CIMMYT 25
1966·1991

Enduring Designs for Change

An Account of CIMMYT's Research, Its Impact, and Its Future Directions

Nothing endures but change.
Heraclitus

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 improving the productivity of agricultural resources in developing countries. It is one of 16 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 some 40 donor countries, international and regional organizations, and private foundations.

CIMMYT receives core support through the CGIAR from a number of sources, including the international aid agencies of Australia, Austria, Belgium, Brazil, Canada, China, Denmark, Finland, France, India, Germany, Italy, Japan, Mexico, the Netherlands, Norway, the Philippines, Spain, Switzerland, the United Kingdom, and the USA, and from the European Economic Commission, Ford Foundation, Inter-American Development Bank, OPEC Fund for International Development, UNDP, and World Bank. CIMMYT also receives non-CGIAR extra-core support from the International Development Research Centre (IDRC) of Canada, the Rockefeller Foundation, and many of the core donors listed above.

Abstract: This publication was prepared in commemoration of CIMMYT's 25th anniversary. It consists of three main sections. The first provides an abbreviated account of the Center's research and related activities. The second summarizes the preliminary results of a study of the impact of CIMMYT's work with national programs, giving particular emphasis to improved germplasm. The final section is a discussion of the Center's future research agenda.

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Introduction

CIMMYT's establishment in 1966 coincided with the early stages of a far-reaching transformation of agriculture in the developing world. What became known as the Green Revolution ultimately benefitted hundreds of millions of people and won international recognition for its chief architect, Norman Borlaug. The Center was created in the midst of this experience in an effort to secure and extend the remarkable gains achieved, much as revolutionaries throughout history have sought a means of perpetuating change. Establishing an international center for maize and wheat research was in many ways a compelling maneuver. It was also rather risky. The danger in such a move was that the original dynamism of CIMMYT's loosely structured predecessor organizations might give way in a more permanent institutional setting to the routine business of corporate survival.

The world has learned many lessons in this century about the consequences of revolutionary political and social programs. Some have led to chaos, others to a new and more rigid status quo, and a few to the release of creative and productive forces. All such programs, however, have been mere beginnings. All have left unfinished business that required a somewhat different approach from the one that fomented revolution in the first place. Certainly, that is a fair characterization of the Green Revolution in agriculture. It addressed many urgent problems, but it also opened the eyes of agricultural researchers to a long list of incomplete and possibly interminable tasks — and one to which each decade brings new additions. The global reach of those tasks, their special importance to people in developing countries, and their long-term nature were among the primary justifications for CIMMYT's founding.

The Center's 25 years of experience since then is the subject of this publication. It consists of three main sections. The first is an abbreviated account of CIMMYT's research and related activities. While covering all areas of this work, we have deliberately avoided including the details of particular projects and of the Center's institutional life generally. Instead we concentrate on presenting the main challenges of our work, describing the tasks we have undertaken to meet them and the major outcomes, identifying the unique or otherwise noteworthy features of our approach, and explaining where we have come out on a few major issues that have arisen along the way. The bulk of this account is devoted to germplasm development and improvement, which are CIMMYT's primary activities and the ones in which it has the clearest advantage as an international organization. But we also treat the Center's broader agenda of research in agronomy and the social sciences, activities that emerged as a logical consequence of our work in plant breeding but eventually came to have a logic of their own. Finally, we examine CIMMYT's efforts to strengthen national programs through research, training, and information.

Periodic and systematic assessment of impact will provide a stronger basis for our decisions about the allocation of resources and enable us to keep those who support our work well informed.

We hope it is obvious from this first section that CIMMYT staff have worked with persistence, intelligence, and imagination toward their goal of institutionalizing the innovative program with which the Center began. The question of whether we have actually reached that goal is dealt with in the second section of this publication, which presents a new view on the impact of our work, primarily that resulting from germplasm development but from other pursuits as well.

In CIMMYT's first decade, the impact of its work was quite evident and well known, and there was less need for a thorough and detailed evaluation like the one in which we are engaged now. More recently, however, it has become apparent that an intuitive sense of success is not enough, particularly since the striking achievements of the Green Revolution have given way to more widely dispersed but smaller gains. To measure these changes accurately requires mechanisms for evaluating impact periodically and systematically. Such assessments will provide a stronger basis for our decisions about the allocation of resources and enable us to keep those who support our work well informed. Given those expectations, the information presented here should be taken not as the last word on CIMMYT's impact but rather as the start of an expanding dialogue.

As we envision it, the study of impact has much in common with CIMMYT's other challenges in germplasm development, crop management research, and institution building. Like those activities, impact assessment must be global in scope, encompassing highly diverse circumstances in scores of developing countries. It must also be interdisciplinary and strongly oriented toward the development of specific products as well as better procedures for generating them. Above all, our investigation of impact must reflect an awareness of the synergy of international and national research. Certainly, that is true of the preliminary findings presented in this publication, which record the effects of a truly collaborative, global enterprise.

From the impact information obtained so far, we believe readers may safely conclude that CIMMYT won the bet that its founders made in 1966. As encouraging as this may be, however, we realize that past and current success is not by itself a guarantee of future triumph. We also need a compelling agenda for the future and coherent strategies for addressing key issues, if we are to ensure that CIMMYT's work remains vital and effective. We have moved to satisfy that need in recent years through strategic planning, the major outcomes of which are summarized in the third section of this publication. Our strategic plan and the Center itself are somewhat more complex than the Green Revolution program that led to CIMMYT's establishment. But they are dedicated just as surely to finding enduring designs for beneficial change in the lives of people who rely upon maize and wheat in developing countries.

Enduring Designs for Change

A Dynamic View of Innovation in Agriculture

CIMMYT evolved from a strictly national initiative in Mexico to a collection of international programs and then to an institute with a global mandate (see pages 8-9). Though dramatic institutional change has not altered the Center's focus on helping the poor in developing countries, a number of circumstances have prompted us to modify the way in which we interpret and pursue this goal.

In the 1980s, self-sufficiency ceased to be the watchword of our efforts to assist developing countries. Instead, we began to direct our efforts at raising the productivity of resources available to maize and wheat researchers and producers.

A comprehensive approach to helping cereal producers keep pace with population growth was outlined in CIMMYT's original mandate:

> *To promote and carry out, nationally and internationally, programs to improve in all its aspects maize and wheat production . . . through research, the distribution of germplasm, training, scientific and technical meetings, and information.*

In the 1980s, CIMMYT altered its mission to conform to new thinking about the role of agriculture as an engine of economic growth. Self-sufficiency ceased to be the watchword of our efforts to assist developing countries, and our work with national programs was no longer focused on increasing crop production. Instead, we began to direct our efforts at raising the productivity of resources available to maize and wheat researchers and producers.

This approach views improved agricultural technology not just as a source of increased output but of new income obtained by various means and in different parts of the economy. For example, farmers who adopt technical innovations gain additional income from increased productivity of their land, labor, and other investments either by increasing output or lowering costs. as noted in an FAO study, *World agriculture: Toward 2000,* "better agricultural performance generally results in a lower price of food, higher agricultural wage rates and employment and consequently a lower incidence of rural poverty." Eventually, these improvements begin to exert positive effects outside agriculture. Lower grain prices, for example, enable consumers to spend less on food and more on other items. These purchases in turn channel new income into diverse sectors of the economy. among the principal beneficiaries are both the rural and urban poor, who benefit most from lower food prices and from the new jobs that are created in a more vigorous agriculture and in other areas of the economy that eventually profit from its development.

Events in the 1980s have added another dimension to our focus on the productivity of resources in agriculture. In the latter half of the decade particularly, growing concern about sustaining nature's endowment has put the challenge in a longer and more daunting perspective. It is disturbing enough to survey the consequences of low resource productivity for the current generation in some countries. It is even more disconcerting to realize that future generations can fare no better if the resources they will need tomorrow are pillaged today by a rapidly growing human population engaged in a desperate scramble to feed itself. Given the potential for such consequences, increased production at any price is clearly an unacceptable prescription for agricultural development.

By giving rise to new income streams, research aimed at increasing the productivity of farmers' resources helps alleviate poverty and thus dampens the principal cause of environmental degradation in developing countries. This approach also emphasizes the use of cost-saving technologies that offer the further advantage of being environmentally safe. Disease and insect resistant varieties, for example, can eliminate the need for potentially hazardous chemicals. and more efficient methods of applying fertilizer can reduce indiscriminate use of this input. Thus, in various ways the current orientation of CIMMYT's research is more consistent with the goal of helping the poor and of protecting natural resources than was the production campaigning of previous decades.

This more dynamic view of innovation in agriculture is reflected in CIMMYT's current mission statement:

> *To increase the productivity of resources committed to maize and wheat in developing countries while protecting natural resources, all through agricultural research.*

In pursuing this mission, our aim continues to be opening options for the poor in developing countries. We work toward this goal through agricultural research and direct support to national maize and wheat programs. Our research focuses mainly on developing improved germplasm but also generates information and efficient methods for plant breeding, crop management research, and agricultural decision making. Our support activities take the form of training and consulting services. These make up our principal products.

In Pursuit of Higher Grain Yields

In responding to the grain production imperatives of the past several decades, both CIMMYT and its predecessor organizations went to great lengths to raise the yield potential of maize and wheat germplasm. The urgency of this task has been lessened only slightly by the Center's more recent emphasis on raising the productivity of farmers' resources. Higher grain yields and production are not the only means of accomplishing that end, but they are an extremely important one.

Semidwarf wheats

The high yield potential of improved wheat germplasm is partly the result of incremental gains over many cycles of selection. These gradual advances build on the more dramatic progress that has been made possible at various times both before and after CIMMYT's founding by new insights into plant genetics. The first of these masterstrokes was the introduction by Norman Borlaug of Norin 10 dwarfing genes into Mexican wheat breeding nurseries during the 1950s. Their effect was to drastically alter the way the plant apportions photosynthate among its vegetative and reproductive parts. In semidwarf materials grain constitutes 40 to 50% of the total weight, compared to only 25 to 35% for tall varieties. Dwarfing genes thus provided a means of bringing the biological priorities of the wheat plant more closely in line with those of the new campaigns for boosting grain output in developing countries.

The new wheats proved to be more compatible than tall varieties with a principal thrust of the production programs, which was to encourage the use of nitrogen fertilizer. When this input was applied at reasonable doses to tall varieties, the extra grain they produced, together with their weaker straw, caused them to fall over or lodge. This reduced their harvestable yield to such an extent that much of the fertilizer was essentially wasted. The short, strong stems of the semidwarfs, in contrast, resisted lodging under increased fertility, making them more efficient users of inputs. The millions of farmers who adopted these varieties — in India, for example, through a vigorous campaign led by plant breeder R. Glenn Anderson — immediate and dramatic yield increases and thus realized greater gains from their investments in fertilizer and other inputs.

Reduction of plant height in maize

Though significant progress has also been made in raising the yield potential of maize, the spread of new varieties and consequent improvement in farmers' yields have taken place more slowly in developing countries than with wheat. In an early effort to develop higher yielding genotypes for the lowland tropics, CIMMYT maize scientists embarked on a project during the late 1960s (under the leadership of plant breeder Elmer Johnson) whose objectives were much the same as the work on semidwarf wheat varieties. They hoped, by reducing the generally excessive height of tropical maize (3 m or more), to derive genotypes that would show lodging resistance under higher nitrogen fertility and intense tropical rains and use farmers' inputs more efficiently to produce higher grain yields.

Since the intended end of this work was identical to that on semidwarf wheat, it was tempting to employ similar means. The Maize Program thus experimented briefly with crosses between various sources of mutant dwarfing genes and the population Tuxpeño Crema I (so named by its creators, Elmer Johnson and Edwin Wellhausen, because it consisted of the cream of various materials derived from Tuxpeño, one of the most productive of the Mexican maize races). Though products of the crosses with genetic dwarfs tended to introduce new problems, Tuxpeño Crema I proved to be an ideal candidate for the effort to reduce plant height. It already showed relatively good lodging resistance and responsiveness to higher fertility. In an effort to further enhance these features of the race and raise its yield potential, Johnson and others carried out a long-term program of direct selection for reduced plant height, with the aim of gradually accumulating genes with minor effects for this trait. This was a somewhat slower route to improved plant type than that open to Borlaug's team, but it achieved a comparable effect. After 15 cycles of selection, according to a 1978 study later published in Crop Science by Johnson and others, plant height had been cut by 37%, the harvest index (ratio of grain to stover) had risen from 0.30 to 0.45, and yield had increased dramatically (Figure 1).

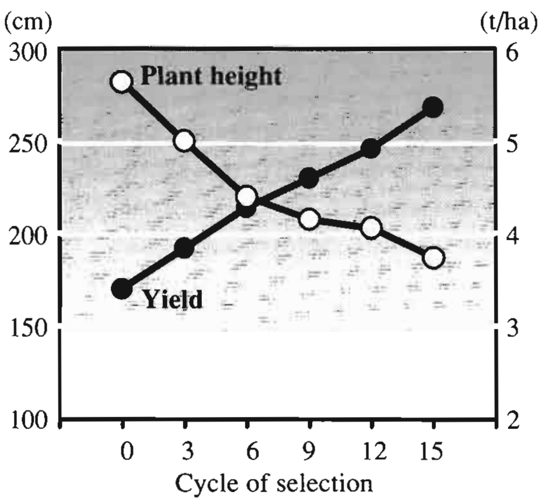

Figure 1. Effect of plant height reduction on grain yield (at the optimum plant density for yield performance) of the maize population Tuxpeño Crema I, grown at six location/years, Mexico, 1978-80.

What made these gains especially remarkable was that they were achieved with tropical materials that previously had been untouched by the tools of modern plant breeding. Much additional experience in the Center's Maize Program has further reinforced the point that landrace germplasm can gradually be recast in the mold of a modern maize variety through long-term selection for reduced plant height, improved yield, and other key traits. During the 1970s the Program went on to develop a wide array of improved populations (in which Tuxpeño germplasm featured prominently) and since then has achieved steady gains in their performance through 18 or more cycles of selection.

CIMMYT's Predecessors

Though now international in character, CIMMYT grew directly out of national experience in Mexico and from the country's long and fruitful relationship with the Rockefeller Foundation. Their first joint endeavor began in the 1940s, when the Foundation sent a commission of eminent agricultural scientists to survey conditions in Mexican agriculture. They came at the request of US Vice-President Henry Wallace, who in turn had been asked by Mexico's Minister of Agriculture, Marte R. Gómez, to provide technical assistance in helping Mexico overcome its chronic food shortages.

Office of Special Studies

The commission's report called for a determined assault on the country's food production problems through research, education, and extension with a sharp focus and adequate support. To help implement this strategy, the Rockefeller Foundation assembled a small multidisciplinary team of researchers in 1943, for whom the Mexican government set up an autonomous organization, the Office of Special Studies, within the Ministry of Agriculture. In researching a range of basic crops, including maize and wheat, the Office of Special Studies established research plots in farmers' fields and developed extension methods. A key element of its ambitious program was to employ recent university graduates as interns and help them get fellowships for advanced training.

The experiment proved successful, and by the mid-1950s the country was almost self-sufficient in maize and wheat. Expansion of the area planted, better cultural practices, selection of superior varieties from native strains, and improvement of their disease resistance all contributed to the gains in maize. Major contributions in wheat were the development of varieties with resistance to stem rust and other diseases and the incorporation of these traits into high-yielding semidwarf varieties. The impact of these technical achievements was multiplied by the Mexican government's substantial commitment to agriculture. By 1959 a cadre of well-trained Mexican agricultural professionals had been developed and a graduate school of agriculture was established at Chapingo. On the strength of these achievements, the government formed the National Institute for Agricultural Research (INIA) in 1960.

International programs

After the Office of Special Studies was closed in 1961, several of the Rockefeller staff remained in Mexico to extend the lessons learned to other countries. They had already gained some international experience through regional networks set up during the 1950s for germplasm and information exchange. After 1961 they formed international wheat nurseries to distribute the new Mexican wheats more widely and began to accept training participants from outside the Western Hemisphere.

A NEW INSTITUTE

In 1963, at the suggestion of President Adolfo López Mateos (who the previous year had visited the new International Rice Research Institute, IRRI), the International Maize and Wheat Improvement Center was established as a cooperative program of Mexico's Ministry of Agriculture and the Rockefeller Foundation. The center absorbed what had been the Foundation's Inter-American Food Crop Improvement Program. It quickly became evident, though, that the resources of the new institution were insufficient to handle the growing demand for germplasm and training from countries in Asia and Africa. In response the original founders, joined by the Ford Foundation, rewrote the charter, establishing CIMMYT on 12 April 1966 as a nonprofit civil association under Mexican law, responsible to an internationally representative board of trustees.

CAMPAIGNS AGAINST HUNGER

Although Mexican wheats had been undergoing evaluation in India and Pakistan since the early 1960s, it took the imminent prospect of famine to crystallize plans for their introduction on a large scale. In 1966, 18,000 t of seed of the Mexican varieties were shipped to India, and the next year Pakistan received 42,000 t. In combination with appropriate management practices worked out by scientists in the national programs and from the Rockefeller and Ford Foundations, the new wheats raised yields enormously in both countries when more favorable weather returned during 1967. By 1969 Pakistan was self-sufficient in wheat, and India had boosted national production to the unprecedented level of 17 million tons. These successes gave impetus to local breeding programs and to changes in government policy that favored agriculture. Other wheat-producing countries began to follow suit. The spreading revolution in agriculture benefitted millions of farmers and consumers immediately and brightened the prospects of many more by giving birth to a new confidence in agricultural research.

CIMMYT INTERNATIONAL

The Center continued to operate as a Mexican civil association from 1966 to 1989. At that time, with support from the United Nations Development Programme (UNDP) and the World Bank and with sympathetic consideration from the Mexican government, CIMMYT became an international institute with headquarters in Mexico.

RAISING THE YIELD CEILING IN WHEAT

Though it was not necessarily the Wheat Program's foremost concern, there was much discussion at CIMMYT during the 1970s of a yield plateau or ceiling. In the 1960s the semi-dwarf varieties had raised the yield potential of spring wheat from about 3.5 to 7.5 t/ha. Continued selection in subsequent years added little to this figure but did improve yield stability. In the hopes of making yet another great leap forward, the Center's wheat scientists began during the 1970s to explore the possibilities of large-scale crossing between spring and winter wheats, a technique that had been pioneered in the preceding decade.

Among the noteworthy products of CIMMYT's spring x winter wheat crosses were the Veery lines, whose yield potential exceeds that of the previous generation of improved materials by about 10%.

The lure of this approach was that each of the two groups contained genetic diversity that might be usefully combined with that of the other, thus enhancing both types. To winter wheats, spring germplasm could bring stronger resistance to leaf and stem rust and better baking quality, while the winter germplasm could contribute greater drought tolerance and resistance to various foliar diseases.

