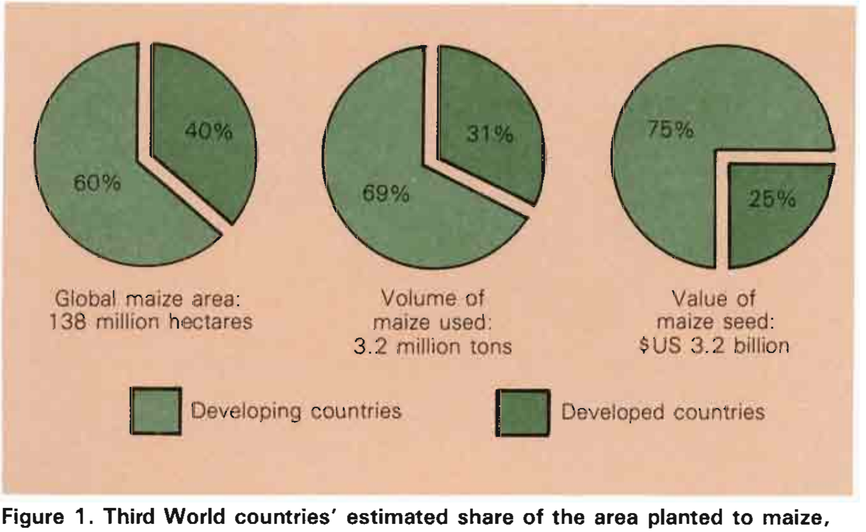

Figure 1. Third World countries' estimated share of the area planted to maize, tons of seed used, and value of seed worldwide.

describe the different seed types in terms of a continuum or progression from local varieties to improved ones, followed by nonconventional and then conventional hybrids (Conventional hybrids are formed entirely from inbred lines created through self-pollination for three or four successive generations, whereas nonconventional hybrids are formed through crosses in which at least one parent is *not* an inbred line.) The continuum is seen in the yield capability of the seed types, in the technology employed to produce them, and in relative prices of different types of maize seed

Performance of Seed Types— Farmers, like seed producers, assess the yields of different varieties and hybrids and are attuned to the differences in their performance and in the risks incurred by growing them Of course, the yields of hybrids and other maize types vary considerably according to environmental conditions, management practices, and the genetic makeup of the commercial seed Even so, the evidence available suggests that, across the whole spectrum of growing conditions, the various seed types show a general progression in productivity, as follows: local varieties, improved varieties, nonconventional hybrids, double cross hybrids, three-way crosses, and single crosses.

This pattern is manifested most distinctly (and hybrids are likely to display their superiority most clearly) when the seed is grown under extremely good conditions. That conclusion is evident in data from US trials in which average yields were around 10 t/ha. From this data and other information obtained informally, it appears that under very favorable experimental conditions single-cross hybrids show a yield advantage of about 30% over improved varieties having the same genetic base.

The yield gap between those two types of maize may narrow substantially outside the temperate zone. Yield data from experiments conducted at 12 locations in Mexico and Central America (representing a number of different environments) indicate that the difference in yield between single-cross hybrids and open-pollinated varieties was less than half of what it was in the US trials (Table 1). Data from those sites may underrepresent the yield potential of hybrids, though, considering that less work has been done to develop hybrids for those particular tropical and subtropical locations than has been conducted in the temperate zone. Much the same pattern was observed in Thailand, where the average yield of the best hybrid was 18% higher than that of the improved variety in a trial with average yields ranging from 4 to 5 t/ha for various hybrids and varieties.

The trials in Mexico and Central America were done at experiment stations under favorable growing conditions. Under poorer crop management and harsher environmental conditions, the yield advantage of hybrids is diminished even further. In the tropics and subtropics, where farmers' average yields often do not exceed 1.5 t/ha and maize production is still in its infancy, differences between the yields of hybrids and improved varieties are likely to be small. Even if hybrids do maintain a sizable percentage increase in yield over improved varieties, the actual difference in kilograms per hectare may be so small in areas where yields are generally low and variable that farmers cannot readily perceive it. In on-farm trials conducted in several developing countries, it has been observed that under difficult growing conditions there is little perceptible difference between the yields of hybrids and improved varieties. This evidence is not necessarily conclusive, however, since hybrids are not generally targeted for such harsh environments.