Bringing off such a desirable match required a special effort to overcome barriers erected by nature between the two gene pools. Ordinarily, they seldom mix, because outcrossing is uncommon in a self-pollinated crop like wheat, because spring and winter wheats are cultivated in climatically distinct regions, and because they have very different growth habits. Whereas the spring wheats develop over a continuous 4- to 5-month cycle, the growth of winter materials must be interrupted by a period of low temperatures to induce flowering (a requirement referred to as vernalization). The crop is ready for harvest by summer, some 10 or 11 months after planting.

To synchronize flowering of the two types and permit large-scale crossing, two procedures are used, one at CIMMYT's Toluca station and the other at the Mexican government's Northwestern agricultural Research Center (CIANO) near Ciudad Obregón. The high elevation and resulting cold winters of Toluca ensure vernalization of winter wheats. Planting of the spring materials is moved back to January to ensure that they will flower at the same time as winter wheat in May. Conditions at the hotter Obregón site require a more complex routine. There, potted winter-wheat seedlings are grown in cold chambers to achieve vernalization. They are then transplanted in the field, where electric lamps are used to extend the daylength and hasten flowering, so that it coincides with that of spring wheat in March. Together, these two procedures permit wheat scientists to make more than 1,000 crosses each year. CIMMYT staff employ the progeny of these crosses primarily in the development of spring wheats, while cooperators at Oregon State University, USA, and scientists in the Center's cooperative program in Turkey exploit them in winter wheat breeding.

By the late 1970s, it was evident that CIMMYT's high expectations from spring x winter wheat crosses would be fulfilled. Throughout the decade progeny of these combinations consistently ranked among the best entries in the Center's International Spring Wheat Yield Nurseries, which are conducted annually at over 100 locations. among the most noteworthy products of the spring x winter crosses was Veery 'S', a group of sister lines from the same cross. The yield potential of these materials, developed by plant breeder Sanjaya Rajaram, exceeds that of the previous generation of improved varieties by about 10%. according to the most recent count, nearly 20 developing countries have released 36 Veery-based varieties.

Hybrid maize for developing countries

Several decades before CIMMYT was founded, plant breeders already knew that the secret to raising maize yield potential lay in the phenomenon of hybrid vigor or heterosis, which results from the mating of distinct genotypes and is expressed as increased performance in relation to that of the parents. Since each hybrid variety is the result of a unique combination of parent materials, farmers must purchase new seed every cropping season rather than save their own seed from the previous harvest. as a result, the development and dissemination of hybrids offers attractive opportunities for private sector investment.

Following the widespread adoption of hybrid maize in the USA during the 1940s, it spread quickly throughout the industrialized world and also aroused keen interest in the developing countries, a number of which started hybrid programs during the 1950s and 1960s. Though some were successful (in Kenya and Zimbabwe, for example), the experience of others proved disappointing. By the early 1970s the majority of maize programs in the Third World were focusing chiefly on the development of high-yielding open-pollinated varieties (OPVs). Drawing lessons from that experience, CIMMYT's own maize scientists acted cautiously in supporting hybrid development, gearing their work to the pace of change in the maize research and production of developing countries.

Throughout the 1970s, the Center's contribution was only indirect. Its improved maize germplasm, though occasionally employed in hybrid development, was not specifically shaped to that purpose. By the 1980s, however, changing circumstances had prompted CIMMYT to reconsider its exclusive emphasis on OPVs. One important consideration was that in a number of developing countries average yields had risen impressively. as long as yields are below 2.5 t/ha, farmers are highly unlikely to adopt hybrids. But wherever average yields have climbed above that level (as in Egypt and Thailand, for example), crop management and growing conditions are good enough that many farmers can realize sufficient yield improvement with hybrids to justify the annual purchase of higher priced seed. another precondition for hybrid production that at least some countries had fulfilled by the 1980s was the establishment of a reasonably effective seed industry.

Largely in response to interest expressed by national programs, Ronald Cantrell, director of CIMMYT's Maize Program from 1984 to 1990, took the decision to begin supporting hybrid maize development in specific ways. among these was to enhance the usefulness of some currently available germplasm for hybrid formation and to generate information indicating how breeders might exploit the Center's materials most effectively in their hybrid projects.

This is not to say, however, that the Program has done a complete about-face in its views on hybrids. Though now more sanguine about their prospects in developing countries, we continue to be cautious about our own involvement in hybrid work for two main reasons. First, the areas where average yields are high enough to warrant the introduction of hybrids still constitute a rather limited proportion of the developing world's total maize area. and second, where conditions are right for these materials, private seed companies are moving quickly and effectively to satisfy the demand for seed. Thus, while aiding in hybrid development, the Center still devotes the bulk of its maize resources to the development of new OPVs.

The breeders' bottom line

A strong argument against seeking further increases in the yield potential of maize and wheat would seem to be the sizeable gap between the yield of currently available improved germplasm at experiment stations and the generally lower yield of these same materials in farmers' fields. Why engage in work that only makes the discrepancy even more pronounced? Does it not make more sense to concentrate on reducing the yield gap by trying to improve farmers' crop management? CIMMYT has done precisely that in allocating a substantial share of its resources over the years to agronomy research. Meanwhile, though, selection for higher yield has continued to be a fundamental part of the Center's on-going germplasm development programs. This is seldom the result of a plant breeder's myopic fixation on yield potential for its own sake but is based rather on much experience suggesting that gains in yield potential do translate into improved yield performance in farmers' fields. The emphasis on yield is also a necessary part of the multitrait selection approach that our staff employ.

Making gains simultaneously for several characteristics requires that the crop be grown under normal levels of various stresses typical of those occurring in farmers' fields. In order to make selection as precise and effective as possible, our scientists manipulate some of these stresses through disease inoculation, artificial insect infestation, and other techniques. CIMMYT's experiment stations thus represent not ideal environments but more or less realistic ones (at least in terms of biotic stress), in which some of the major variables are controlled. Selecting strictly for yield potential, in contrast, would require more perfect conditions under which the control of stresses is so absolute that they do not limit the crop's inherent capacity to produce grain.

Within our breeding schemes, yield is considered in its complex relationships to other traits. It is the breeders' bottom line, reflecting progress from selection for a whole range of characters. Thus, when CIMMYT maize staff recently evaluated their subtropical populations for resistance to turcicum leaf blight, they knew they had made progress, both because the ratings of disease symptoms indicated as much but also because the yield under this stress was much higher than before. Our emphasis on yield in relation to other important traits may account in part for a kind of spillover effect, especially noticeable in wheat, whereby the yield gains achieved under optimum moisture and fertility may also be reflected under less favorable conditions. In marginal areas and under poor crop management, the yield advantage of a modern variety may be small. But seldom does the improved genotype perform worse than the local variety under the often difficult circumstances of crop production in developing countries.

Broad Adaptation: A Radical Amendment

Before the advent of science-based agriculture, plant breeding was strictly a local activity. Farmers selected genotypes according to their own needs and preferences and for adaptation to a particular place. With the creation of agricultural research programs in the 19th century, the scope of plant breeding was broadened considerably, though still confined to relatively limited areas of individual countries. against that background the development of crop varieties for global distribution came as a radical amendment to the timeworn principles of plant breeding. The first article of the new creed called for genotypes with broad adaptation, expressed as high yield across a wide range of climates.

The elements of broad adaptation

Early progress toward this goal was more coincidental than deliberate, resulting from a desperate battle against the epidemics of stem rust that devastated wheat crops in northern Mexico during the 1940s. To speed the breeding of resistant varieties, Norman Borlaug devised an improvement scheme in which two generations were produced per year, each at a different location. From November to May, the crop was grown and selections made at Ciudad Obregón in northern Mexico and from May to November at Toluca, near Mexico City. What began as an effort to gain time, however, ultimately had as much to do with space. as the products of Borlaug's work reached other projects in Latin America, it became apparent from their successful performance at diverse locations that the new varieties were suited to an unusually wide range of climatic conditions, which is a key element of broad adaptability.

Because of its unique advantages, the approach Borlaug had adopted became standard practice in the Mexican program and has been applied even more broadly by CIMMYT's wheat scientists. In the early 1970s, Haldore Hanson, the Center's director general during 1971-78, suggested that it be called "shuttle breeding," after US Secretary of State Henry Kissinger's shuttle diplomacy in the Middle East. The term is thus fittingly reminiscent of Borlaug's message in his 1970 Nobel Peace Prize lecture about "the vital role of agriculture and food production in a world that is hungry, both for bread and for peace."

By the time the Green Revolution got underway in the 1960s, wide climatic adaptation and other major elements of broad adaptability had been assembled in a sizeable body of improved wheat germplasm. One important additional factor was resistance to a broad spectrum of diseases. (This subject is so fundamental to CIMMYT's work that it is treated at length in a subsequent section of this publication.) another was the semidwarf character (discussed earlier), which showed much the same effect throughout the developing world of translating inputs into grain with unprecedented efficiency. In combining these two factors to broaden the adaptation of the new wheat varieties, shuttle breeding was instrumental. Not only did it increase the pace of this work, but by exposing the germplasm to contrasting sets of disease and other pressures, it enhanced the effectiveness of selection against a wide range of production constraints.

Broadly adapted maize germplasm

The challenge of breeding maize germplasm on an international scale was little different from that for wheat. In both cases the trick was to develop germplasm that either outperforms locally available varieties or can be usefully combined with them to improve yield and other traits. The path maize scientists took toward this objective in the 1960s and 1970s was broadly similar to that followed in wheat research. In some ways, however, the going was much harder. For example, developing a shorter, more efficient tropical maize plant (as explained in an earlier section) proved more time-consuming than breeding semidwarf wheat varieties.

An even larger obstacle to broadening the adaptation of maize, though, was the greater number of distinct environments in which the crop is grown across the developing world. In wheat production, fairly extensive use of irrigation tends to level the playing field, giving CIMMYT germplasm an excellent chance to demonstrate its high yield potential at many locations. But such uniformity is rare in maize production, which takes place under highly diverse and generally less favorable conditions (with low use of fertilizer and other inputs), frequently putting introduced germplasm at a serious disadvantage and reducing the likelihood that it will excel at many sites. Given these circumstances, it is easy to imagine why CIMMYT steered away from maize hybrids in the 1960s and 1970s. Concern about the relationship between genetic diversity and broad adaptability, as well as the affordability of hybrids for poor farmers, led the Maize Program, then under the leadership of plant breeder Ernest Sprague, to follow a strategy that centered on populations with a broad genetic base and on germplasm testing at multiple sites to generate performance data from a wide range of environments.

THE PROVING GROUND OF ADAPTABILITY

If the notion of broad adaptability was heresy in the 1950s, the international distribution of advanced germplasm seemed like sacrilege. By making the best materials freely available to scientists worldwide, it exposed contributing plant breeders to the risk that others would name and release their cultivars without giving due credit. Moreover, conventional wisdom at the time reinforced a view of crop improvement as a largely local activity. But scientists working in the Mexican program and later at CIMMYT were acting according to a new and entirely different code. Their purpose was to develop germplasm for many environments, not just one or a few, and to disseminate this material as widely as possible.

Scientists in the Mexican program and later at CIMMYT were acting according to an entirely new code. Their purpose was to develop germplasm for many environments and to disseminate this material as widely as possible.

The instrument they employed to great effect for germplasm distribution was international testing. The first wheat nurseries went out in the 1960s, and by the following decade the foundation of CIMMYT's current wheat testing system was firmly in place. The major building blocks were screening nurseries including the best materials from the bread wheat breeding program in Mexico as well as replicated yield trials containing advanced lines and commercial varieties of spring bread wheat. To these were added trials focusing on durum wheat, triticale, barley, and specific stresses of the Center's target crops. By the 1980s the Wheat Program was distributing annually some 2,500 sets of 30 or more nurseries (Figure 2). The recipients in developing countries have drawn upon these materials heavily for further breeding, retesting, and release to farmers. They have also reported enormous amounts of useful data that have helped CIMMYT scientists identify the most promising lines for continued breeding as well as weaknesses, such as flagging disease resistance, that must be remedied. Thus, in addition to placing improved germplasm in the hands of hundreds of developing country scientists, the international trials and screening

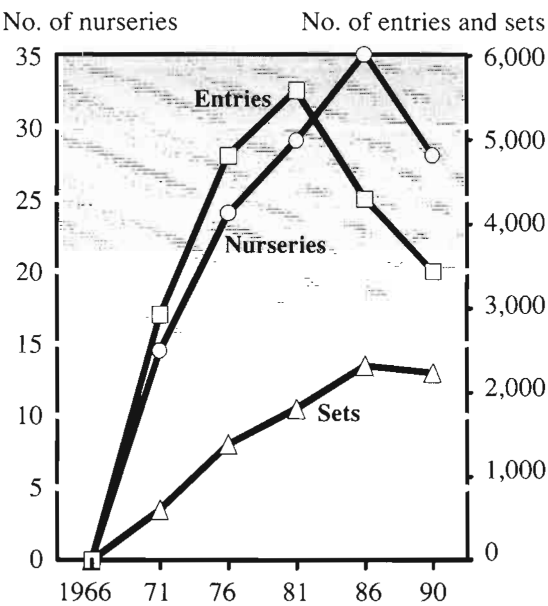

Figure 2. Distribution of CIMMYT wheat nurseries, 1966-90.

nurseries have served as a proving ground for broadly adapted materials and contributed substantially to their enhancement.

In the Maize Program's international testing system, which took shape in the early 1970s, germplasm distribution and improvement was even more closely wedded. Though currently undergoing modification, the system has for most of CIMMYT's history focused on several dozen broad-based populations, each consisting of a set number of families. With every two-year cycle of selection, some of the populations, each in the form of an International Progeny Testing Trial (IPTT), are sent to national programs for evaluation. a given IPTT is grown at one of the Center's own stations in Mexico, either Poza Rica in the lowland tropics or Tlaltizapán in a more subtropical climate, and at four or five other sites in other developing countries. The progeny are thus exposed to a wide range of disease pressures and other conditions. Data from the IPTTs are used, first, to determine which families will be recombined to constitute the next cycle of the population and, second, to select superior families to form experimental varieties (EVs). as indicated in Figure 3, these latter materials are disseminated to scores of national programs in Experimental Variety Trials (EVTs) and Elite Variety Trials (ELVTs). Note that the decline in the number of maize trials distributed in recent years reflects more selective targeting and a shift toward regional and special purpose trials that are not included in Figure 3. Based on the results of testing, cooperators request seed of promising EVs for incorporation into their own breeding programs or further testing and possible release to farmers. This system, while giving quite respectable rates of gain in population improvement, has gone

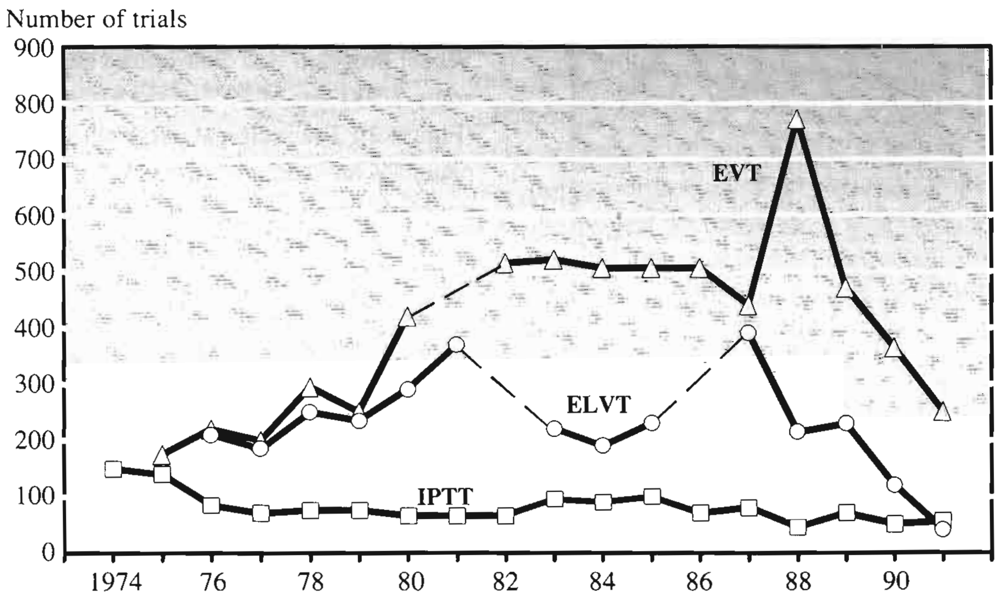

Figure 3. Distribution of CIMMYT maize trials, 1974-91. The dotted lines indicate one-year periods in which EVTs or ELVTs were not distributed.

far toward relieving the dearth of improved tropical and subtropical germplasm that prevailed in developing countries until the 1970s.

The limits of adaptability

In spite of the sweeping success of broadly adapted wheat varieties, no one ever claimed that, like some items of apparel, "one size fits all." CIMMYT scientists realized that trying to breed maize and wheat germplasm for everyone would have amounted to breeding it for no one. International testing proved helpful in defining the limits of broad adaptability at the same time that it demonstrated the validity of this concept. By maintaining a constant flow of data from national programs, the trials brought into sharper relief key features of the mosaic of maize and wheat production in developing countries. This information, combined with the travel and international experience of CIMMYT staff, guided efforts to shape broadly adapted germplasm more to the demands of distinct categories of environments.

By the 1980s the Center had devised a scheme for defining and delineating major production zones, which we now refer to as mega-environments. Each of these is an area of no less than 1 million hectares throughout which a distinct class of germplasm, possessing a unique combination of traits, is adapted to the prevailing conditions. The minimum area is the cutoff point below which we cannot justify an effort at CIMMYT to develop the required type of germplasm. Practically all mega-environments are international, and most are transcontinental, encompassing many areas of maize or wheat production that may be separated by thous-ands of kilometers. What binds these individual areas together is the relative uniformity of the response of a specific class of germplasm within them and of the climatic and other conditions (especially the prevalent biotic and abiotic stresses) affecting this response.

The Wheat Program caters to seven mega-environments, distinguished according to the crop's growth habit, moisture availability, temperature regime, biotic and abiotic stresses, and consumer preferences as to grain color and quality. The largest of these environments, encompassing some 32 million hectares (about a third of the total wheat area in developing countries) consists of lands where the climate is essentially temperate and wheat is irrigated. Typical of these are the Yaqui valley in Mexico, the Gangetic plains of India, and Egypt's Nile valley. at the opposite end of the spectrum lie the more challenging, acid soil environments, occupying under 2 million hectares, mostly in Brazil. The maize mosaic has an even more intricate design, containing a minimum of 25 mega-environments defined by climatic adaptation, length of the maize growing season, prevailing stresses, and the preferred grain color and type. a majority of these environments lie within the lowland tropics, constituting roughly 45% of the developing world's total maize area of some 80 million hectares. The large number of maize mega-environments has required special efforts, presided over by Ripusudan Paliwal, the Maize Program's current director, to ensure that CIMMYT's germplasm development work is properly geared to the complex requirements of maize production in developing countries.

The information available on mega-environments is less complete and precise than we would prefer, and efforts are underway to improve it. Nonetheless, even in its current state, the data provide a reasonable idea of the combinations of traits needed in materials destined for particular areas of the developing world. In addition to improving the targeting of our germplasm development programs, the data provide a basis for the allocation of resources to them. The proportion committed to a given environment depends, in general, on its level of production, severity of poverty, alternative sources of supply, and on the probability of gain. Within this framework the goal of the Center's breeding programs is broad adaptation within mega-environments, which is a reasonable compromise between the equally impossible goals of developing genotypes with almost limitless adaptation or generating as many different varieties as there are distinct production niches in the developing world.

Containing the Disease Threat: Chromosomes for Chemicals

A persistent misconception about the products of modern cereal breeding programs is that, like thoroughbred horses, they express their genetic superiority only if handled with great care. Common use of the term "high-yielding variety" (HYV) has perhaps reinforced this notion of "high-strung" genotypes that fall apart under stress. The grain of truth in this view is that high-yielding varieties do tend to show their yield advantage over traditional genotypes most distinctly under increased fertility and other modifications in crop management. What the critics of HYVs often overlook, however, is that improved germplasm is also bred to endure the hardships it will experience in farmers' fields. as a result, it is generally no more likely to succumb to these problems and in many cases is less susceptible to them than local landraces.

The most pernicious of the stresses affecting wheat and maize are scores of pathogens, which cause substantial yield losses in developing countries each year. Though many environments are not affected significantly by insects, drought, and soil problems, few escape the depredations of disease. Some pathogens constitute an almost continual source of stress on the crop season after season, while others show a wicked predilection for the surprise attack, reaching epidemic proportions only on occasion but with devastating effect. Because of the magnitude and ubiquity of the disease threat to wheat and maize, CIMMYT has made genetic resistance a central aim of its breeding programs, viewing this attribute as a vital complement of high yield potential, a chief contributor to broad adaptation, and a necessary means of reducing threats to the environment.

The wheat rust treadmill

Stem, leaf, and stripe rust are by far the most destructive diseases of wheat worldwide, and resistance to them is a critical requirement in all of the Center's advanced lines. Satisfying this condition is an almost endless task because of the rust fungi's ability to recombine and mutate into new virulent races. Having accomplished this metamorphosis, they can then multiply at an explosive rate, especially in the more productive wheat environments. In many areas it takes no more than five years for a new race to arise, requiring that the current resistant varieties be replaced by new ones with different resistance genes. To neglect this task is to invite the disaster of a rust epidemic. Thus, a major challenge for wheat scientists is to keep pace with the pathogens' rapid evolution, while seeking an exit from the perpetual-motion machine of rust resistance breeding.

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In the case of stem rust, it would seem that the Sisyphean struggle is over, though given the nature of the enemy we have not yet relaxed our guard. No epidemics of this disease in bread wheat have been reported anywhere in the world over the last 30 years. a complex of resistance genes (*Sr2* and others), carried by nearly all of CIMMYT's bread wheat germplasm, apparently confers durable resistance on the varieties now in production. On the long journey to reach this end, starting in the 1940s, we drew upon a wide range of sources to broaden the base of resistance, exposed the experimental germplasm to heavy disease pressure through inoculation, and searched for chinks in the armor of resistance through multilocational testing.

Using much the same research formula, we have been searching since the 1960s for a gene complex that will hold leaf rust in check. So far, the resistance in most improved varieties has depended on single major genes, which bear up against a specific race of the leaf rust pathogen for a while and may then succumb to a new mutant strain. although epidemics have been relatively rare in most parts of the developing world, a severe one in northwestern Mexico during the late 1970s dramatically illustrated the need for more durable resistance.

Now, we are on the verge of achieving, not the outright defeat of leaf rust, but a kind of truce. By analyzing varieties that have withstood the disease for 10 years or more, we have compiled data suggesting that the *Lr34* gene, along with several others, confer at least partial resistance on some of CIMMYT's high-yielding, broadly adapted varieties, as evidenced by a slow-rusting response. Under leaf rust attack, these materials show typical symptoms of the disease, but its progress is retarded to such an extent that the effect on yield is minimal. The result is a peaceful coexistence between the wheat crop and its major enemy. In the less advanced effort to control stripe rust, we also hope to identify genes responsible for partial resistance. Toward that end we are conducting genetic analyses of bread wheats that have shown durable resistance in various disease hotspots at high elevations and in other cool environments where this disease thrives.

The disease challenges of maize

Resistance to diseases of global importance is just as much a prerequisite of broadly adapted maize populations as it is of improved wheat. Though hardly a simple business, meeting this requirement has not been as trying an ordeal as the wheat scientists' quest for durable rust resistance. Particularly in the improvement of lowland tropical germplasm, the Maize Program was able in the 1970s to make fairly quick work of some of the principal diseases. Resistance to polysora rust and maydis leaf blight, for example, was probably already good in the original components of the Program's improved populations. Mostly landraces, these source materials had evolved near the center of origin of maize, where they were exposed continually to rust and blight. Resistance to these diseases has been maintained or improved at CIMMYT's station near Poza Rica, where their incidence is more than adequate for effective selection.

Our subtropical maize is also resistant to the two major diseases of this class of germplasm worldwide — turcicum leaf blight and common maize rust — though success was longer in coming than with the lowland tropical materials. The primary handicap was logistical. At CIMMYT's subtropical station in Tlaltizapán, conditions are not conducive to natural occurrence of leaf blight and rust and do not even permit adequate artificial infection. In the absence of disease pressure, obviously no progress could be made in improving resistance to these diseases. For various reasons little was done to overcome this obstacle during the 1970s. The main one was that CIMMYT did and still does assign higher priority to the lowland tropical maize mega-environments, which are more extensive than those of the subtropics and less adequately served by private seed companies.

Nonetheless, by the early 1980s, it was clear that we could not meet the germplasm needs of subtropical mega-environments, even at a comparatively modest level, as long as our populations lacked good resistance to turcicum leaf blight and common rust. By the middle of the decade, we had begun to apply a somewhat cumbersome but necessary remedy for this shortcoming. We continued improving the subtropical materials at Tlaltizapán but in combination with selection at Poza Rica during the winter season and at El Batán (the highland site that serves as CIMMYT's headquarters) in summer. The rust pathogen occurs naturally in the latter environment and that of leaf blight in both. Within this scheme selection for rust resistance was limited to one cycle per year, and the poor adaptation of subtropical germplasm at the highland site was somewhat problematic. But in spite of these drawbacks, recent evaluations of the subtropical populations have demonstrated conclusively that the procedure is effective in raising polygenic resistance to leaf blight and rust.

Targeting regional diseases of maize

Shortly after the Maize Program set in motion its population improvement scheme in conjunction with international testing, it also embarked on three projects that complemented this system by focusing on major diseases of primarily regional importance. Since these occur only at low levels or not at all in Mexico, resistance breeding programs had to be set up under various cooperative arrangements in areas where the diseases do pose a threat.

The first of these projects was established in Thailand during 1974 to develop germplasm resistant to downy mildew (DM). This disease attacks maize in various parts of the lowland tropics but is particularly severe in Southeast Asia, where it has depressed some countries' maize yields by 40% or more in some years. Epidemics in Thailand during the 1960s and 1970s seriously inhibited the government's efforts to promote maize production for export and for the country's rapidly expanding livestock industries. In addressing this problem, we capitalized on earlier research done by Rockefeller Foundation and Thai scientists. The first step was to establish a shuttle breeding program, in which three broad-based populations were selected in alternate crop seasons for DM resistance at locations in the Philippines and Thailand and for agronomic traits in Mexico. By 1980 the DM resistance of those materials had been significantly improved, and a new project was initiated to incorporate the trait into another three advanced populations from CIMMYT. The effect of this and similar work on other diseases was to enhance the utility of germplasm that had already proved popular in a certain region by adding to it resistance to a major disease endemic in that area. Additional populations have been developed more recently in an effort to guard against the breakdown of DM resistance in previous materials and to provide germplasm with even more desirable agronomic traits (Table 1).

In a variation on the theme of the DM work, CIMMYT joined forces during 1980 with the International Institute of Tropical Agriculture (IITA) to develop germplasm resistant to the maize streak virus, whose severe epidemics can devastate production in sub-Saharan Africa. Although we had been working on this problem since the 1970s under bilateral projects in Tanzania and Zaire, we had found it difficult to make progress through selection under natural disease pressure. Meanwhile, IITA had established facilities at its headquarters in Nigeria for mass rearing the leaf hopper vector of the streak virus and had worked out effective infestation and resistance screening techniques. To take advantage of these important contributions, CIMMYT shifted its own streak breeding program to IITA and was soon making rapid progress in converting experimental varieties to resistance and improving one of its populations for this trait. This work was centered exclusively on lowland tropical germplasm. But the streak virus also affects maize in the midaltitudes,

Table 1. Progress in breeding for resistance to downy mildew in Thailand and the Philippines

Population/ cycle	Grain yield (kg/ha)	Disease score (% infection)
Early white		
C0	5,171	59.7
C3	6,110	24.4
Early yellow		
C0	4,638	75.0
C3	6,510	18.4
Late white		
C0	5,770	63.8
C3	6,724	16.9
Late yellow		
C0	5,152	53.1
C3	7,113	15.9

which are concentrated mostly in the eastern and southern parts of the continent. To help deal with the streak problem in those regions and fill a significant gap in its collection of improved germplasm, the Center launched a new breeding initiative in Zimbabwe during 1985 (see pages 24-25).

Another of the Maize Program's projects for combatting regional disease threats has provided a new model for future cooperation with national programs in generating stress resistant genotypes. The specific aim of this work, begun during 1975 in cooperation with the national programs of El Salvador and Nicaragua, is to develop germplasm resistant to corn stunt, an important constraint of maize production mainly in Central America and the Caribbean. By 1980 good progress had been made in population improvement, and a number of resistant varieties had been tested and used in the region. In 1985 cooperative research on corn stunt was reorganized, using different germplasm and a new approach. What distinguishes the current arrangement in this project from others is that scientists in El Salvador and Nicaragua handle the breeding activities at their own experiment stations while CIMMYT staff support this work and assist in coordinating its international aspects. Apart from achieving its immediate objectives of developing and disseminating stunt resistant maize, this approach has demonstrated the possibilities of a more dynamic role for national programs in shaping the Center's maize germplasm to regional requirements.

Wheat diseases of more limited distribution

Like maize, wheat is attacked by various diseases that pose a serious threat but within relatively limited domains. They do not occur widely enough in the developing world to require that all of CIMMYT's advanced wheat germplasm be screened for resistance. Doing so would constitute a quixotic attempt to achieve ultrabroad adaptation, a goal the Center has rejected in opting for its focus on maize and wheat mega-environments. A more practical measure is to develop resistance in germplasm that is better suited for regions where the diseases occur.

The Wheat Program first encountered the need for such an approach in the late 1960s, when its new semidwarf varieties succumbed to septoria leaf blotch in the fairly cool, high-rainfall environments of Mediterranean North Africa. Yield losses in farmers' fields were as high as 50%. Afterwards, septoria also proved to be a severe problem in the highlands of East Africa, Mexico, and the Andean zone as well as in the Southern Cone. In seeking genetic variability f · resistance, the Program has hauled out just about every weapon in its research arsenal. At the outset of their campaign against septoria in 1971, CIMMYT wheat scientists distributed the first Regional Disease and Insect Screening Nursery to begin screening a wide range of materials. Some of the best resistance sources were derived from crosses of spring with winter wheat and through shuttle breeding between Mexico and Brazil. Additional resistant germplasm has emerged more recently from cooperative work with Chinese researchers and from CIMMYT's wheat wide cross program. Since 1985 we have also drawn heavily on the expertise of the Plant Protection Institute in the Netherlands and Tel Aviv University in Israel. The results of studies at these institutions suggest that the sources of resistance currently employed in the Center's breeding program have quite distinct genetic backgrounds, providing a reasonably firm guarantee of stable resistance.

During the 1980s CIMMYT has brought these same strategies — extensive screening, shuttle breeding, research networks, and wide crosses — to bear on another group of diseases that limit wheat production in the warmer areas. This work was begun in a period when Robert Havener, director general from 1978 to 1985, was encouraging greater emphasis on marginal areas and on the yield dependability of the Center's germplasm. The research on diseases is part of a broader effort to develop suitable germplasm and crop management practices for environments where wheat has not traditionally been grown (see discussion on page 38). Among the formidable barriers that stand in the way are helminthosporium spot blotch, fusarium head scab, and other diseases. Screening nurseries for these first two and for the warmer areas in general are now in circulation. Shuttle breeding is underway between Mexico and China to incorporate scab resistance into germplasm appropriate for the warmer areas, and a network involving both developing and developed countries has been set up to contend with spot blotch.

Rising disease threats to wheat

Two other diseases that have forced their way onto the international stage in the 1980s are barley yellow dwarf (BYD) and Karnal bunt. Though the former occurs in many parts of the world and affects various cereals, its damage to wheat may not become apparent until more aggressive diseases, such as the rusts, have been controlled. Karnal bunt, in contrast, has been observed only in India, Mexico, Nepal, and Pakistan but has acquired a notoriety far beyond these countries and out of proportion with the actual damage it has caused so far. Though it exerts little effect on yield, the disease reduces the quality of grain, with high levels of infection making it practically unmarketable. For that reason and because Karnal bunt is seedborne (it is soilborne as well), its presence is considered by some to be sufficient grounds for halting the movement of wheat grain across international borders.

CIMMYT and its collaborators are vigorously pursuing genetic resistance to both these diseases. We have been distributing specialized nurseries widely since the mid-1980s and have formed research networks. In the work on BYD, the Italian government is supporting efforts to transfer technology for integrated pest management from institutions in developed countries to the developing world by way of CIMMYT. To develop germplasm resistant to Karnal bunt, the Center has entered into a breeding partnership with Punjab Agricultural University in India. Considerable progress has been made in elucidating factors that affect the occurrence of these diseases and in developing effective procedures for selecting resistant germplasm; promising materials have been identified and are being evaluated by cooperators. The work on Karnal bunt has produced a device (referred to informally as the "killer Jacuzzi") that effectively removes Karnal bunt spores from wheat seed; this system is now used to wash all of our wheat germplasm destined for international nurseries.

Decentralization of Crop Improvement

CIMMYT's 25 years of experience in maize and wheat breeding have amply demonstrated that broadly adapted germplasm can be developed through astute selection at representative sites in Mexico, along with international testing. At the same time, this experience has revealed the limits of broad adaptability and the need to supplement the work in Mexico with plant breeding at locations outside the country. For that purpose the Center has initiated shuttle breeding projects and decentralized selected activities. In some of the latter cases, the Maize Program has had little choice but to undertake selection for particular traits outside Mexico (see discussion of regional diseases). In other cases both the Maize and Wheat Programs have decentralized their work on whole categories of germplasm, either out of necessity or simply because other locations offered compelling advantages.

Midaltitude maize in Zimbabwe

A mixture of these motives led the Maize Program to establish a station at Harare during 1985 for developing midaltitude tropical germplasm in cooperation with the University of Zimbabwe. The chief advantage of this site was its suitability for improving resistance to the prevalent midaltitude diseases worldwide. Another attraction was its central position in a region that has witnessed the development of efficient seed production industries and of significant achievements in maize breeding. It would have been hard to find more fertile ground for this new breeding initiative.

In any case the station had to be located in sub-Saharan Africa (which encompasses a large share of the developing world's midaltitude area) to ensure that CIMMYT's germplasm for this environment would have resistance to maize streak virus, a disease that is endemic in the region. To satisfy that requirement, we set up facilities in Zimbabwe (with IITA's participation) for mass rearing the insect vector of streak. Then, in a departure from the Maize Program's traditional approach of improving a more or less fixed set of populations over a long period, we devised a system in which many new populations are continually created from a large collection of elite germplasm. In subsequent stages of improvement, some of these populations are discarded, while the more promising ones are put to various uses. The result is to provide national programs with a continuous flow of new materials and a wider range of options in germplasm development.

Winter wheat in Turkey

CIMMYT's interest in winter wheat dates back to the early 1970s, when extensive crossing between spring and winter wheats was begun (see page 10). In adopting this approach, we were interested not so much in improving winter wheat per se as in making this germplasm serve as a handmaiden for the improvement of spring wheat, which was and still is given higher priority. By the mid-1980s, however, we had raised winter wheat from its lowly Cinderella status and given it a more significant place among CIMMYT's major breeding enterprises. This change in the fortunes of winter wheat followed from our new recognition that alternative sources of supply in the developing countries are few and of the possibilities for the Center's Wheat Program to contribute importantly in its improvement.

Toward that end we embarked on a cooperative project with Turkey's national program during 1984, with the aims of enlarging the pool of winter and, more recently, facultative wheats (the latter are in a sense intermediate between winter and spring wheats), broadening the adaptability of this germplasm, and enhancing its stress resistance. The experience and commitment of the country's national program, its wide range of environmental conditions, and broad spectrum of disease pressures made Turkey a logical partner for this international venture, which is concerned particularly with winter wheat areas of the West Asia and North Africa region. Among the most notable accomplishments of the project was to establish the International Winter Wheat Screening Nursery, which has greatly accelerated the exchange of germplasm among both developed and developing countries. In recent years we have further strengthened the international dimension of the project by joining forces with ICARDA and by engaging in more intensive cooperation with institutions in the USA and eastern Europe.

A New Prescription for Insect Resistance

Though CIMMYT now offers germplasm (particularly maize) with resistance to multiple insect species, for many years few, if any, of its improved materials showed a significant advantage under pest attack. In the case of wheat, little was done to alter this situation, because insects were not such a great problem worldwide, though some pose a serious regional threat. In maize production, on the other hand, they are a constant and widespread hazard, and slow progress in developing resistant germplasm has resulted from the extreme complexity of the task.

A growing menace to wheat production

Many insect species feed on the wheat crop, and some, such as the Hessian fly, may cause severe damage over sizeable areas. But until recently none has been considered so grave a threat to wheat production in developing countries that it warranted intensive breeding for resistance at CIMMYT. Entomology research in the Center's Wheat Program has focused instead on aphids that serve as vectors for disease. During the late 1980s, however, the Russian wheat aphid came crashing upon this tranquil scene. Damage caused by the aphid has so far been documented most thoroughly in the USA, but the insect has also been recorded in Africa and may pose a serious problem in other parts of the developing world as well. In an effort to contain this menace to the world's supply of wheat and other small grains, scientists from CIMMYT and the International Center for Agricultural Research for the Dry Areas (ICARDA) are testing thousands of barley, wheat, triticale, rye, and wheat wild relative materials, focusing on germplasm bank accessions that were collected in or near the aphid's area of origin. Promising germplasm identified so far is being put to use by the breeding programs of both centers.