The overall yield advantages of hybrids and improved open-pollinated varieties obviously vary according to growing conditions, farmers' circumstances, and the level of maize research that has been conducted locally. Farmers in many parts of the Third World are not likely to adopt hybrids, or even improved varieties, until further improvements in growing conditions and crop management practices occur, and until they are convinced that the extra yields will more than compensate for the outlays on improved seed.

The Cost Continuum—Some of the patterns just described are reflected in the costs of maize seed production and the prices farmers pay for maize seed. Costs and prices vary widely from one region to another, but there is a general continuum of costs and prices from improved varieties to conventional hybrids.

At any given location, growing commercial maize seed is a much more costly proposition than producing maize grain. Likewise, it costs more per hectare to grow hybrid seed than commercial seed of improved varieties, since the former require more complicated field layout, planting, and harvesting, a higher degree of

Table 1. Ranking of maize seed types used in this study

Type	Average yield (kg/ha)	Percentage of OPV yield
Open-pollinated varieties	4894	100
Varietal or family hybrids	5324	109
Double-cross hybrids	5351	109
Three-way cross hybrids	5551	113
Single-cross hybrids	5594	114

Source: Calculated from Cordova (1986).

management and supervision, additional training of growers, extra labor for detasseling and roguing, and greater quality control. Variation in the costs of growing different maize seed types generally depends on their relative seed yields.

To illustrate patterns in the prices of different seed types, all maize seed prices are presented as ratios of the seed price to that of grain (Figure 2). This conversion allows for differences in the price of maize across countries and eliminates having to convert local prices to a standard currency. Retail prices relative to the grain price were obtained for seed of improved varieties, varietal and topcross hybrids among the nonconventional types, and double-cross, three-way, and single-cross hybrids among conventional types. When more than one enterprise in a particular country quoted a price for a certain type of maize seed, the average of the prices for that country was taken. As seed and grain prices fluctuate over time, obviously so will the ratio between them; the ratios reported here are for 1985-86.

There was wide variation between countries in the prices of different seed types. In Colombia, for example, the average price of single crosses was less than 5 times the price of grain, whereas in the USA the figure was 30 times. Such large discrepancies are explained to some

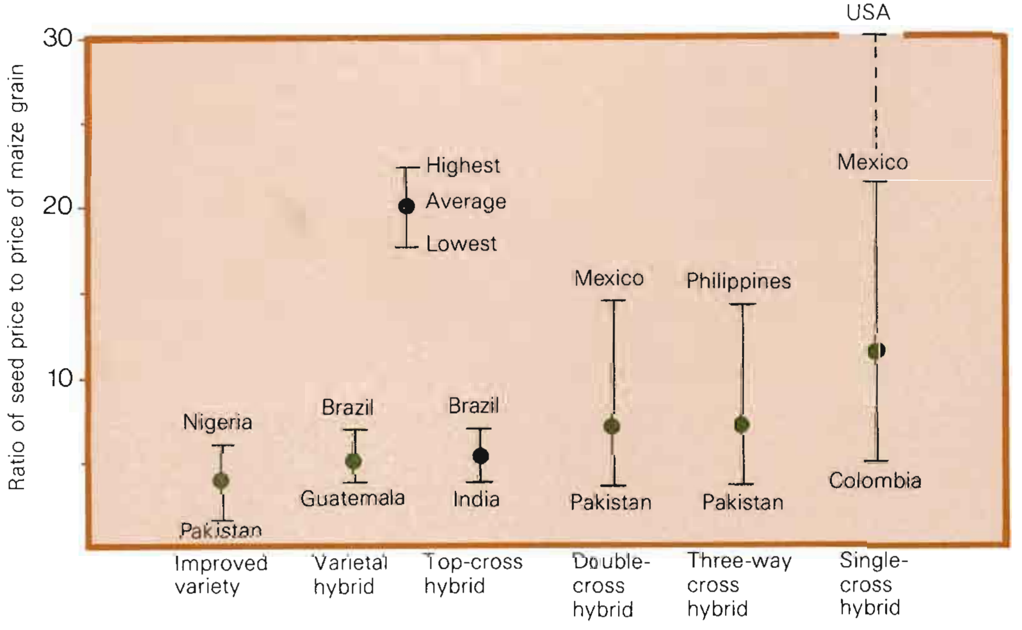

Figure 2. Ratio of maize seed price to price of maize grain, by seed type. Note the wide variation between countries in the prices of different seed types.

extent by large differences in seed enterprise input costs, such as wages, interest rates, and retailers' margins. Another consideration is that in some countries seed prices are kept artificially low.