Early research on maize insects

Unlike their counterparts in wheat, maize entomologists and their number one pest problem — the stem borers — are old adversaries. Developing germplasm resistant to these and other species has been one of the Maize Program's objectives since its inception. Toward that end Center entomologists evaluated a wide range of materials under natural insect infestation in the early 1970s and identified some possible sources of resistance. They were not able to do much with this germplasm, though, because the techniques employed then for mass rearing insects and artificially infesting maize plants with them were not able to create enough insect pressure for effective selection. By the late 1970s, this limitation had been overcome. A new system, developed through years of painstaking study and experimentation, enables us to mass rear fall armyworm, two species of borers, and corn earworm in sufficient quantities to infest more than 200,000 plants per year. The business end of this well-oiled machine is an insect applicator, referred to as the "bazooka," with which an experienced user can infest up to 1,500 plants per hour with insect larvae.

Upon clearing one obstacle, however, we came abruptly upon another, which prevented us from moving very far or fast toward the goal of insect resistance. We had gotten the entomology right but still had the breeding wrong. For some years after the new insect rearing and infestation methodologies were developed, we tried to improve resistance to single pest species in particular maize populations, using the same multitrait selection scheme that had proved effective for developing broadly adapted, disease resistant germplasm. The effort turned out to be essentially futile, because the populations at hand contained little genetic variation for insect resistance and because the effect of selection for this trait was diluted by simultaneous attempts to improve many other characters. The primary lesson of this experience was that insect resistance is a special trait whose development requires a somewhat different prescription from the work on diseases.

Multiple borer resistance

In 1984 the Maize Program began to experiment with a new formula in its work on insects. The first step was to find more promising germplasm to bolster the resistance of materials already available at CIMMYT. For that purpose we sent out requests for seed samples of all maize thought to have borer resistance. Interestingly enough, some of the germplasm we received had originally been obtained from the Center's own maize germplasm bank by scientists at several US universities, who had then put it to good use in developing insect resistant inbred lines. After initial resistance screening of the diverse collection of materials received from colleagues around the world, we then combined this germplasm with selections from some of our own materials to form the Multiple Borer Resistant (MBR) Population. What distinguished the subsequent improvement of MBR from previous attempts with other populations was that insect resistance received first priority, though not to the neglect of grain yield, adaptation, and plant type. As a result of this key difference, we made notable and fairly rapid progress in accumulating multiple genes controlling various mechanisms of resistance in the MBR population.

The proof of this accomplishment came in 1987, as the results from international testing of MBR began to trickle in. According to a 1988 conference paper by entomologist John Mihm and plant breeders Margaret Smith and David Jewell, data from the USA and from the Center's own stations in Mexico confirmed the population's resistance to European corn borer, southwestern corn borer, sugarcane borer, and fall armyworm. That was logical, since MBR contained sources of resistance to these species and had undergone intensive selection for resistance to them. Data from locations in Africa, however, provided an unexpected surprise. They indicated that the population also contains high levels of resistance to maize stalk borer and spotted stem borer, species to which it had never been subjected. These results illustrated dramatically the wide reach of MBR's resistance mechanisms and thus the feasibility of combatting various regional insect pests simultaneously through an international breeding program (Table 2).

Table 2. Progress in breeding for resistance to various insect species, 1989-90

Material		Grain yield[a] Infested (kg/ha)	Grain yield[a] Protected (kg/ha)	Mean damage score[b]
Susceptible checks:	Fontanelle 6230	2,900	5,270	7.5
	B73/Mo17	2,940	5,190	7.2
	Ki3/Tx601	3,620	4,910	6.7
	Pioneer 3184	2,800	4,670	6.4
Resistant materials:[c]	Across 86590-2 (ECB)	4,340	5,170	4.8
	Poza Rica 86590 (SCB)	4,230	5,100	4.7
	Mbita 86590 (Chilo)	4,510	5,270	4.7
	Tlaltizapán 85590 (SWCB)	4,160	5,170	4.8
	Across 86590 (IR)	4,250	5,000	4.6
Resistant check:	P47s3/CML139	6,070	7,190	4.5

[a] Mean for 8 locations.
[b] Mean for 12 locations. Damage was rated on a score of 1-9, in which 1 = highly resistant and 9 = highly susceptible.
[c] ECB = European corn borer, SCB = sugarcane borer, Chilo = spotted sorghum stem borer, and IR = insect resistant (that is, to various species).

CIMMYT continues to improve this population and to develop products from it that can serve as sources of insect resistance. Using these materials, national programs can invest locally adapted germplasm with insect resistance, and the Maize Program can incorporate this trait into broadly adapted populations for wide distribution in developing countries. To further enhance these possibilities, we have developed and are testing internationally the Multiple Insect Resistant Tropical (MIRT) Population. Unlike MBR, which is essentially subtropical or temperate in adaptation, MIRT has the disease resistance and other traits needed to provide an excellent source of insect resistance for lowland tropical germplasm. Eventually, we hope to apply the lessons learned from the work on stem borers and fall armyworm to other species as well. It is also clear that the development of special purpose populations, like MBR, has possibilities beyond the realm of insect resistance. The approach is already being applied in the Maize Program's work on drought, for example. Moreover, some CIMMYT scientists, such as George Varughese, associate director of the Wheat Program, speculate that one of the Center's principal tasks in the future will be to generate both maize and wheat populations that provide national programs with sources of particular traits.

The Abiotic Constraints of Maize and Wheat

The abiotic constraints of maize and wheat can be even more intractable than the crops' live enemies. So elusive are genetic solutions to some of them that the scientists working on these problems tend not to aim for resistance at all but are content with tolerant germplasm, which at least mitigates the effects of abiotic stress. The difficulty of achieving even this limited goal is that it generally requires a radical alteration of the plant's physiology, which may involve numerous genes. Once achieved, however, tolerance to an abiotic stress is essentially fixed, whereas the capacity of a genotype to resist a given biotic constraint may be cancelled by the evolution of the pathogen or pest.

Acid soils

Soil acidity is a common condition in high-rainfall areas where the native vegetation is forest or savanna, but it seriously limits maize and wheat production only in certain areas of South America, Asia, and Africa. The damage results from various factors — mainly toxic levels of aluminum and manganese and deficiencies of other elements, such as phosphorus — which act together or independently to limit plant growth. As is the case with most abiotic stresses, the problems associated with acid soils can be ameliorated through crop management practices, mainly deep liming. This measure is not always effective, however, and because of its considerable expense is beyond the reach of many farmers. A more practical means of assisting them is to develop and disseminate tolerant germplasm. Soil acidity has proved relatively amenable to a genetic solution, and both the Maize and Wheat Programs have developed tolerance at a minimal cost to yield potential under normal soil conditions.

The problem of acid soils first caught the attention of CIMMYT's Wheat Program in the late 1960s, when scientists realized that, mainly because of this condition, Brazilian farmers were not adopting the new semidwarf varieties. In spite of heavy applications of lime, the improved germplasm was placed at a serious disadvantage by its extreme susceptibility to aluminum and manganese toxicity as well as phosphorus deficiency. By the mid-1970s we had further realized that this problem was not peculiar to Brazil but occurred elsewhere in South America and other regions as well.

In 1972, CIMMYT and Brazil's national program (actually various national and regional research organizations in the country) initiated a shuttle breeding project in an effort to combine the high yield potential and other desirable traits of Mexican semidwarfs with the tolerance of the less productive Brazilian wheats to aluminum toxicity. Scientists at both ends of the shuttle make crosses between these two germplasm pools and then send subsequent generations to the other partner for screening under local soil conditions and disease pressures. To accelerate the process, CIMMYT researchers began in the late 1970s to screen lines for tolerance to aluminum toxicity, using laboratory procedures, whose results correlate well with those of field testing. Shortly afterwards the Brazilian program followed suit by setting up its own aluminum laboratory. By the early 1980s, the shuttle breeding scheme had achieved the desired result (Figure 4). Varieties are now

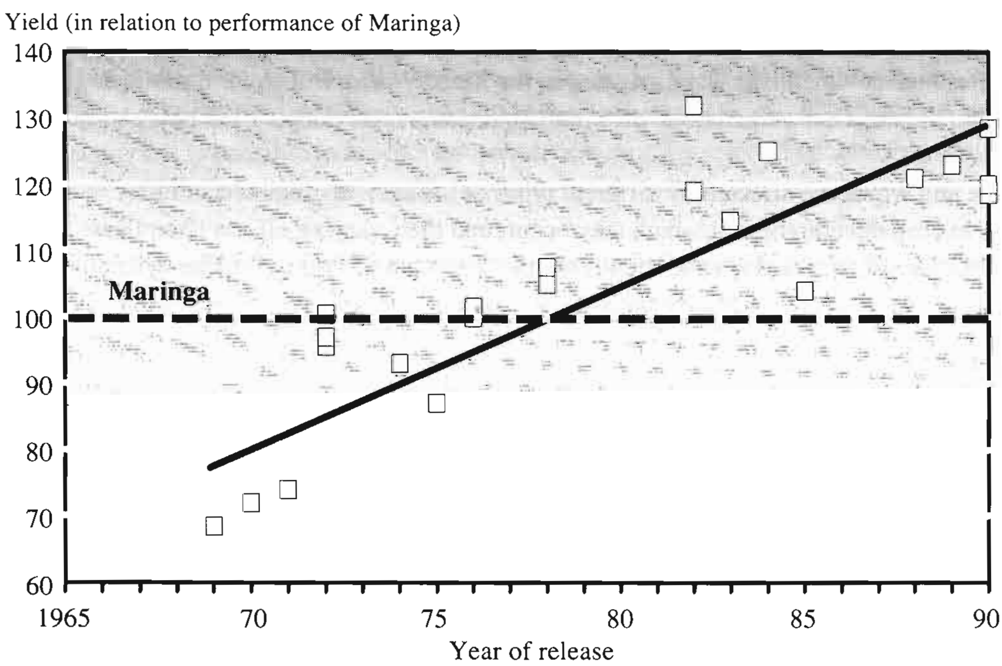

Figure 4. Yield of aluminum-tolerant wheat varieties released in South Paraná, Brazil. Since 1968 yield gains in this area, in spite of its formidable challenges to wheat production, have averaged just over 2% per year.

available to Brazilian farmers that have aluminum tolerance (plus improved efficiency in using P_2O_5) and show at least 25% higher yield potential than their local, aluminum tolerant predecessors. To give other countries access to advanced lines emanating from the shuttle scheme, the Center distributes the Acid Soil Wheat Screening Nursery to some 50 locations worldwide.

The Maize Program's efforts to contend with the problem of acid soils began in the late 1970s, when its Andean regional program, based in Colombia, developed a population specifically for improvement of aluminum tolerance. This work was intensified in 1985 with the development of four additional populations. Each year their progeny are evaluated under different concentrations of aluminum in about 8 developing countries in South America, Africa, and Asia, and cultivars derived from the populations are evaluated in some 20 countries around the world. As in the work on wheat, Brazil's national maize program (which initiated research on acid soil tolerance in the early 1970s) is an important contributor to and beneficiary from our testing network. The work in Colombia is complemented by the efforts of staff based in Thailand to combine acid soil tolerance with downy mildew resistance and other traits required in maize germplasm for the Asia region.

Drought

As is evident from various episodes in this account of CIMMYT's work, there are numerous parallels between maize and wheat in their research challenges but quite marked distinctions in the ways these must be addressed. No single problem brings the differences more sharply into focus than drought. It is a significant constraint of both crops, affecting about 40% of developing countries' total wheat area and an even greater share of maize, which is seldom irrigated in the Third World. But so far the Maize and Wheat Programs have taken quite different approaches in developing tolerant germplasm.

Maize and wheat are affected by different types of drought, distinguished mostly by the stage in crop development at which they occur, and their varying effects complicate the choice of a research strategy for countering this stress. In the case of maize, we have decided to focus on drought at flowering, both because it is common and because maize is extremely susceptible to it. The relative weakness of the crop under drought and some other types of stress lies in certain rather unusual features of its reproductive system. Unlike wheat, for example, a self-pollinating crop in which the male and female flowers are situated close together within a protective glume, maize is cross pollinating, and its floral parts, though occurring on the same plant, are separated by a considerable distance.

The battle of the sexes in maize

Equally unusual is the maize plant's decidedly "macho" behavior under drought at flowering, a stress that drastically reduces the plant's supply of photosynthate. More than enough of this scarce resource is apportioned to the male flower or tassel to ensure that pollen is shed at anthesis, but the female flower or ear is likely to get short shrift. So little is its share of photosynthate under stress at flowering that it often cannot accumulate sufficient biomass in a short enough time after anthesis to produce viable silks, receive pollen, and develop fertile seed.

In the course of its evolution, maize has come under little pressure to alter this pattern of behavior. Two factors express nature's apparent leniency in this case. One is that maize cross pollinates. The other is that in every genetically variable population there seem to be at least some plants in which the ear gains the upper hand over the tassel under stress at flowering and commands enough resources to produce fertile seed. These two circumstances permit the maize plant to pursue a male-oriented strategy for survival. By producing large amounts of pollen, it greatly increases the chances that at least some will reach the relatively few ears that develop fertile seed under drought at flowering. Often, these few seeds are sufficient to perpetuate the maize population.

Anthesis-silking interval

In the improvement of open-pollinated maize, plant breeders are obliged to be less indulgent than Nature. Because they are interested not just in a population's survival but in maximum grain production under stress, they must try to liberate maize from its habit of male dominance. Research at CIMMYT in the last few years points to a fairly straightforward means of accomplishing this end. The key is the phenomenon in maize under drought of a widened anthesis-silking interval (ASI). This is the most visible sign of the crop's male favoritism and an easy one to measure and manipulate. Increased ASI results from a postponement of silking, which in turn is a consequence of the inadequate supply of photosynthate to the developing ear (Figure 5). For each day of delay beyond the normal ASI of about two days, grain yield per plant drops by about 10% for up to eight or nine days. It is possible to reverse this trend, however, by selecting plants that show a narrower ASI under severe drought at flowering.

The effectiveness of this approach has been borne out by recent studies of the population Tuxpeño Sequía. Starting in 1975, this material underwent eight cycles of selection under three different moisture regimes for yield and a whole range of traits that are thought to be associated with drought tolerance. The only trait that showed a significant relationship with improved performance under drought was ASI. Largely as a result of selection for reduced ASI under drought, cycle 8 of the population shows a grain yield advantage of some 30% over nontolerant genotypes under drought severe enough at flowering to reduce yield potential by about two-thirds. The link between ASI and grain yield has been further confirmed by other CIMMYT studies of a wide array of germplasm, ranging from landraces to single-cross hybrids. Another intriguing observation from the studies on Tuxpeño Sequía is that the ability of cycle 8 to partition more photosynthate to the ear is quite independent of the environment. Genetic gains achieved under stress should thus translate into improved performance under more favorable conditions as well.

Cycle 8 of Tuxpeño Sequía is now one of numerous components of a drought-tolerant population, whose development was initiated in 1986 and whose purpose is to provide maize researchers with a readily usable source for this trait. Another component of the population is Michoacán 21, a maize landrace collection. In the early 1950s Robert Osler, who worked as a maize breeder in the Office of Special Studies and later became CIMMYT's deputy director general for administration, found that this material possesses a drought-tolerance mechanism, by which it defers plant development until drought is lifted.

Improving drought tolerance in wheat

Much experience in CIMMYT's Wheat Program supports the proposition that at least some materials selected for higher yields under optimum moisture conditions can show improved performance under drought. What probably accounts for this paradox, at least in part, is the semidwarf character of modern wheats, which makes them extremely efficient

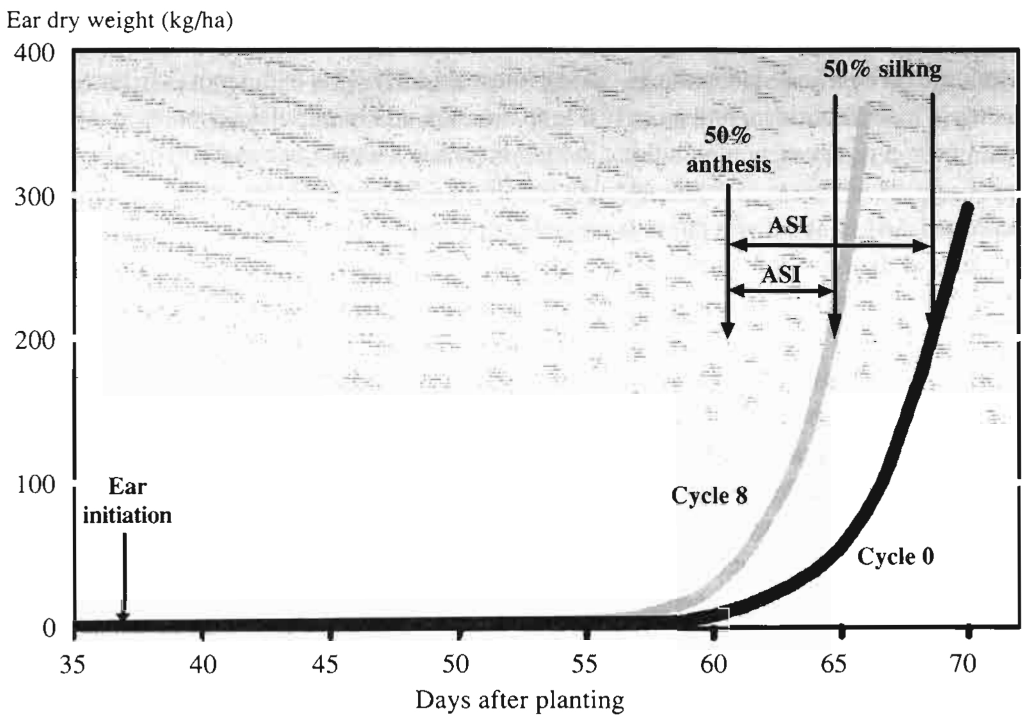

Figure 5. Ear dry weight accumulation in cycles 0 and 8 of the maize population Tuxpeño Sequía. In both cycles of selection, ear initiation and anthesis occur at roughly the same time. But then cycle 8 reaches the critical ear biomass necessary for silking much earlier than does cycle 0, giving it a reduced anthesis-silking interval (ASI) and higher grain production under drought.

producers of grain. Though expressed most clearly under favorable conditions, this ability may be apparent even under drought, perhaps because wheat has no Achilles' heel comparable to the extreme vulnerability of maize to drought at flowering. Semidwarf varieties derived through crossing of spring with winter wheats are especially likely to have a measure of drought tolerance. The evidence for this is circumstantial, consisting only in the wide acceptance of some such materials in semiarid environments. Nonetheless, the trend has been marked enough to provide CIMMYT with strong encouragement to screen germplasm developed under favorable conditions in pursuit of drought-tolerant genotypes. That is the approach we followed in the mid-1960s, when international wheat nurseries were first evaluated in drought-prone environments. By the early 1970s, the Center was also distributing early generation materials of dryland origin and in 1976 created the Drought Screening Nursery.