Notwithstanding the price variation among countries, a distinct progression in the price of various seed types was observed. The price of improved varieties was cheaper than that of hybrids. Among hybrids the seed of single crosses was the most expensive, followed by three-way crosses, double crosses, and improved varieties (Figure 3).

Surprisingly, the average price of the nonconventional hybrids was only around 20% higher than that of seed of improved varieties, and in general price margins between various types of maize seed were narrower than we had originally anticipated.

These fairly small differences between prices must be seen against the circumstances of Third World farmers, many of whom face difficult growing conditions and severe input constraints. As a result, when they switch from local varieties to improved ones or to

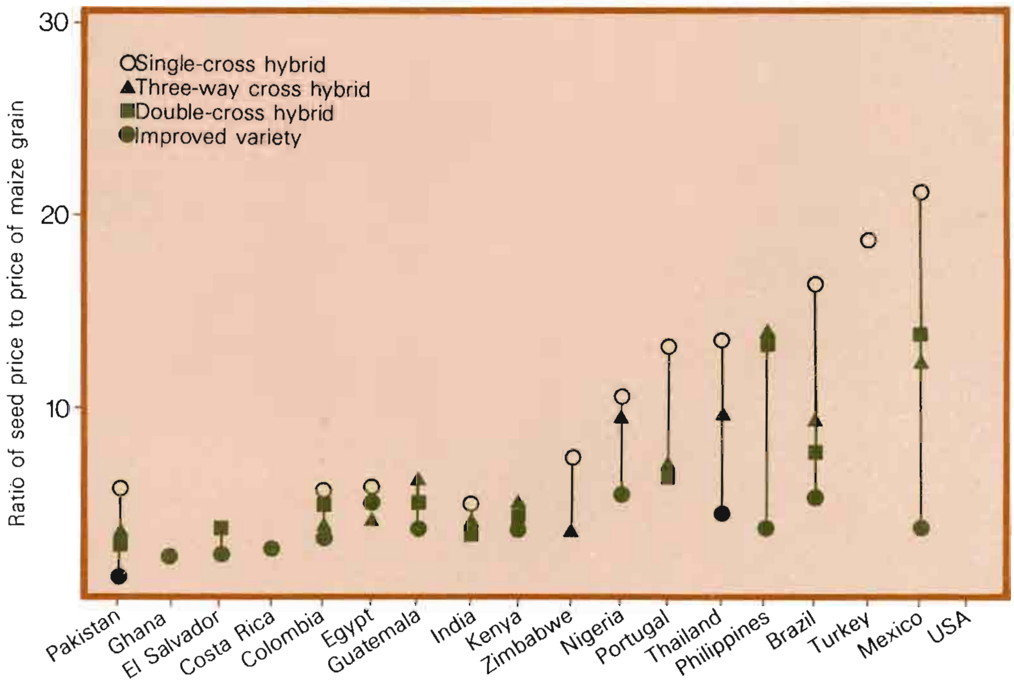

Figure 3. Ratio of seed price to price of maize grain, by country. There is a distinct progression in the price of various seed types, that of improved varieties being lower than the price of hybrids.

hybrids, the innovation does not have as much of a discernible impact on yields as it might under more favorable conditions. In the absence of a strong incentive to change seed types, farmers will tend to be very price conscious when deciding whether to purchase seed and will not pay much of a premium if they have doubts about the quality of the seed or the advantages it offers them. This reluctance is reinforced by the shortage of cash and difficulty in obtaining credit in developing countries.

Processing maize seed in Indonesia.

Another reason for the relatively small difference in price between open-pollinated varieties and hybrids in developing countries is the fairly high share of value added in seed processing and marketing. The value added for seed production covers the cost of all production activities up to, but not including, transportation of the seed to a processing facility. The value added for processing represents all costs the seed enterprise incurs until it delivers the seed to distributors, and that added for retailing reflects all expenditures during the final stages of seed marketing.