Even though this strategy has worked reasonably well, we decided in the 1976 to experiment with other approaches as well. By that time it was evident that a distinguishing feature of some important wheat environments is their high risk of water shortage. In an effort to tailor some of CIMMYT's germplasm more closely to the conditions of those environments, we began to select, screen, and test certain materials with and without adequate moisture, sometimes employing shuttle breeding to sample the germplasm under both conditions.

Breeding in dry environments is even more central to our cooperative program with ICARDA to develop both spring bread and durum wheats. About 70% of the area planted to the latter (which yields a glutenous flour used to make pasta, unleavened bread, and various other products) is dryland, and much of it is concentrated in the West Asia and North Africa region. The major elements of the cooperative Program's breeding approach are the use of landraces as parents in crosses with improved germplasm, multilocational testing, and selection for traits believed to be associated with drought tolerance. Though good progress is being made, the work is hindered by our inability so far to identify one or a few traits (like the anthesis-silking interval in maize) that show an unequivocal relationship with improved performance under drought. While actively participating in the search for solutions to these and other problems associated with selection for drought tolerance in dry environments, CIMMYT continues to evaluate the tolerance of outstanding germplasm developed under well-watered conditions. Out of the lively competition that has arisen between these two approaches, we hope to obtain more concrete evidence that one or the other is more effective. We will then have a firmer basis for supporting drought tolerance research in national programs.

High-Risk Ventures in Crop Improvement

Like its predecessor organizations, CIMMYT has shown a willingness to explore new approaches in meeting global germplasm requirements. As risky as some of these endeavors may have seemed at the outset, in retrospect most can be considered fairly safe bets. The relatively high rate of success from the Center's work has no doubt had much to do with the clarity of its aims. Rarely has there been much doubt about the need for a given line of crop improvement research in our programs or about the potential value of its contribution to agricultural development. Our challenge in most cases has been simply to come up with a satisfactory product to meet evident demands at the farm level.

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CIMMYT has deviated from this general pattern in three projects, dealing with 1) protein quality in maize, 2) triticale, an entirely new cereal produced by crossing wheat with rye, and 3) the expansion of wheat into warmer areas. (Arguably, wide crosses and applied molecular genetics research belong in the high-risk category as well but are dealt with in another section.) Though quite distinct in their details, these three enterprises have two general features in common: Each has presented a formidable scientific challenge, and each was undertaken to create a new option for farmers.

Quality protein maize

In the 1960s scientists at Purdue University, USA, discovered that the mutant *opaque-2* gene enhances the nutritional quality of maize. It does so by practically doubling the grain's content of lysine and tryptophan, two amino acids that are important in the diets of humans and monogastric animals. This development aroused keen interest among nutritionists who were forecasting at about that time an impending protein crisis in the developing world. The special appeal of *opaque-2* maize was that it promised to convert a staple of the poor into a cheap and accessible solution for what some perceived to be the poor person's number one nutritional problem.

Because of its global mandate to improve maize production "in all its aspects," CIMMYT seemed a logical candidate to help develop and disseminate suitable *opaque-2* varieties. In cooperation with various other organizations, the Center took up these tasks energetically in the hope of reducing both the protein gap and food gap in developing countries with one blow. But experience with *opaque-2* materials in the late 1960s proved disappointing.

They yielded somewhat less than other commercially available varieties, suffered heavy losses in storage, and had pale, lusterless grains as well as other drawbacks. Since producers and consumers naturally gave more weight to tangible qualities than to an imperceptible nutritional benefit, adoption of the new maize was almost nil.

But what if *opaque-2* varieties could be made to perform and look exactly like normal maize? This intriguing possibility would have seemed too remote for serious consideration if CIMMYT scientists had not observed in the early 1970s the action of modifier genes in reversing the deleterious effects of the *opaque-2* gene. On the strength of this finding, the Center launched a long-term breeding program (supported by a cereal chemistry laboratory under the leadership of Evangelina Villegas) to develop *opaque-2* germplasm that could compete with normal varieties. By the early 1980s, plant breeder Surinder Vasal had essentially reached this goal, and the Maize Program was offering national programs a wide range of quality protein maize (QPM) populations and experimental varieties with an acceptable grain type and reasonably good yields.

The underlying assumptions of this work throughout the 1970s were that the obstacles to acceptance of *opaque-2* maize had been largely technical and that, if these could be removed, rapid adoption would follow. Well over a dozen developing countries did experiment with this maize, and some released QPM varieties. But so far the area planted to them has not exceeded a few thousand hectares, most of which lies in Brazil, China, and Vietnam. Obviously, the circumstances governing the adoption of this germplasm are more complex than was originally thought. One problem that was perhaps underestimated in the 1970s is the cost to national programs of promoting a special product like QPM, whose nutritional advantage is not readily apparent and can quickly be lost (because of the recessive nature of the *opaque-2* gene) through contamination with pollen from normal maize. Most developing countries, hard pressed to disseminate seed of normal varieties successfully, could not easily afford the extension and marketing efforts required to get around those difficulties.

Moreover, by the 1980s their motivation to take such pains was far weaker than it might have been in the late 1960s. Concern about a protein gap had long since subsided. In the judgment of most nutritionists, malnutrition among the poor in developing countries was due not so much to the inferior protein quality of their food as to its inadequate quantity. Even in cases where protein deficiency is obviously a dire problem, especially for children and lactating mothers, there is no hard evidence that QPM provides a more effective and economical solution than other commodities with far higher protein content than maize. The new currents in human nutritional research greatly diminished the original vision of QPM as a means of providing the poor with a cheap source of protein. This revision did not, however, eliminate the possibility that a smaller but still important product niche might be found for QPM, especially in livestock production.

Within the last decade, CIMMYT has taken steps that should result in a fair evaluation of this option. One was to cease improvement of the QPM populations around the mid-1980s and to channel a moderate amount of resources into the development of QPM hybrids for a few target countries. In general, maize producers that adopt hybrids purchase new seed for each planting rather than selecting their own seed from the previous crop. This practice entirely eliminates the possibility that QPM will become contaminated with pollen from normal maize. Moreover, farmers adopting hybrids are likely to operate on a larger scale than subsistence farmers and have better access to markets. They are therefore better placed to provide an affordable supply of QPM to the large-scale livestock producers that would be most likely to realize a cost savings from substituting it for other protein sources.

In an effort to determine how significant those savings might be and under what conditions, CIMMYT's Economics Program conducted studies in El Salvador and Brazil during 1990 and in 1991 is making preliminary analyses of the possibilities in Southeast Asia. The initial results suggested that QPM does have potential as an ingredient in pig feed. If so, perhaps QPM could make an existing source of protein slightly more accessible to the poor by helping to lower the cost of pig production. A recent decline in the price of artificial lysine, however, has cast doubt upon even that possibility.

As a result of these considerations, we are phasing out QPM breeding at CIMMYT and will confine any future work on this maize to cooperation with national programs that continue to show an interest in promoting it. In spite of the disappointing results of our search for a product niche, we are proud of the important contribution of QPM development to breeding methodology. This work provided a convincing demonstration of the potential for altering maize germplasm by pyramiding numerous modifier genes.

Triticale

Unlike QPM, there is nothing even mildly surreptitious about triticale, no hidden nutritional benefit in an otherwise normal genotype. From the start of CIMMYT's work on this crop in the mid-1960s, its objective has been to provide farmers with a new and distinct alternative to wheat and other small grains. The main business of this highly ambitious project has been to complete the transformation of a botanical oddity (fashioned by European scientists in the 19th century) into a commercially viable cereal. Important breakthroughs had already been achieved between the 1930s and 1960s, but the triticale germplasm the Center inherited still had liabilities, mainly a high degree of seed sterility and seed shrivelling, a tall plant type, and fairly narrow adaptation.

In their first efforts to remedy these problems, CIMMYT scientists employed shuttle breeding in Mexico, the same approach by which broadly adapted semidwarf wheats were being developed. They were aided in this work by the entirely fortuitous outcross, later named Armadillo, of triticale with a Mexican semidwarf bread wheat. Armadillo and the materials derived from it showed a number of improvements, including higher seed fertility and yield, daylength insensitivity, and semidwarfism. The adaptation of this germplasm was subsequently broadened through further expansion of the triticale gene pool and wide evaluation in the International Triticale Yield Nurseries (ITYNs) initiated in 1969. But in spite of these advances, yields were not yet on a par with those of the best wheat varieties commercially available in Mexico. Only after continued efforts in the 1970s, under the leadership of plant breeder Frank Zillinsky, was the yield gap finally closed and the adaptability of triticale sufficiently broadened.

Farmers thus had their new option, but they still lacked a compelling incentive to chose triticale over wheat, given comparable yields in favorable environments. Strong hints that triticale might have a unique advantage in specific situations came from the results of the 14th ITYN, conducted in 1982-83. While yielding only slightly less than the best wheat varieties under optimum conditions, the top triticales performed markedly better under acid soil conditions and in highland tropical environments and also showed a distinct advantage in dry areas. The top performers were so-called "complete" triticales — those carrying the full complement of rye chromosomes — rather than "substitute" types (like Armadillo), in which a wheat chromosome is substituted for one of rye (Figure 6). These results prompted triticale breeders to exchange their strategy of competing with wheat for one ofcomplementing it. Starting in the mid-1980s, they greatly reduced the emphasis on triticale performance under favorable conditions and began to mold their germplasm, using mainly complete types, more deliberately to the harsher demands of marginal environments. This is a quite different response from that of QPM researchers to a somewhat similar predicament, but it reflects just as clearly a new focus on target environments and countries.

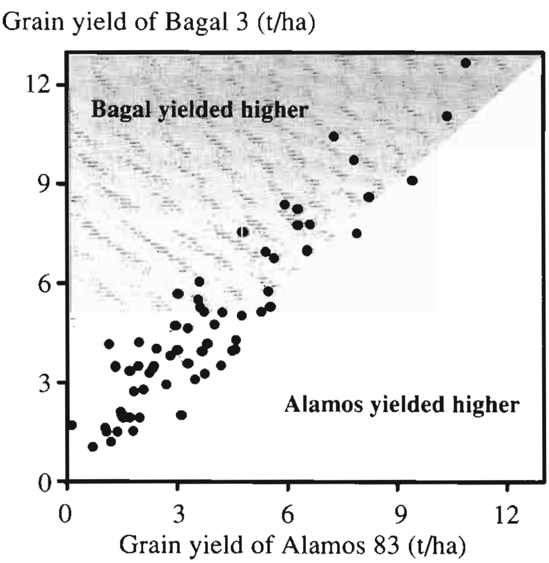

Figure 6. Yields of the complete triticale Bagal 3, compared to those of the substituted triticale Alamos 83 in the 19th International Triticale Yield Nursery. The more numerous points in the shaded area represent locations at which Bagal yielded higher than Alamos.

To create a larger niche for triticale in marginal areas will require vigorous promotion in selected developing countries. Whether or not to pursue this course is obviously a matter for the concerned national programs to decide. Where they are interested, CIMMYT can assist by helping to examine the possibilities for triticale production under particular circumstances and by formulating promotion strategies, providing appropriate germplasm, and supporting crop management research. In 1986, we conducted a study of triticale production in the central Mexican highlands and expect to initiate another in Tunisia. From the information gathered so far, it appears that triticale has potential as a source of forage and feed. Even so, the jury is still out on triticale, and in accord with CIMMYT's Strategic Plan, its role will be reassessed in 1993.

Wheat for warmer environments

During the early 1980s, CIMMYT embarked on a comprehensive project to extend wheat beyond its normal limits—from the temperate zone into warmer areas characterized either by very humid or dry but irrigated conditions. In the previous decade, the Center's international wheat nurseries had brought to light some varieties that were reasonably well adapted to such environments. A number of countries lying within or near the tropics had adopted these materials and had gone to considerable lengths to introduce them where wheat had not traditionally been grown.

The chief rationale for these exertions was a prior departure from tradition. In many areas of the tropics, rapid urbanization has been accompanied by a rising demand for wheat products. Their convenience, association with affluence, and low price (often the result of heavy government subsidies) has made them quite attractive to urban consumers. The price of turning away from traditional foods, though, has been hefty expenditures on imported wheat. By stimulating domestic production, many governments hope to reduce this burden, if not eliminate it altogether.

Helping national programs achieve this goal would seem to be a less hazardous undertaking than QPM or triticale. After all, the transfer of a major crop beyond its traditional bounds is not unprecedented. The introduction of maize in Europe, for example, and of soybeans in North America and Brazil has generally altered the agricultural geography of these regions for the better. Developing countries on three continents are already committed to a similar expansion in the climatic range of wheat. Even so, this work has proved to be somewhat controversial, drawing criticism on both biological and economic grounds.

On the biological front, the challenges are indeed formidable. In many of the warmer environments, wheat is beset by a different array of diseases than is found in the temperate zone, and it is much more likely to suffer from various abiotic stresses, including aluminum toxicity, drought, and heat. As described earlier good progress has been made in dealing with some of these problems, particularly the diseases and aluminum toxicity (Figure 7). We have also found that better crop management can improve yields dramatically under hot, dry irrigated conditions. The search for heat tolerant genotypes, on the other hand, is going more slowly. The key economic questions are whether wheat contributes more effectively than competing crops to national income or to savings of foreign exchange and under what circumstances it will be economically attractive to farmers.

Managing risk

CIMMYT's inclination to press ahead with these projects in spite of skepticism in some quarters is partly a product of its Green Revolution experience with semidwarf wheats. They, too, sparked a controversy. But its outcome was a clear endorsement of sustained efforts to cope with the biological, economic, and political barriers to any technical innovation with a reasonable chance of benefitting farmers in the developing world. The difficulty, of course, is defining "a reasonable chance." Ideally, one would thoroughly assess the economic prospects of new technology before investing in its development. But in practice one cannot always divorce the economic from the biological considerations so easily. What is required is a sense of the probability of achieving various yield levels, and this is a tenuous judgment at best.

Admittedly, the three projects discussed here are especially risky. But to some degree, so is all research. Rather than avoid taking chances altogether (and forego a possible payoff), CIMMYT attempts to manage risk by keeping the number of high-risk ventures relatively low and by periodically reassessing their outlook and then adjusting the research agenda accordingly. This is a common approach and one we apply broadly in all of our activities.

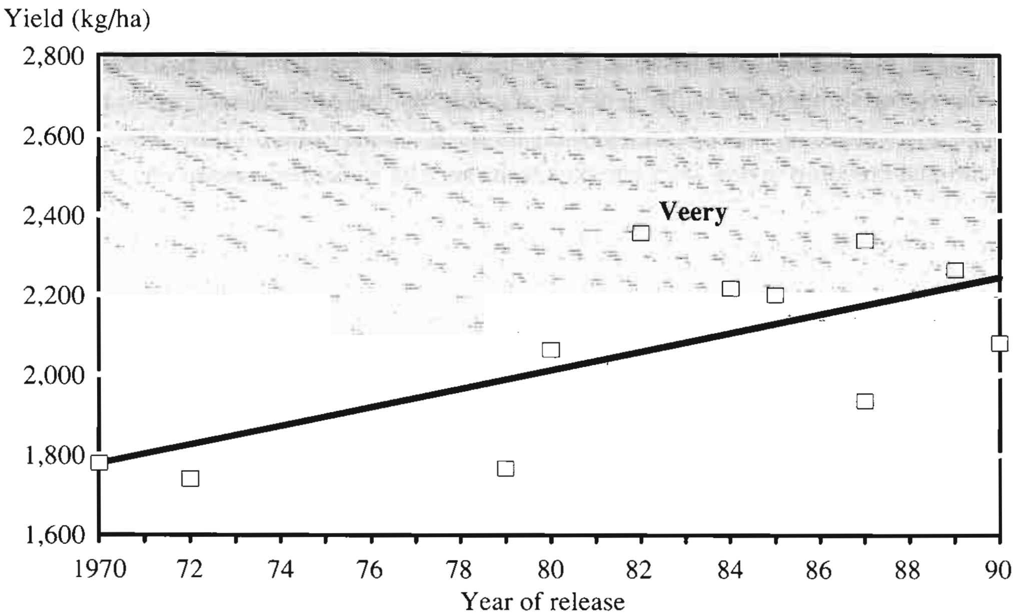

Figure 7. Yield of varieties released in Paraguay (averages across four sites for one year, without fungicide treatment). From 1972 to 1990, the annual rate of yield gain is estimated to be 1.3%, a quite respectable figure in a country where wheat is grown in fairly warm environments with heavy disease pressure. Notice that the Veery-based variety is well above the trend line.

Old Materials and New Tools

CIMMYT's crop improvement programs work mostly with improved germplasm and proven breeding techniques. But they have also been engaged for many years in various tasks aimed at marshalling less refined genetic resources — the landraces and wild relatives — for the purposes of maize and wheat improvement. In most developing countries, the landraces have been displaced to a considerable extent by improved varieties, and change in agricultural communities has similarly diminished populations of the wild relatives. As this germplasm has disappeared from the rural landscape, much of it has been systematically collected and preserved in germplasm banks, with the expectation that it could prove helpful, perhaps essential, to crop breeding. The steps by which CIMMYT has arrived at its current commitment to conserving genetic resources are described on pages 44-46.

One of the keys to maintaining this commitment is a clear demonstration of the immediate value of the germplasm that has been rescued. Particularly during the last five years, the Center's breeding programs have worked toward this goal by attacking some of the barriers to wider utilization of landraces (such as the lack of readily accessible documentation) and by searching these materials more actively for useful traits. For an even longer time, we have employed techniques to transfer genes from the wild relatives of maize and wheat into improved germplasm of the cultivated crops. Though difficult and time-consuming, these wide crosses have proved to be quite effective as a means of harnessing genetic diversity that is lacking in the landraces and improved germplasm. Quite recently, CIMMYT has made major commitments to examining the potential of new tools developed through molecular genetics research. By these means we hope to both enhance our wide-cross procedures and increase the efficiency of our efforts through conventional breeding to deal with complex traits such as insect resistance.

Wheat wide crosses

Especially in the case of wheat, CIMMYT has had powerful incentives to make a determined effort in wide-crosses research. The most compelling perhaps are the ability of some wheat disease pathogens (most notably those of the rusts) to mutate rapidly into new virulent forms and the heightened importance of certain biotic and abiotic stresses in areas where modern semidwarf wheats have spread since the late 1960s. Both circumstances have compelled us to search far and wide for new sources of resistance genes. What tempted us to look beyond the wheat gene pool for additional genetic variation was the large number of genera and species related to wheat and the evident richness of these materials in useful traits.