In view of their circumstances, it is understandable that many farmers in the Third World opt for the low-cost alternative of planting seed of local varieties. The average price of local varieties traded among farmers exceeded the price of grain by just over 30%, a difference that reflects storage costs, physical and financial losses, and additional costs associated with carrying and selling small lots of seed. Generally, the volume of seed traded in this manner is much lower than the amount developing country farmers grow themselves and retain for planting their next crop.

Choosing the Appropriate Seed Types

One of the first steps toward developing a viable seed industry is to identify the appropriate options for farmers. Should seed enterprises produce only hybrids, only improved varieties, or some combination of various seed types, including local varieties? All of those possibilities exist in developing countries, and no single one is universally applicable. The appropriate seed types will be those that, under prevailing maize production conditions, offer farmers a clear-cut economic advantage over other alternatives and thus a strong incentive to change seed types.

For lack of information about yields, the seed price ranges at which farmers are likely to switch from one seed type to another could not be estimated. But by simple budgets it is possible to calculate the yield increases that would give farmers sufficient encouragement to change seed types. The increase was the extra maize needed to pay for the extra seed cost, plus a 100% margin for risk and the cost of capital. The average seed prices given in Figure 2 were used to determine the yield increases; average seeding rates in developing countries were assumed to be 27 kg/ha for local varieties, 25 kg/ha for improved varieties, and 22 kg/ha for hybrids.

The magnitude of the yield increase required to motivate farmers to choose purchased seed of improved varieties over their own seed of local varieties depends very much on the average yield of the local variety. If that average is only about 1 t/ha, then the improved variety would have to yield 8% more than the local variety to compensate the farmer for the extra cost of the seed purchased, plus the margin for capital costs and risk. The yield difference drops to 3%, however, if the average yield of the local variety is 3 t/ha. The difference is smaller because at this higher average yield, the extra cost of purchased seed represents a smaller proportion of the extra income per hectare that is gained form the yield increment.

We observed much the same pattern in yield increments in considering the choice between various types of hybrid seed purchased every year and that of improved varieties purchased every 4 years. Where the average yield of the latter is only 1 t/ha, farmers might be induced to purchase single-cross hybrid seed if it shows a 30% yield advantage over the improved varieties. However, this is quite unlikely, according to the maize specialists we consulted, with such a low average yield. If, on the other hand, the improved varieties' average yield is as high as 6 t/ha, farmers would probably purchase single-cross hybrid seed since a yield increment of only 2% would meet the extra costs of seed, capital, and risk. The required yield difference is also quite small, even at low average yields, to make nonconventional hybrids a more attractive option to farmers than improved varieties.

A Public or Private Seed Sector?

Having identified the appropriate seed options for farmers, agricultural decision makers will have to confront a number of other issues concerning the way in which various seed types can be made readily available to farmers. One central question is the extent to which public organizations, private enterprises, or both should be permitted and even encouraged to operate in developing countries.

In the Third World, wide differences exist in the balance between public and private seed enterprises. In many developing countries, the public sector is quite deeply involved in seed production. This contrasts greatly with developed countries, where private enterprise predominates.

In deciding the extent of public and private participation in a given country's seed operation, one should consider the overall performance of the two sectors. Data we received from 35 developing countries on the volume of sales of hybrids and improved varieties indicate that, in spite of the public sector's close involvement in seed production, the bulk of commercial maize seed is produced by private seed enterprises (Table 2). (Countries with centrally planned economies were excluded from this analysis, since all seed enterprises in those nations are public.) It is not surprising that the production of hybrid seed is heavily concentrated in the private sector. The more striking circumstance is the private sector's large share (almost two-thirds) of commercial seed of improved varieties. Only 11 out of 34 countries reported that public seed enterprises provide at least two-thirds of the commercial seed of improved varieties sold.

Although private seed enterprises performed much more effectively in comparison with their public counterparts, privatization is not the only prerequisite for success. No such simple formula can be applied indiscriminately across the whole range of diverse political, social, and economic conditions in the Third World. Alternatives that fall short of privatization are open to decision makers, and include restructuring incentives and adjusting procedures in national seed organizations, and giving play to competition that would encourage seed industries to seek efficiency in production and value for money in pricing.

Conclusion

Creating effective seed industries and maintaining high-quality seed production would be more daunting tasks than they are, were it not for two important considerations. The first is that very successful seed

Table 2. The private sector's percentage share of maize seed sales in non-centrally planned economies, 1985-86

Region	Number of countries reporting	Private enterprises' percentage share of total sales: Seed of improved varieties	Hybrid seed	All commercial maize seed
Eastern and southern Africa	4	45	96	92
West Africa	6	9	77	61
North Africa	1	73	100	78
Total, Africa	11	57	95	83
Middle East	2	0	45	38
South Asia	3	38	63	54
Southeast Asia and Pacific	4	69	38	39
East Asia, excluding China	2	69	38	39
Totally, non-centrally planned Asia	11	62	62	62
Mexico, Central America, and Caribbean	6	66	71	68
Andean region	4	65	91	86
Southern Cone of South America	3	81	98	97
Total, Latin America	13	70	96	92
Latin America, excluding Argentina and Brazil	11	66	80	73
Non-centrally planned developing countries	35	65	92	85
Developed market economies	7	100	100	100
Total, all non-centrally planned economies	42	65	98	94

Note: Total sales of commercial seed are the sum of sales by private and public enterprises.

enterprises have already been established on every continent in the Third World and can serve as models for other developing countries. The principles upon which those enterprises are based can be instituted elsewhere.

The second consideration is that developing countries can choose from a range of seed options, each having different benefits and costs. During the early phases of seed industry development, the most prudent course will generally be to encourage seed producers to concentrate on improved varieties, especially in low-yielding environments. As maize-growing conditions and management practices improve, farmers should be able to perceive greater yield differences between seed types, and should gradually increase their use of hybrid maize. Naturally, there will be much variation by region and type of farmer in the adoption pattern over time. As suggested by the results of this study, farmers in high-yielding environments will find it economical to adopt hybrids rapidly, whereas those in low-yielding environments will not. Maize research programs must take into account those differences in farmers' circumstances as they decide which seed types warrant the greatest investment of resources.

As Third World countries develop and alter their maize seed strategies accordingly, we expect that some will opt for nonconventional hybrids as a useful intermediate step in the development of their seed industries. Generally more productive than improved varieties, the nonconventional types are simpler and cheaper to produce than conventional hybrids and can be identified more rapidly.

Gearing the pace of seed industry development to overall improvement in maize cultivation will not be an easy task but will require considerable insight, judgment, and patience on the part of the various groups involved in seed production and distribution. We hope that the results of this study will give them new insights and a broader basis on which to form judgments.

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Addressing Market Imperfections with Farm-based Policy Research: Fertilizer Provision in Les Cayes, Haiti

M. Yates, G. Sain, and J.C. Martinez[1]

CIMMYT has developed a set of cost-efficient procedures for identifying improved, appropriate agricultural technologies through on-farm research (OFR). These procedures are now being implemented by national agricultural research programs in many parts of the world, increasing their capacities to generate appropriate technologies that can be adopted by target groups of farmers.

In the course of their work, researchers in many OFR programs have seen how policy-related constraints can limit gains associated with the introduction and diffusion of new technologies. Consequently, the Economics Program has recognized the need to develop procedures to identify, where appropriate, such policy-related constraints or opportunities associated with the use of new technologies and to effectively communicate this information to policymakers to help them formulate or implement improved agricultural policy. This type of analysis has come to be called farm-based policy research.

As this case of market imperfections in fertilizer provision in Haiti illustrates,[2] there can be close links between OFR and farm-based policy research. In on-farm research, socioeconomic circumstances—including the current policy environment—are assumed to be a given. In farm-based policy research, policy is seen as a variable, and a case for modifying policy constraints is built by applying microeconomic tools to farm-level data that is supplied by OFR programs.

Although the Economics Program is just beginning to develop a set of procedures for farm-based policy research, initial work suggests that the following sequence of steps[3] can be helpful:

1) Identify the policy (or policies) constraining gains from new technologies.

2) Understand the rationale behind the policy in question, and how the policy affects relevant sectors of society.