Inspired by early progress in the improvement of triticale (a wide cross between wheat and rye), CIMMYT began in 1975 to hybridize wheat with the related genera *Agropyron* and *Elymus* in conjunction with a somewhat brief experiment with wheat-by-barley crosses. Not until 1979, though, when we assigned a cytologist, A. Mujeeb-Kazi, full-time to this work, did wheat wide crosses shift into high gear. Since then the program has, at least until recently, dedicated most of its effort to intergeneric hybridization, by far more difficult than interspecific wide crosses. At the outset the focus on alien genera was considered a risky, long-term venture but one the Wheat Program could afford as a modest supplement to its substantial efforts in applied research with a more certain payoff. In retrospect it is apparent that, by concentrating first on an especially arduous task, the wide crosses program has provided a thoroughly convincing demonstration of its ability to contribute importantly to germplasm improvement.

Through intensive efforts in applied cytogenetics, we have devised effective procedures and developed advanced derivatives of wide hybrids that possess resistance to various diseases and tolerance to salt.

Numerous technical challenges lay in the path toward successful hybridization of wheat with alien genera, particularly the reduction of natural barriers to these crosses, the recovery of embryos resulting from them, and confirmation of the presence of desired alien genetic material in early generation progeny. Through intensive efforts in applied cytogenetics, we have devised effective procedures for accomplishing these steps and developed advanced derivatives of wide hybrids possessing resistance to leaf rust, septoria leaf blotch, helminthosporium spot blotch, and fusarium head scab as well as tolerance to salt. The wide-crosses program delivered these materials to our breeding programs within about a decade after the research was begun in earnest, a remarkably short time for this type of work, and some of them are now undergoing yield testing in national programs.

In 1986, with its research on alien genera well along, the Wheat Program initiated interspecific hybridization. Using a procedure that imitates the natural cross believed to have produced the first bread wheat — that is, durum wheat with the primitive grass *Triticum tauschii* — we have developed about 250 so-called synthetic wheats. Evaluations of these materials indicate that they include sources of resistance to several important diseases, such as helminthosporium spot blotch and Karnal bunt, and tolerance to saline soils. It also appears that certain of these synthetics are especially suitable for a project in which CIMMYT and Cornell University, USA, are laying the groundwork for use of restriction fragment length polymorphism (RFLP) technology in conventional wheat and barley breeding. Another way in which we are supporting this research is to provide wheat germplasm derived by crossing the crop with maize. This procedure has proved more widely applicable and less cumbersome than other methods for generating the homozygous wheat materials required by the RFLP project.

Maize wide crosses

Though potentially useful for crop improvement, hybridization of maize with its wild relatives would appear to be a somewhat less enticing proposition than wheat wide crosses. A primary deterrent is the relatively limited number of options. Interspecific hybridization, for example, so promising an avenue in wheat, is essentially pointless in maize. Since the crop crosses naturally with several other *Zea* species referred to collectively as teosinte, it seems likely that whatever useful variation this wild relative carries has long since found its way into the cultivated crop. The only promising candidate for intergeneric hybridization is *Tripsacum*. And though it has numerous desirable attributes (including resistance to most common diseases and insect pests of maize), there are other more accessible sources for many of them. Genetic variation for disease resistance, for example, is already adequate in CIMMYT's wide array of improved germplasm and is also abundant in our landrace collection. A far more desirable prize is *Tripsacum's* insect resistance, which would bolster that present in maize populations developed since the mid-1980s to serve as sources of this trait.

For insect resistance or any other character, however, the *Tripsacum* gene pool is still largely untapped. This state of affairs reflects both the difficulty of the task and hence the Center's relatively modest allocation of resources to it. Since the work on *Tripsacum* was begun in 1973, the Maize Program has seldom made this the primary responsibility of at least one scientist. And until the early 1980s, *Tripsacum* was not even the exclusive focus of the wide-crosses program but competed for resources with hybridization of maize with sorghum and millet. In spite of these limitations, "considerable improvement" had been made by 1983, according to a CIMMYT report from this period, "over previous attempts" to isolate maize x *Tripsacum* hybrids. The primary challenge that remains is to derive successive generations from those hybrids through techniques such as backcrossing, an essential step for developing maize germplasm with the desired alien genes.

More recent events at CIMMYT have raised expectations that in time this barrier, too, can be overcome. The results of studies involving in vitro culture of embryos from maize x *Tripsacum* hybrids indicate that this technique could be helpful in accomplishing gene transfer between the cultivated crop and its wild relative. The process should also be facilitated by a project we initiated during 1988 in cooperation with the University of Minnesota, USA, to employ RFLPs for monitoring the introgression of genetic material from *Tripsacum* into maize. The work received a notable boost in 1989 with the start of a project (conducted by visiting scientists from France) to form a more complete collection of *Tripsacum* germplasm and to cross this material with maize. The project's ultimate objective is to invest crop germplasm with the wild relative's ability to reproduce by means of apomixis (or asexual seed production) and with its stress resistance.

Fields with four walls

CIMMYT's persistent advocacy of a strong field orientation in research has tended to mask its lesser but still substantial commitment to laboratory investigations, of which the wide-crosses work discussed above is a prominent example. In addition, the Center's laboratories have provided certain general services in cereal chemistry (mostly in connection with the development of quality protein maize) and in soils and plant nutrition. Other tasks are undertaken by the following specialized laboratories:

- *Industrial quality:* Evaluates breeding materials from the Wheat Program for their milling and baking qualities.
- *Insect mass rearing:* Annually produces several million larvae of maize insect pests for resistance selection under artificial infestation.
- *Pathology:* Develops techniques for detecting, isolating, and analyzing the disease agents that attack maize and wheat.
- *Seed Health:* Monitors germplasm introductions, international nurseries, and the multiplication and handling of seed to ensure that germplasm imported or exported by CIMMYT is in the best possible condition.

These units are so closely integrated with our breeding programs as to make any sharp distinction between field and lab work somewhat misleading. All of them perform functions without which effective crop improvement for key traits would be impossible. And this interdependence between laboratory tools and field operations is becoming even more complete as the methodologies of conventional plant breeding are augmented with techniques emerging from molecular genetics research. To begin exploring the possibilities of these new tools, CIMMYT constructed a laboratory at headquarters for applied molecular genetics research. Staff involved in this research have been notably successful in quickly incorporating it into some of our main crop improvement endeavors and in establishing good relationships with plant breeders.

The new lab makes it possible for us to work on the use of molecular markers to analyze the genomes of maize, wheat, *Tripsacum*, rye, and related species. Our scientists have also started developing procedures and computer software to enhance the use of these markers in crop improvement. One important innovation is a protocol for detecting RFLPs that does not use radioactive substances but rather involves first labeling probes with a nonradioactive compound, attaching enzyme-linked antibodies to probes bound to DNA fragments, and locating the enzyme by means of a light-emitting substrate. Though currently centered on RFLP technology, our applied molecular genetics research is likely to include in the near future various projects related to the transformation of maize with genes from the soil bacterium *Bacillus thuringiensis*, some strains of which are toxic to corn borers. All of this research features strong collaboration with institutions in developed and developing countries. In RFLP research we are working with Cornell University, USA, to develop an RFLP map for bread wheat; with the Mexican Center for Research and Advanced Studies of the National Polytechnic Institute to determine relationships between RFLP probes and genomic segments associated with drought tolerance in maize; and with an international group studying the use of RFLPs in research on complex traits in maize, such as corn borer resistance.

CIMMYT's Germplasm Banks: Custodians of Diversity

As an institution dedicated primarily to plant breeding, CIMMYT since its inception has been inherently both a user and a generator of crop genetic resources. Not until the mid-1980s, however, did the Center explicitly recognize major curatorial responsibility for an important part of the world's endowment of maize and wheat germplasm.

CIMMYT's germplasm inheritance

Our early attitudes toward genetic resources were influenced by the Center's predecessor organization in Mexico, whose experience dramatically illustrated the value of this material but provided little encouragement to undertake its long-term preservation. It seemed especially pointless to assume such a responsibility in the case of wheat. By the 1940s germplasm of the crop had already been well collected and studied at centers in North America and elsewhere. Like gardeners shopping from seed catalogues, scientists could mail-order the materials they needed from anywhere in the world. That was very much the manner in which Norman Borlaug obtained seed bearing the Norin 10 dwarfing genes, which permitted the development of high-yielding semidwarf wheats. In view of such precedents, CIMMYT had little reason to doubt the efficacy of existing arrangements for preserving wheat genetic resources. As a satisfied customer of this system, the Center needed only an active collection without the higher cost facilities required for long-term conservation.

For the improvement of tropical maize, in stark contrast to the situation in wheat, promising genetic resources were not available from existing collections in the 1940s. Consequently, maize scientists had to build a modern breeding program practically from the ground up, recalls Edwin Wellhausen (who would become CIMMYT's first director-general) through the "systematic collection of indigenous varieties in Mexico's principal maize-growing areas." These original collections became the foundation of the Center's maize germplasm endowment, to which additional materials from other Latin American countries were added subsequently. All of these resources were placed in a new medium-term storage facility (under the supervision of Mario Gutiérrez) upon the inauguration of CIMMYT's headquarters in 1971.

But the original impulse that led to the establishment of this collection did not accord with the temper of the 1960s and 1970s. The population time bomb was ticking; the countdown to famine was nearing zero: The Center's maize breeders, like their colleagues in wheat, raced to turn out high-yielding varieties. Opting for the most efficient breeding strategy, they focused on advanced and elite materials, into which earlier breeding had already incorporated much of the most obviously useful variability from the landraces. By the early 1970s, with few clients among the breeders, both maize and wheat genetic resources at CIMMYT were suffering from neglect.

The genetic resources movement

In 1980 practical considerations compelled CIMMYT to undertake construction of its first proper seed bank for wheat. The new facility, completed in 1981, provided enough space for the breeders' growing collection of improved materials. By this time, however, such strictly utilitarian concerns were out of step with scientific and public opinion on genetic resources. Previously submerged in academic obscurity, this subject now held the public and political spotlight. Genetic vulnerability and related issues surfaced increasingly in the mass media as well as in scientific journals. The heightened attention paid to genetic resources underscored the extent of past neglect. In 1975 the International Board for Plant Genetic Resources (IBPGR) could count in the entire world, developing and developed, only eight institutions with adequate facilities for long-term storage of seeds. As a leader in the utilization and development of maize and wheat germplasm for the developing world, CIMMYT came in for its share — perhaps more than its share — of criticism. One critic asserted that the world's seed banks were little better than "morgues."

The challenge from within

While many Center scientists questioned various specifics of such indictments, they welcomed the strong endorsement of a larger role for CIMMYT in genetic resources. It was apparent that developments in crop improvement had gradually invalidated the central assumption underlying the Center's utilitarian views on genetic resources — namely that these materials have little or no value for practical breeding programs. By the mid-1980s, CIMMYT breeders were showing new interest in the genes of previously depreciated distant relatives, superannuated landraces, and obsolete varieties in the gene banks. Wide crosses between distantly related genotypes, though difficult with conventional breeding techniques, were becoming routine. It was expected that just over the biotechnology horizon were methods for isolating desirable genes from otherwise undesirable genomes and for inserting them directly into improved germplasm. For such promising scientific enterprises, comprehensive, thoroughly documented gene banks at CIMMYT would be indispensible assets.

A house in order

In 1985, preparing for what its annual report heralded as "more active stewardship over its genetic resources," the Center undertook a thorough overhaul of the maize germplasm collection. A new curator, Suketoshi Taba, was appointed as the maize germplasm bank's first full-time head in a decade. With support from IBPGR, one of the cold-rooms built in 1971 for medium-term storage of maize germplasm was renovated in 1985 to maintain -15°C, the temperature needed to preserve a base collection for 60-100 years without regeneration. Garrison Wilkes, a leading expert on genetic resources issues, was brought in that same year primarily to assess the condition of the maize germplasm bank and to help organize into accessible computer data an overwhelming backlog of handwritten information about the bank's accessions. In this latter task, the contribution of technician Guadalupe Guevara proved invaluable, since he had many years of experience in regenerating the bank accessions and recording data on them.

One strategic consideration that emerged from these efforts was that CIMMYT should be responsible for certain parts of the world base collection of maize germplasm. At its March 1986 meeting, the Program Committee of the Center's Board of Trustees strongly endorsed this line of thinking, concluding that "CIMMYT should continue to collect, conserve, document, and evaluate these races and their wild relatives . . . in cooperation with, and with the support of, IBPGR . . . thus playing CIMMYT's part in the network of conserving maize genetic resources." Later in 1986, at CIMMYT's initiative, a series of exchanges with IBPGR culminated in a landmark definition of the Center's role as curator of portions of the world's collection of maize and wheat germplasm. These discussions led to CIMMYT's final acceptance of responsibility for maintaining a base collection of landraces of maize native to the Western Hemisphere and a global base collection of bread wheat and triticale.

CIMMYT's Broader Research Agenda

Any organization whose central aim is the successful development and dissemination of a relatively complex product must know the circumstances surrounding its acceptance and use. Does the product fit users' needs? Does it perform as expected? How can it be improved? These are the sorts of questions — as applicable to improved germplasm as to automobiles or computer software — that accounted for CIMMYT's original commitments to agronomy and social sciences research. By providing answers to those questions and going on to address further issues that transcend but still impinge on the Center's breeding programs, these two disciplines firmly established a place at the Center and acquired an identity that extends beyond their relevance to crop improvement. To a certain extent this identity is a shared one, rooted in the mutual interest of CIMMYT agronomists and social scientists in technology design and evaluation, especially through on-farm research.

Agronomy in the campaigns against hunger

Well before 1966 agronomists had carved out a niche for themselves in CIMMYT's predecessor organizations, which showed a keen awareness of the relevance of crop management issues to their efforts in plant breeding. As semidwarf wheats emerging from CIMMYT's work gained ground in India and Pakistan, agronomists were called upon to help formulate packages of practices that would enable farmers to realize large increases in crop yields with the new seed. Though affecting a huge area, this work was highly focused, centering initially on a few countries and mainly on favorable and relatively uniform environments where wheat is irrigated. According to the authors of Wheat in the Third World (Haldore Hanson, Norman Borlaug, and Glenn Anderson), which chronicles the Green Revolution in these and other countries, agronomists were able to devise a more or less standard set of practices, including a "generalized fertilizer formula," that was applicable for the semidwarf wheats all across India's northern plains.

By addressing issues that transcend but still impinge on the Center's breeding programs, agronomists and social scientists acquired an identity at CIMMYT that extends beyond their contribution to crop improvement.

Social science: Ally or adversary?

The beginnings of social science research at CIMMYT were not so auspicious. In fact, the Center conducted none at all until the early 1970s, mainly because management saw little need for it. In a recent document looking back at the Economics Program's 20-year history, Derek Byerlee, its current director, describes the prevailing attitude during CIMMYT's early years as follows: "Its semidwarf wheats were spreading rapidly, . . . and one of its scientists had become the first agriculturalist to win a Nobel Prize. With such success, who needed social scientists?" Indifference bordered on hostility among some Center staff, who felt that social science could be a subversive influence. After all, some social scientists questioned the success of the Green Revolution, contending, among other things, that semidwarf wheats had made the rich richer and the poor poorer.

All the while, however, a number of influential figures — including some at the Ford Foundation and others among the Center's Board of Trustees — argued that there was an important role for social scientists at CIMMYT. After discussing the question over a period of at least two years, the Board voted in 1969 to hire a single economist. Oddly enough, just as the reasons for not having social scientists stemmed from the Green Revolution, so did CIMMYT's motives for reversing this decision. The Board felt that the Center needed an in-house social science capacity to blunt criticism from outside the Center, to investigate so-called "second-generation" problems of the Green Revolution, and to help increase the pace of change in maize production.

The global challenge of crop management research

Soon after the successes of semidwarf wheats in South Asia, agronomists followed the rapid movement of this new germplasm into other countries of Asia, North Africa, and South America. In some cases the crop management issues proved to be more challenging than earlier efforts to assemble packages of practices. It took nearly a decade, for example, to devise a new system for winter wheat production on Turkey's semiarid Anatolian plateau.

Like their counterparts in wheat, maize agronomists employed by or associated with CIMMYT fanned out across the developing world in the early 1970s to help national programs develop new production practices for different situations. But from the start they were faced with a far greater diversity of production environments and systems, which limited progress to somewhat less than revolutionary proportions. Improvements in maize production did come, but they were more gradual than was the case with wheat.

The experience of both maize and wheat agronomists during this period brought into sharper focus the central question with which they have been grappling ever since. Given the relatively site-specific nature of crop management research (CMR) and the great diversity of circumstances that determine crop management, how can CIMMYT agronomists work effectively on a global scale?

From the production campaigns of the 1960s, it was already obvious that the answer to this question lay primarily in the relationships of Center staff with agronomists in national programs. The production strategies that were used by millions of farmers were approximations of those elaborated by scientists in these institutions, with assistance from CIMMYT and other international agencies. Clearly, the chief mission of our own agronomists was to help developing countries strengthen their capacity to improve crop production practices.

In its interpretation of this mission, CIMMYT has always assumed that most of the agronomists should be dispersed among developing countries and not based at headquarters in Mexico. The reasoning behind this choice has been that, only by immersing themselves in the CMR of national programs, can these scientists help improve the effectiveness of their colleagues' research through training and consultation.

Although the intent of this arrangement was to enhance the impact of our efforts, it has placed our agronomists in a somewhat unusual and difficult position. What made their situation so unconventional, as noted in the *CIMMYT Review 1975*, was that they had "no research plots of their own." While freeing these individuals to concentrate on enhancing the capabilities of others, this circumstance also deprived them of the researcher's customary focal point for data analysis, reflection, and reporting. Even so, agronomists in our outreach programs were able to generate compensating benefits through their work with colleagues in national programs.

The anatomy of technology adoption

The question faced by CIMMYT's first social scientist, who joined the staff in 1971, was essentially the same as that concerning the agronomists: how to apply the discipline's tools in support of maize and wheat production worldwide. The first order of business for the Center's new economics section was to investigate the charge that semidwarf wheats favored large-scale farmers, who could afford fertilizers, irrigation, and other inputs, while further impoverishing poorer farmers, who could not. Whether justified or not, the criticism stung, prompting CIMMYT to conduct a substantive evaluation of the benefits of new agricultural technology to various classes of farmers.