3) Identify the decision-makers most directly linked to the policy in question, to better target results of the analysis.

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1 Michael Yates (based in Haiti), Gustavo E. Sain (based in Mexico), and Juan Carlos Martinez (based in Mexico) are working in the Central America and Caribbean Region for the CIMMYT Economics Program.

2 This summary is based on Yates, M., J.C. Martinez, and G. Sain. 1987. Fertilizer provision in Les Cayes, Haiti: Addressing market imperfections with Farm-based Policy Research. CIMMYT: Mexico, D.F. Unpublished draft.

3 For more details see Martinez, J.C., G. Sain, M. Yates, and A. Hibon. 1986. Toward Farm-based Policy Research: Learning from experience. Paper presented at the Farming Systems Symposium, October 1986, Kansas State University, Manhattan, Kansas.

4) Identify solutions or policy options, with relevant performance measures that can satisfy the target audience, again taking into account the potential impact of these options on relevant sectors of society.

Microlevel data from OFR can thus serve a dual purpose. They can be used to develop appropriate technology as well as information that can be applied by policymakers *to create an environment more* conducive to positive technological change.

The Haitian OFR Program and the Study Area

Haitian agriculture faces serious challenges. Low maize yields are obtained on the country's small farms (typically less than 1 ha), and improved technologies are rare. Maize is Haiti's most important cereal, covering approximately 30% of all cultivated land. During recent years, production per capita has declined, while population pressure is an estimated 470 persons per square kilometer of cultivated land. These conditions place great demands on existing resources; maize production has expanded onto Haiti's most marginal lands and problems with soil erosion have accelerated. There is an obvious need to identify and encourage the use of improved and appropriate technologies to increase farmers' productivity.

To help meet that need, the Haitian Ministry of Agriculture (MARNDR) decided to explore the potential contribution of on-farm research methodologies to the development of appropriate maize technologies for small-scale farmers. An area-specific OFR program for the Les Cayes District in southwestern Haiti (Figure 4) was designed to be carried out by the Ministry with technical assistance from CIMMYT's Economics and Maize Programs.

One of the important research opportunities identified by the program was nitrogen fertilization. In experiments conducted in the *fields of representative farmers,* the application of 80 kg N/ha had a highly consistent positive effect on yield across sites and years (e.g., 20 of 22 experiments), with increases averaging 850 kg/ha.[4]

However, important changes in the ratio of maize to nitrogen prices from year to year (Table 3) and the risk they implied for a potential farmer recommendation made it apparent that risk considerations should be given priority when determining an economically appropriate rate of nitrogen fertilization. Subsequent field trials led to the identification of 40 kg N/ha as the best rate to

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4 The OFR program also obtained good experimental results with some CIMMYT maize varieties (La Maquina 7827, La Maquina 7928), though other experimental variables, such as phosphorus fertilization and higher plant density, gave unpromising results and were eventually eliminated from the research program. For more details, see CIMMYT. 1985. On-Farm Research Methodologies at Work in Les Cayes, Haiti. In *Research Highlights 1984*. CIMMYT: Mexico, D.F. Pp. 90-98.

recommend. This level consistently offered excellent rates of return, yet called for only modest investments.

However, it was seen that two elements strongly conditioned the economic returns to nitrogen fertilization: land tenure and fertilizer availability. Approximately half of the farmers sharecrop some maize. Typical arrangements compel sharecroppers to give 50% of the harvest to the landowner, though fertilizer costs are generally not shared. Under these circumstances, the economic returns to nitrogen fertilization for sharecroppers and landowners are dramatically different.

The type of fertilizer available to farmers was even more important than difficulties arising from land tenure arrangements. Nitrogen prices varied significantly according to whether the source of nitrogen was urea (46% N) or an N-P-K blend (Table 3). (Experiments generally showed no response to P or K.) Rates of return to investment capital were generally unsatisfactory with MARNDR's fertilizer blends, but they were excellent with urea (i.e., well above the opportunity costs of investment capital, estimated to be 60% for the crop cycle).

It was clear that the potential demand for nitrogenous fertilizer from local maize growers had two distinct segments: 1) farmers who owned their maize plots, and 2) those who sharecropped maize. In addition, it was apparent that the recommendation to landowning farmers would be closely associated with the availability of urea.