The major finding of the adoption studies, conducted in cooperation with local economists in seven countries, was that farm size is not a major factor in the use of improved varieties, except during the early years after their release. Though large-scale farmers adopt these materials first, smaller scale farmers soon follow suit, an observation that confirmed the views already held by CIMMYT's plant breeders and agronomists. An even more instructive outcome of the studies was evidence that technology adoption is governed to a large extent by farmers' agroclimatic and socioeconomic circumstances. Thus, in formulating recommendations, researchers must examine whether a given technology — quite apart from its potential at experiment stations — is suited to farmers' realities.

A focus on farmers' circumstances

In the early 1970s, CIMMYT agronomists, though not insensitive to farmers' circumstances, lacked a systematic means of gathering information about them and applying it to technology development. They did promote the use of on-farm trials, however, and reinforced this message in training at Center headquarters. But most of the on-farm work conducted in this period was somewhat rudimentary, consisting largely of trials managed by researchers and focused on maximum yields. A central assumption underlying this work apparently was that, having familiarized themselves with crop production in target areas, agronomists could then develop a standard package of practices largely on the basis of results from experiment stations. From on-farm demonstrations, farmers could judge for themselves the merits of improved varieties and other elements of the new technology.

The limitations of early efforts to demonstrate improved practices on-farm had become quite evident by the mid- to late 1970s. CIMMYT publications from this period chart the growing awareness of a yield gap between experiment stations and farmers' fields. Though particularly pronounced in areas where adoption of the new technology packages was slow or nonexistent, the gap was apparent even in areas where most farmers had adopted improved varieties and begun using chemical fertilizers. That being the case, lower yields on the farm could not be attributed entirely to ineffective extension or inadequate supplies of seed and other inputs but seemed to reflect deficiencies in the recommendations farmers were receiving.

None of this was news to CIMMYT's economics section; its adoption studies had suggested quite similar conclusions. In an effort to impress the radical implications of these findings on agronomists, Center economists added a new feature to the CMR training courses offered at headquarters — simple methods for deriving economically sound recommendations for farmers from experimental results. In 1976 these methods were published in our first training manual for agronomists, which has since been translated into at least eight languages, revised and expanded, and adopted by dozens of national programs and by other centers in the CGIAR system.

By the mid-1970s, these efforts in training were starting to pay off. In 1975 a survey of small-grain farmers in Mexico (conducted by Center economists in conjunction with the wheat CMR course) was noteworthy because it preceded the on-farm experimentation program planned for the next year and thus provided important information for designing the experiments. Subtle changes were also taking place in CIMMYT's outreach programs. There was a new emphasis on the use of on-farm trials not just to demonstrate technology but to develop it. By 1977 the principle aim of CMR training at headquarters, according to that year's *CIMMYT Review,* was to improve participants' ability to conduct "trials in their home countries that will rapidly produce information useful in formulating realistic recommendations."

A CONVERGENCE OF DISCIPLINES

Though a link between on-farm surveys and experiments had been established during the late 1970s, it was still somewhat tenuous. In effect, if not in theory, surveys were still the task of social scientists, while experiments were the exclusive preserve of agronomists. This decidedly unproductive division of responsibilities was altered in time through a sometimes heated dialogue between the disciplines in two forums: the CMR courses offered at Center headquarters and the training and other activities taking place in CIMMYT's outreach programs.

Between 1977 and 1980, the number of core-funded social scientists increased from two to seven, with nearly all of the expansion occurring away from headquarters. The experience of these staff with a wide variety of farming systems in different regions strongly reinforced their message that research planning and the development of recommendations should be guided by an assessment of the "critical natural and economic circumstances which influence the behavior of farmers," as economist Donald Winkelmann (the Center's current director general) put it in the *CIMMYT Review 1979.* This task could be done properly only through collaboration between biological scientists and economists.

Two developments finally transformed on-farm research (OFR) into a truly interdisciplinary endeavor in the Center's programs. One was the evolution of informal or exploratory survey methods from earlier, rather crude attempts to characterize farmers' circumstances. Featuring less structured interviews with farmers and observations in their fields, informal surveys helped bring agronomists into what became known as the "diagnostic phase" of OFR. The second development was that CIMMYT economists became more actively involved in conducting on-farm trials. This was a consequence of their fuller integration into CMR training at headquarters and their close contact with agronomists in national programs, which often had few if any of their own social scientists. The upshot of these developments was that specialists in each discipline became more sensitive to the distinct perspectives of the other. Out of this convergence of disciplines came a new training manual explaining general concepts in OFR and providing detailed guidelines for conducting diagnostic surveys and using the results to plan on-farm trials. Like its predecessor, this publication was widely used by developing country scientists in establishing OFR programs.

Our agronomists and social scientists dedicated most of their efforts to helping national programs acquire the necessary skills and find workable formulas for applying on-farm research in technology development and dissemination.

INSTITUTIONALIZING ON-FARM RESEARCH

By the early 1980s, agronomists and social scientists at CIMMYT had worked out their differences on the main features of OFR. There was a clear consensus on the use of surveys to characterize farmers' circumstances, on the application of survey results to research planning, and on the development of recommended practices through on-farm experimentation. It was also generally recognized that in focusing on a single commodity OFR examines it in the context of the farming system, that the success of OFR hinges on cooperation among various agricultural disciplines, and that it is especially relevant in working for resource-poor farmers. To a large extent this approach became the active ingredient in our solution to the problem of addressing crop management issues in ways that are consistent with the Center's global mandate for maize and wheat. Rather than conduct OFR themselves, our agronomists and social scientists dedicated most of their efforts to helping national programs acquire the necessary skills and find workable formulas for applying this potentially powerful collection of tools for technology development and dissemination.

The initial success of OFR prompted a number of developing countries (including Ecuador, Malawi, and Zambia) to begin establishing a nation-wide capacity for this type of research. Among the growing body of OFR proponents, CIMMYT and especially our Economics Program (which in 1980 had been given the same status as the Maize and Wheat Programs) achieved recognition as a leader. In search of ways to increase the productivity of small-scale farmers, various donor organizations — especially the US Agency for International Development (USAID) but also the Canadian International Development Agency (CIDA), World Bank, and others — embraced OFR enthusiastically and provided us with special-project funds for intensifying efforts to institutionalize this approach in eastern and southern Africa and Central America.

Toward that end the Center's economists and agronomists devoted a large share of their time to conducting in-country and regional courses, often in cooperation with other CGIAR centers. In general, they used an approach referred to as the "call system," in which course participants come together for one or two weeks at key stages in the research cycle (to conduct on-farm surveys or evaluate trial results, for example) and then resume their normal duties during the periods between "calls." With wholehearted support from the donors, active participation on the part of national programs, and near unanimity among the disciplines engaged in this research, the OFR enterprise promised great things.

Assessing on-farm research

By the late 1980s, after nearly a decade of vigorously promoting this approach, CIMMYT scientists decided it was time to assess the results. If judged strictly according to farmers' adoption of new technologies, the outcome is disappointing. Fewer cases of adoption have been documented than one might have hoped from the widespread application of OFR in developing countries. Part of the problem is simply that many projects never included any systematic attempt to monitor technology adoption, making the search for hard evidence of success difficult. But it is also apparent that in numerous cases limited impact was the result of serious flaws in the implementation of OFR. Although these results hardly measure up to expectations raised during the golden age of OFR — the early to mid-1980s — they do provide a firm basis for shaping its future role in agricultural research.

Crop doctors

In appraising the methodology's past effectiveness and in seeking a way forward, some CIMMYT scientists have focused on shortcomings at the diagnostic stage of OFR. Apparently, the mere convergence of agronomic and social science perspectives, achieved with some difficulty during the late 1970s, was not always sufficient to guarantee thorough and accurate assessment of problems in crop production, making subsequent research wide of the mark from the very beginning.

In measuring the achievement of OFR in eastern and southern Africa, for example, CIMMYT staff have noted that superficial diagnosis is one of the problems that has led to poor planning and implementation of many projects and prevented them from meeting original expectations. Because of the weakness of their problem-solving approach, these efforts have tended to degenerate into somewhat mechanical exercises in OFR methodology and have failed to forge strong links with commodity researchers and extension. Without the one, OFR practitioners have lacked a source of innovative technologies, and divorced from the other they have had no way of delivering recommendations widely and effectively. The antidote, outlined in a 1989 paper by CIMMYT economist Allan Low and agronomist Stephen Waddington, is a "better partnership between research and extension." It is essential, moreover, that both groups begin to view themselves "as diagnosticians and doctors," who work with farmers to identify and solve problems, and not as prophets proclaiming "the one and only true word."

Fortunately, some national programs in sub-Saharan Africa are already moving decisively in the right direction. In Ghana, Lesotho, Swaziland, Zambia, and Zimbabwe, concrete measures have been taken to align research and extension organizations more closely and to give both a stronger problem-solving orientation. Some of these programs, most notably in Ghana, have thoroughly demonstrated their capacity to identify problems and develop solutions that farmers will adopt on a large scale in a relatively short time.

On-farm research with a long-term perspective

This emphasis on short-term results, which was an explicit feature of most earlier OFR initiatives, may at times have detracted attention from sustaining the productivity of agricultural systems. Even so, many of the developing countries that achieved short-term impacts are now reasonably well placed to begin addressing longer term issues. Having established some credibility as problem solvers, these countries now possess much of the requisite expertise for developing and promoting technologies whose beneficial effects are more complex and less immediate than most shorter term changes in crop management. CIMMYT is well prepared to help national programs make this transition, as a result of more than a decade of experience with resource-conserving technologies, especially conservation tillage.

Currently, we are applying insights gained from this experience in studies of two major cropping systems: 1) hillside maize cultivation in Central America, where soil conservation is an urgent necessity, and 2) the rice-wheat rotation in South Asia, where a host of problems appear to threaten the productivity of this system. Research focusing on these sorts of situations will involve fairly sophisticated diagnosis, in which "agronomic variables," as pointed out by CIMMYT economists Derek Byerlee and Paul Heisey and agronomist Peter Hobbs in a 1989 article, will acquire particular importance. With its experience in conducting diagnostic surveys, CIMMYT already has a powerful tool at hand for examining the highly complex questions related to long-term crop productivity. The main responsibility for applying this and other tools lies with biological and social scientists in national programs; our role will be to help coordinate and support their efforts.

Another tale of two disciplines

The Center's worldwide OFR initiative has required that most of its agronomists work in bilateral projects or regional networks in close contact with national programs. A few of these specialists, however, have been based at CIMMYT headquarters, where one of their main challenges has been to help improve the efficiency of the Center's breeding programs. One obvious way in which agronomists can work toward this goal is to deal with crop management problems that arise at the experiment stations Center staff use. This service has become especially important in recent years, as the stations have begun to show the effects of continuous, intensive maize and wheat cultivation.

Some agronomists have contributed even more substantially to germplasm development through research on crop physiology, which occupies a fertile common ground between plant breeding and agronomy. As physiologist Gregory Edmeades notes in the Center's 1986 Research Highlights, we "examine aspects of crop phenology and development that have both genetic and environmental controls." Like the agronomists participation in OFR, the story of their work at headquarters is thus very much a tale of two disciplines.

Crop physiologists made an auspicious beginning at CIMMYT in the early 1970s. Their charge, notes the Center's *1970-71 Annual Report,* was to "determine the important physiological and morphological characteristics leading to high grain yield." In retrospect it is obvious that physiologists' early efforts to reach this objective produced important results, which have influenced the practice of plant breeding at CIMMYT and improved selection efficiency. In examining season-to-season variation in wheat yields in northwestern Mexico, for example, they identified the critical period in crop development that determines yield, documented the effects of temperature and solar radiation at this period, and suggested ways in which this information could be employed to improve wheat performance.

Physiologists also established that the increased yield potential of semidwarf wheats available in the early 1970s resulted from their higher harvest index (the ratio of grain to total dry weight). What seems obvious now — namely that short plants distribute dry matter more efficiently — was not so clearly understood before this work was done. In a 1975 report, Anthony Fischer, physiologist and current Wheat Program director, explains that the advantage of the semidwarfs in dry matter distribution was so marked that they outperformed older, tall wheats under dryland conditions, "even though the latter may have specific genes for drought tolerance."

During this same period, physiologists in the Maize Program reached conclusions quite similar to those of their colleagues working on wheat. They determined that the limited productivity of tropical maize at that time was partly related to its low harvest index and excessive leafiness. Shortly afterwards, they identified ways of increasing the harvest index of tropical maize (such as selection for reduced plant height) and later perceived a relationship between improvements in this trait and better maize performance under drought.

In spite of its propitious start, crop physiology at CIMMYT, particularly in the Wheat Program, suffered a major setback in subsequent years. Perhaps because new insights into the physiology of wheat yield did not translate immediately into simple selection techniques, confidence in the possibilities of this research began to wane in 1976, and by 1979 the work had been phased out altogether. During this period crop physiologists in the Maize Program shifted their emphasis almost entirely to abiotic stresses, mainly drought. Until genetic solutions to this problem had been found, they believed, the more efficient maize genotypes developed in the 1970s would be severely handicapped under the difficult conditions of many tropical environments.

Almost a decade after crop physiology's initial flourish at CIMMYT, the discipline was once again in the good graces of the Center's crop programs. Picking up the thread of work done in the 1970s, new physiological studies in the early 1980s produced exciting information about yield improvement in bread and durum wheats. One of the most surprising conclusions was that increased grain yields since about 1975 had resulted partly from a greater rate of biomass production. As indicated in a 1986 journal article by Stephen Waddington and others, these findings flew in the face of the widespread and almost dogmatic belief that "breeding has failed to raise the biomass of wheat" and that "yield improvements [are] solely the result of a higher harvest index." Meanwhile, physiologists in the Maize Program had begun a series of studies (see pages 31-32) that pinpointed the anthesis-silking interval as a key to improving maize performance under drought as well as favorable conditions. Largely as a result of developments like these (see also Figure 8), crop physiology currently receives strong support in the Center, and expectations are high that it will generate valuable information and tools for continued crop improvement.

The case for agronomy research at headquarters

Well aware that CMR tends to be site specific, CIMMYT agronomists maintain that this general rule does not preclude some work at Center headquarters in support of agronomy research conducted elsewhere, especially by scientists in national programs. One of their

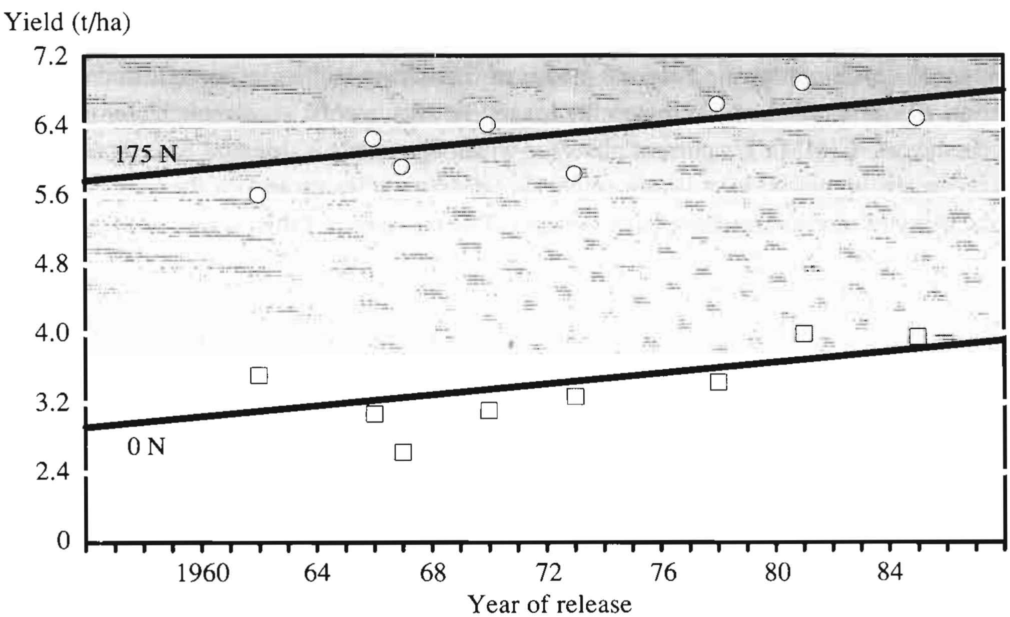

Figure 8. Progress in yield, under high and low nitrogen, for prominent CIMMYT-based wheat genotypes released since the early 1960s (results from a three-year study conducted by Center agronomists). Whether or not nitrogen fertilizer is applied, the genotypes show much the same upward trend in yield, suggesting that the Center's germplasm has become more efficient in the uptake and use of the nutrient.

earliest attempts to prove this point was a maize project established during the late 1960s in the valley of Puebla, a fairly short distance from Mexico City. According to project leaders, its overall purpose was to demonstrate "how the traditional farming sector can be transformed," and its centerpiece was a package of improved crop management practices. Even though the project was successful, the Maize Program has not engaged since then in any major crop management initiatives in Mexico. The lesson of this experience is that it makes little sense for the Center's agronomists to conduct adaptive research themselves as part of a production campaign in Mexico or any other country. That type of work, which CIMMYT can support through training and consultation, is best done by the national programs. It does not necessarily follow, however, that our agronomists have no role in Mexico, apart from training and experiment station support. Recently, they have argued that increased activity in the discipline at headquarters, focusing particularly on sustaining natural resources, can complement agronomy research in developing countries.

Wheat agronomists at headquarters have been a little less inhibited than their Maize Program counterparts in addressing research topics of broad interest. In the mid-1970s, they were presented with a unique opportunity to do so. The Wheat Program had embarked on a long-term project to popularize triticale and needed to work out suitable agronomic practices for the new crop. Mexico was the logical place to carry out this task, since triticale showed some promise in the country's central plateau and was not yet being grown anywhere else. During this same period, wheat agronomists at headquarters also began to study the control of various grass weed species. What began as an effort to tackle a severe problem at the Center's experiment stations led to a quite innovative research program to develop integrated control measures (involving herbicides as well as crop rotation, tillage methods, and preplanting irrigation) that may be applicable under many circumstances. CIMMYT's current plans for wheat agronomy in Mexico, like those for maize, are distinguished by a strong emphasis on strategic issues and on the long-term productivity of wheat-based cropping systems. The outcomes of this work will no doubt finally decide the case for agronomy research at headquarters.

Economics and crop improvement

In the 1980s, CIMMYT's social scientists made a heavy commitment (over 80% of the Economics Programs resources in 1987) to developing and promoting OFR in developing countries. Unquestionably, this was a necessary and profitable endeavor; among other benefits it forged strong links between our social scientists and agronomists and between both groups and their colleagues in national programs. These valuable assets were won, however, at the expense of a closer relationship between the Economics and crop improvement programs.