Despite the clearly assessed profitability of nitrogen fertilization in maize, area farmers were generally not applying any nitrogen to the crop, though fertilizers were used with other crops. Consequently, while the on-farm experiments

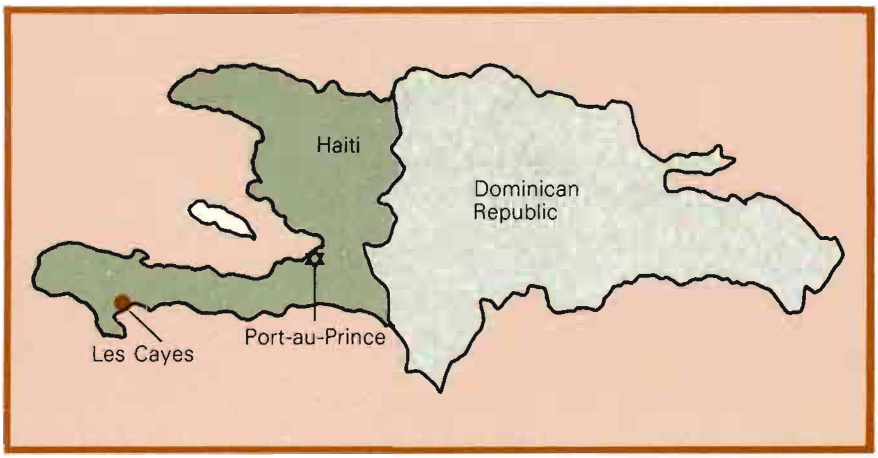

Figure 4. The Les Cayes study area capital, Haiti

confirmed the nitrogen response and fine-tuned a potential farmer recommendation, the clear association of this recommendation with the availability of urea led to a detailed supply-side analysis of the local fertilizer market.

Market Conditions

In 1981 there were five sources of fertilizer in the Cayes Plain. By far the most important was the Les Cayes office of MARNDR, which in that year sold 690 t of various fertilizers. Four other concerns provided smaller amounts exclusively to their clients (rice, tobacco, sugarcane, and tomato growers). Although urea was clearly the cheapest source of nitrogen, it represented just 5% of the total fertilizer provided by MARNDR to Les Cayes. There were no private

Table 3. Average annual maize and nitrogen field prices (US$/kg), Les Cayes, Haiti, 1981-85

Year	Field price of maize[b] (US$/kg)	Field price of nitrogen[a]		Price ratio (r)[c]	
		Urea (US$/kg)	Blends (US$/kg)	Urea	Blends
1981	0.182	0.478	1.32	5.1	12.5
1982	0.130	0.930[d]	1.37[e]	12.7	18.1
1983	0.205	0.860	1.61	7.5	13.3
1984	0.165	0.770	1.61	8.4	16.6
1985	0.310	0.720	1.52	4.2	8.4

[a] Average field prices at planting time. Field price includes transportation costs.

[b] Average post-harvest (peak sales period) field price of maize. Field price includes all costs that farmers pay that are proportional to yield.

[c] The values of r were calculated as: $r = (1+C)(Pn+L)/Pm$, where C is the cost of capital, L the cost of labor for the nitrogen application, Pn the field price of nitrogen, and Pm that of maize.

[d] No urea was actually available locally for the 1982 planting season. This estimate is based on the retail price for urea in the capital, Port au Prince (200 km away), adjusted by transportation costs to Les Cayes.

[e] Limited supplies of remaining MARNDR subsidized fertilizer.

Source: Yates, M., J.C. Martinez, and G. Sain. 1987. Fertilizer provision in Les Cayes, Haiti: Addressing market imperfections with Farm-based Policy Research. CIMMYT, Mexico. Unpublished draft.

sector fertilizer distributors in Les Cayes at that time, and if representative maize farmers wished to obtain urea, they had access only to MARNDR's minimal supplies.

In 1982 and 1983 the market situation was still quite restricted. No urea was available from the public sector, and supplies of blends were down sharply. One merchant in Les Cayes began selling small quantities of fertilizer in 1982.

It was apparent to the OFR team that the potential adoption of the recommendation, and consequent gains in area productivity and income, were threatened by the scarcity of urea in the local market. The Ministry's fertilizer distribution policy was certainly not in the best interests of farmers growing maize in the Les Cayes Plain. The team concluded that a policy giving priority to increasing urea supplies would be most beneficial for local maize production.

Targeting Audiences and Communicating Findings

Once the policy constraints were identified, the OFR team targeted two different audiences for the information it had assembled: the public sector, represented in this case by MARNDR, and the private sector, represented by a few private firms selling inputs in the Les Cayes area.

Representatives of both sectors were given regular reports and preliminary research findings. Personal interviews confirmed that the lack of relevant information helped explain fertilizer distribution patterns in Les Cayes.

The OFR team then estimated a set of ''performance measures'' to be used in making the case for changing fertilizer provision policies. For the public sector, measures stressing potential gains in area production and farmers' incomes were emphasized. For the private sector, potential demand was emphasized (i.e., the amounts of additional fertilizer that could be sold to farmers if adequate quantities of urea were available at a reasonable price).

During 1983 and 1984, the OFR team maintained close contact with representatives of the public and private sectors. In January 1984 a final recommendation—the application of 40 kg N/ha, regardless of maize variety, with urea as the source of nitrogen—was made from the program to landowning farmers through MARNDR. With this recommendation, MARNDR acknowledged that the fertilizer blends they offered did not provide an economically appropriate source of nitrogen for area maize farmers, whereas open-market urea did.

The OFR program in Les Cayes had indeed developed a significant recommendation for farmers, and long-term maize and urea price trends augured well for increasing adoption. In addition, a potentially important recommendation had been developed for policymakers in the capital, emphasizing the need to assure adequate supplies of urea for the farmers of Les Cayes.

Results: Changing Patterns of Fertilizer Use in Les Cayes

Even though the results of OFR may have influenced regional demand for urea, the complementary policy analysis was targeted at increasing the regional supply. Note that the provision of urea did increase after the recommendation was made to policymakers, and the response from the public sector was greatly augmented by positive interventions from the local private sector.

As noted earlier, MARNDR provided only minimal supplies of urea in 1981, the year the OFR program was inaugurated. No urea was available from the Ministry in 1982, 1983, or even 1984, the year the project offered its nitrogen fertilization recommendation. The following year, however, MARNDR did provide more than 90 t of urea to Les Cayes, and this represented fully 60% of the total fertilizer distributed by the Ministry in the region. There is some evidence therefore of a shift, consistent with the project recommendation, in the Ministry's fertilizer provision priorities for Les Cayes.

But an even more dynamic force for change in the area has been the private sector's increasing importance in supplying fertilizer. One store in Les Cayes began selling fertilizers in late 1982, and the amounts sold have increased dramatically from year to year, especially in the case of urea.

Those increases have been nothing short of explosive, with an almost ten-fold jump in urea sales from 1983 to 1984 (Table 4). Sales volume growth from 1984 to 1985 continued at a very impressive 174%, and although sales of mixed blends also increased (from 112 to 270 and 521 t in that same period), the changes with urea have been far more pronounced. Both the OFR team and the private sector estimate (based on timing of urea

Table 4. Total urea sales, private sector, Les Cayes, Haiti

Year	Urea sold (t)	Urea sales as percentage of total fertilizer sales
1983	11	9
1984	105	28
1985	289	36

Source: Yates, M., J.C. Martinez, and G. Sain. 1987. Fertilizer provision in Les Cayes, Haiti: Addressing market imperfections with Farm-based Policy Research. CIMMYT, Mexico. Unpublished draft.

sales, and on points of origin of purchasers) that at least half this urea is being applied to area maize fields, and the private sector is optimistic this program will continue. In fact, two new distributors have begun operating in Les Cayes since 1985.

It is clear that the information generated and communicated through this analysis—building on the results of the area-specific OFR program—offered valuable information to policymakers that helped effect positive technological change. It is equally certain that researchers engaged in OFR, who have acquired firsthand knowledge of farming systems and biological responses to alternative practices, are in a special position to identify policy constraints and promote changes in policy to complement technological change. As the case of Les Cayes illustrates, this can have important positive implications for both the target group of farmers and for the nation as a whole.

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