Increasingly, however, the Economics Program is taking up plant breeding issues that are relevant to CIMMYT's primary aims in crop improvement. Currently, for example, we are seeking to define the desirable characteristics of maize varieties in Malawi, where the adoption of improved germplasm is still very low, and we are working with wheat pathologists to measure genetic diversity (especially with respect to rust resistance) and to analyze policies for encouraging the dissemination of a greater diversity of wheat varieties. Other studies are aimed at measuring crop losses to specific diseases at the national level. Through efforts like these, economists are making considerable headway in broadening the role of economic perspectives on plant breeding at CIMMYT.

Influencing the policy environment

Policy analysis — second in importance after OFR on our economics research agenda — is several steps removed from the business of crop improvement but still quite pertinent to it. Much of this work has focused on the potential for technological progress in specific wheat-growing areas, including drylands, sub-Saharan Africa, and warmer areas generally. Largely as a result of studies on the latter, CIMMYT's cooperative research on wheat for these environments is now informed by an awareness of both the biological and economic considerations.

Most of this research is intended not so much to influence policy in one direction or another — and thus risk interfering with strictly national prerogatives — as to provide background information and methodologies that can help improve the quality of the decision making process. Our primary vehicle for such information is the World Maize and Wheat Facts and Trends series, which analyzes major trends and policy issues in developing countries and provides a summary of important statistics in maize and wheat production. Through these publications we have built up a substantial body of information on subjects such as the economics of maize seed production and the current state and future challenges of wheat production in parts of Asia that were affected by the Green Revolution. The series is widely used by CIMMYT staff and other professionals, and it is commonly cited in scientific publications.

The Synergy of International and National Research

CIMMYT's germplasm development and other research activities are predicated upon two basic assumptions that are central to understanding why the Center exists and how it operates. The first is that maize and wheat are so vital to so many nations of the world as to justify, even demand, a coordinated, global effort to support the production of these crops. The second is that the global enterprises of maize and wheat research divide logically into two sets of related activities: those in which an international organization has a distinct advantage and those for which national institutions are uniquely suited. Distributing improved germplasm to all countries that produce maize and wheat falls into the first category, while releasing varieties directly to farmers is an example of the other.

Because these two sets of activities — international and national — are so closely inter-dependent, CIMMYT and the other centers in the CGIAR system have further assumed that they must help strengthen the research capabilities of cooperating countries. For the centers to neglect this task could leave many national programs with less capacity to profitably employ the products and services the centers provide and thus sharply reduce the rate at which the centers' research has an impact in farmers' fields. The issue, though, is not whether to support national programs but how, particularly in ways that do not foster excessive dependence. Clearly, our commitment to this task implies a heavy emphasis on training, but to a large extent it also governs the orientation of all our research and related activities.

Clearly, our commitment to supporting national programs in ways that do not foster excessive dependence implies a heavy emphasis on training, but to a large extent it also governs the orientation of all our research and related activities.

Intermediate germplasm products

In germplasm development, for example, CIMMYT's approach is to reinforce the work of plant breeders in developing countries by providing them with intermediate products, from which they can develop or select superior materials for release. How national programs use our germplasm depends upon their resources and levels of expertise. Whereas smaller or less experienced programs might release a maize or wheat variety selected from one of the Center's international trials, larger programs tend to incorporate this experimental germplasm into their own plant breeding schemes.

That we can cater equally well to both types of programs is largely a consequence of the broad adaptability of our germplasm within mega-environments. Invariably, some of these materials will turn out to be almost ideally suited to particular areas, in which case they can be released with little modification. More commonly, though, the fit between a promising CIMMYT genotype and a specific area is close but less than perfect. Many of the smaller national programs settle for the close fit, while larger ones generally try to tailor the germplasm even more closely to farmers' requirements by crossing it with other materials that possess better local adaptation. In either case the effect of our work is to provide national programs with options for reducing or simplifying some of the steps in plant breeding. By and large they are thus able to generate better final products more quickly and, consequently, are more likely to gain strong local support for the national research establishment.

Tool users and tool makers

To a considerable extent, our scientists work toward that same end by devising more effective methodologies for maize and wheat breeding. CIMMYT's general approach to crop improvement has had a considerable influence on the way in which developing countries organize their breeding programs. In addition, we have fashioned a number of techniques for work on specific traits initially to satisfy the requirements of our own germplasm development projects but also to support complementary efforts in national programs. The Wheat Program, for example, has accumulated a large body of knowledge on disease resistance and conveys this information to clients through a variety of publications and training activities.

On CIMMYT's broader research agenda — that is, in its agronomy and social sciences work — methodology development figures even more importantly than in plant breeding. In fact, the primary product of that research, which has focused heavily on farmers' crop management, is not specific production technologies but an approach for developing them. It is hard to imagine how this could have been otherwise. The output of adaptive crop management research is "usually . . . improved information," according to economists Gregory Traxler and Derek Byerlee, and therefore "much less tangible . . . than a new product or technique." Moreover, the information generally applies only to specific locations and circumstances. For CIMMYT to develop and deliver this type of product on a global basis is an even more remote possibility than supplying maize and wheat varieties for every crop production niche in the developing world. What CIMMYT's specialists in agronomy and economics have done, however, is far more in keeping with our commitment to strengthening national programs. Drawing on a wide range of experience in numerous countries, they have synthesized from crop management investigations of many specific problems in various countries an on-farm research (OFR) methodology of essentially universal application in the developing world (see pages 51-52). National programs have contributed importantly to designing the methodology, and many of them now use this highly versatile tool.

Supporting versus stifling

The development and promotion of OFR methodology has taken place to a large extent under various cooperative arrangements in which CIMMYT has participated away from its headquarters in Mexico. As in our research programs generally, we have tried to structure these outreach activities in such a way that they improve the effectiveness of national programs without posing as a substitute for them. This is one of two primary considerations that led us to invest heavily in the establishment of regional programs during the 1970s.

From CIMMYT's early, somewhat ad hoc support of maize and wheat research in developing countries, more formal arrangements emerged in which we posted scientists to selected national programs. By 1970 about 20 of our senior staff were working in bilateral projects outside Mexico. Resulting improvements in the crop research of some countries inspired requests for similar assistance to others. In 1972 the Wheat Program was involved with a total of 12 national programs in Africa, Asia, and South America, and the Maize Program reported new commitments of staff to 3 countries in addition to the 4 where it already had bilateral projects. The overall success of these programs and the resulting demand for their replication from the Center's growing list of clients provided a strong argument for our decision to turn to a regional strategy. We simply did not have the resources to support bilateral programs in more than a few client countries at any one time.

As with our choice of strategies for germplasm development and crop management research, however, practicability was never the only issue. The strongest reason for moving away from bilateral arrangements, according to Edwin Wellhausen, CIMMYT's first director general and a key promoter of the regional strategy, was their tendency to stifle the contributions of national scientists. "A regional program," says Wellhausen, "was the best way to draw in local talent." His enthusiasm for this approach derived from earlier experience, beginning in 1954, with the Central American Cooperative Food Crops Program (PCCMCA), which connected all of the region's maize scientists in a single network. Still effective in 1991, the PCCMCA, Wellhausen observes, "became the pattern for a whole series of interacting collaborative regional research programs." These enabled CIMMYT to provide a leaner mix of services to the large number of national programs that do not need full-time assistance.

Much of the support provided by our regional programs is somewhat general, covering a broad range of themes and taking the form of regional workshops, in-country training, and periodic consultation (Figure 9). Since the mid-1980s, we have added a new dimension to

1. El Batán, Mexico (headquarters)
2. Guatemala City, Guatemala
3. San José, Costa Rica
4. Cali, Colombia
5. Asunción, Paraguay
6. Bouaké, Côte d' Ivoire
7. Kumasi, Ghana
8. Ankara, Turkey
9. Aleppo, Syria
10. Addis Ababa, Ethiopia
11. Nairobi/Njoro, Kenya
12. Lilongwe, Malawi
13. Harare, Zimbabwe
14. Kathmandu, Nepal
15. Dhaka, Bangladesh
16. Bangkok, Thailand

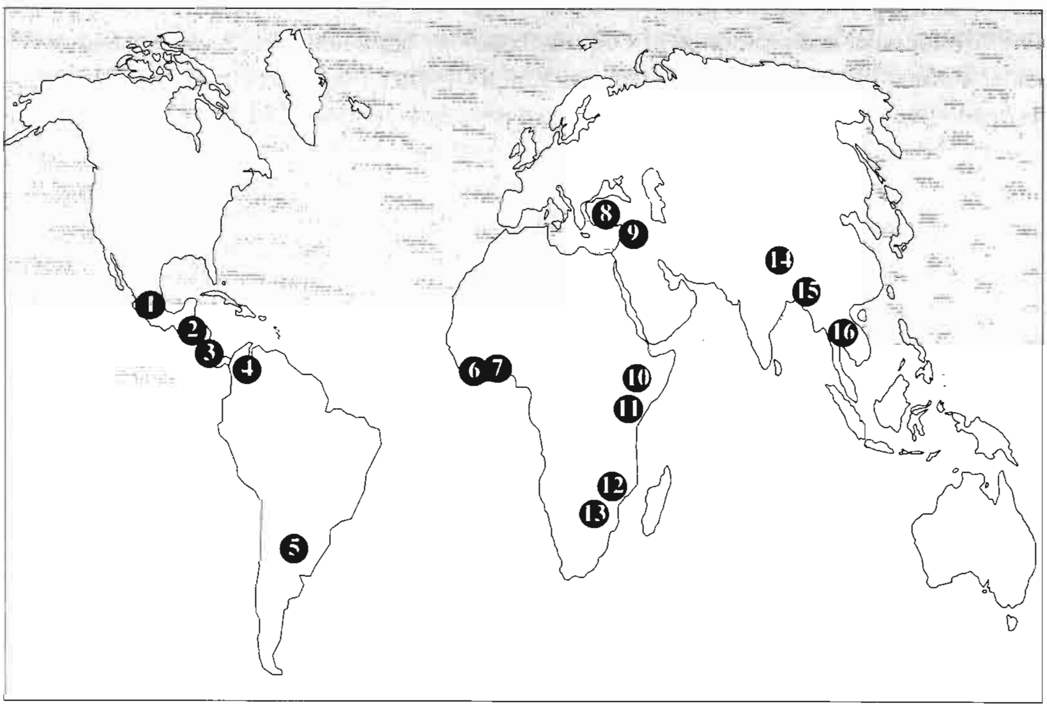

Figure 9. Location of CIMMYT offices, January 1992.

this strategy. Apart from offering general support, staff in practically all of the regional programs now have specific research responsibilities. They are seeking solutions to problems that are endemic or especially severe in their regions (such as maize streak virus in sub-Saharan Africa and acid soils in South America) and that cannot be addressed as effectively in Mexico. In addition to ensuring that our outreach staff remain active and current in their disciplines, this research provides a sharper focus for our collaboration with national programs.

The global invisible college

To a considerable extent, the groundwork for cooperation in the regional programs is established through training at CIMMYT headquarters. In almost every national program with which we work closely, many of the scientists have taken part in germplasm improvement or crop management research courses, which have formed the core of our training program in Mexico, and some have pursued specific research interests at the Center under visiting scientist fellowships (Table 3). One purpose of these activities is to familiarize participants with the objectives and methods of our research programs. Common methods, apart from being directly useful, add to the synergy of international and national research, fostering horizontal collaboration among national programs and with the international centers.

An even more important goal of the courses at headquarters is to provide participants with the research skills they require to address farmers' germplasm needs and crop management constraints. In a significant departure from traditional approaches to learning, which are characterized by almost passive participation, training at CIMMYT strongly emphasizes competence in specific tasks. For example, rather than just describe the effects of nitrogen deficiency on plant growth, course participants are expected to identify this problem in the field. To become genuinely proficient at such tasks, according to a recent

Table 3. Numbers of participants in selected CIMMYT in-service courses, 1966-90

	Crop improvement		Crop management research		
Region	**Maize**	**Wheat**	**Maize**	**Wheat**	**Total**
Africa	111	118	207	139	575
Asia	132	230	162	118	642
Europe	2	11	3	8	24
North and Central America	60	30	185	33	308
Oceania	1	--	2	--	3
South America	83	115	80	61	339
Total	**389**	**504**	**639**	**359**	**1,891**

article by agronomist Mark Bell and others on the crop management research courses, trainees must make habits of certain activities and attitudes: Among other things, they need to be observant in the field, communicate effectively with farmers, and show a propensity for questioning established wisdom.

Their sense of worth and accomplishment is further reinforced by close contact with other scientists taking part in the training as well as with those who conduct it. In reporting the results of an extensive survey of participants in courses sponsored by CIMMYT and other CGIAR centers, reviewers were struck by the "powerful effect" of this contact on the trainee's professional identity: "The former participant . . . need no longer be isolated" but is "now a member of a special . . . group, part of the worldwide . . . community of agricultural scientists, a fellow of a global invisible college."

The information famine

By "college" the authors of that report were obviously not referring to an academic institution but to the term's more general sense (as defined in Webster's Ninth New Collegiate Dictionary) of "an organized body of persons engaged in a common pursuit." Belonging to such a college (like attending a university) implies a sustained effort, not just taking one or a few courses. What then can CIMMYT and other CG centers do to ensure that participation in their training activities is not an isolated event but one of many fruitful encounters in a career-long collegiate experience?

Certainly, one part of the answer is to develop rich and varied training programs that cater to scientists at different stages in their professions. Another is to build research networks in which national programs have an on-going, dynamic role. But beyond these and other specific measures, we must take seriously a responsibility that underlies all of them, which is to satisfy more fully the information needs of agricultural research in developing countries. Every aspect of that work — certainly agronomy and social sciences but plant breeding as well — has a strong information component. Nonetheless, though improved germplasm is now relatively abundant in national programs, the famine of information continues almost unabated, and systems for combatting it in developing countries are not particularly advanced.

A large part of the problem is that national programs, hard pressed to support field work adequately, are often not in a position to improve their access to scientific information or to invest much in their own publishing and related activities. This is not to say they are uninterested. Some national programs have developed quite effective information functions, though these are often somewhat dependent upon special funding. Under a project supported by the US Agency for International Development, for example, CIMMYT staff worked closely with Pakistani scientists to establish a research paper series that is distributed internationally and maintains high academic standards. Likewise, in Ghana scientists from national institutions and one of our own staff have employed funds provided by the Canadian International Development Agency (CIDA) to build a communications program that is strongly oriented toward training. This work has proved instrumental in linking research more closely with extension.

In spite of the dependence of these and other information activities on special funding from a donor or expertise available at the CG centers, some of them can be organized in such a way as to incorporate significant contributions from national programs. Take the case of proceedings for international conferences, of which CIMMYT alone has published dozens jointly with the national sponsors of these events. Some argue that these publications make developing country scientists overly dependent on the centers for dissemination of research results and that the effort might be better spent in helping these scientists publish their work in refereed journals. Certainly, the latter option is a better way of enhancing the reputations of developing country researchers and of bringing their work to the attention of audiences in the developed world. But proceedings do have the advantages, which journals lack, of 1) bringing together a sizeable body of information on specific topics, generated mostly by scientists from developing countries but also from the CG centers and industrialized world, and 2) providing these groups with a means of communicating with one another. Arguably, though, the proceedings should be subjected to more rigorous peer review and technical editing and produced in a more concise form than is generally the case.

Proceedings are hardly the only opportunity for international information exchange, however, and probably not even the best. Other options are to solicit the participation of developing country scientists in more carefully structured publications with a sharper focus on particular sets of research issues, results, and procedures. CIMMYT's series of manuals, for example, especially those dealing with on-farm research, draw upon a wide range of experience with national programs. In the first of the Center's new Research Reports, the collaborative nature of the work described is even more explicit and the contributions of developing country scientists more prominent. Not all information activities, however, lend themselves so readily to this type of cooperation but consist largely of services that the CG centers offer to national programs. CIMMYT's information staff, for example, apply selected computer-based tools and systems to provide abstracts, searches through more than a a score of databases, and the monthly automatic dissemination of information on specific topics, among other services. Even so, in the expectation that eventually scientists in developing countries will enjoy this kind of support in their own institutions, our information staff participate in various national, regional, and global networks that promote the growth of expertise in information science.

A New View of the Impact of Technological Change in Maize and Wheat

In preceding sections of this publication, we have charted CIMMYT's progress in germplasm development, crop management research, and related activities. The advances we have described fulfill a necessary condition for impact, but they hardly guarantee it. Ultimately, the only way to demonstrate impact convincingly is to provide evidence from farmers' fields.

Advances in research fulfill a necessary condition for impact, but they hardly guarantee it. Ultimately, the only way to demonstrate impact convincingly is to provide evidence from farmers' fields.

This section reports on the preliminary results of a systematic effort at CIMMYT to gather such information. Most of the findings we present here pertain to germplasm development. But we also cover crop management research and training and information activities by discussing the general framework in which we are examining the impacts of this work and by summarizing some of the outcomes of recent studies.

The Path of Improved Germplasm

Obtaining information on the impact of improved germplasm requires that we trace the flow of this material after its departure from CIMMYT, examining and documenting what has happened at all stages, even those over which Center staff have sharply limited influence. In 1990 the Center started down that path by conducting a survey of national programs in the developing world. This undertaking both updates and extends work done by others during the 1970s and 1980s. The primary purpose of the survey was to establish an inventory of wheat and maize varieties released to farmers by national programs (we also obtained some information from private companies), along with information about the type and germplasm source of these materials, the agroclimatic zone for which they were targeted, and the approximate area planted to them in 1990.

Since we included all countries with more than 100,000 ha of maize or wheat as well as selected ones with smaller areas, the survey's coverage was fairly complete. In the case of wheat, the countries we surveyed contain more than 95% of the developing world's wheat production, outside China. We excluded much of this country's wheat area, specifically that sown to winter and facultative materials, because we have given close attention to these germplasm types only during the last six years. Moreover, the sheer number of varieties released in China and the complexity of its research system would have greatly complicated the initial development of our inventory. In the case of maize, we excluded all of the area in Argentina, Chile, and Turkey and much of that in China because it falls within the temperate zone, for which we make no direct effort to meet germplasm needs.

The survey results compiled so far constitute a comprehensive database on the utilization of CIMMYT germplasm in national programs and on farmers' adoption of varieties based on this and other materials. For the purposes of the much harder task of gauging benefits, we are still far from having a comprehensive, global database and are less advanced in finding appropriate methods. Nonetheless, we have pulled together a substantial amount of information from a wide variety of published and unpublished sources, showing the benefits that farmers obtain when they adopt improved varieties. Incomplete as they are, the data suggest a sizeable payoff from the work of CIMMYT and its clients in national programs.

Germplasm Utilization in National Programs

Our inventories of maize and wheat varieties released in developing countries provide eloquent testimony to the growing capacity of national programs to manipulate improved germplasm. Here we point out patterns in variety release and indicate trends in the use of CIMMYT materials, that is, germplasm that Center scientists have worked on at some point. In many cases further improvements have been made in the materials by national programs and other institutions. Since maize and wheat improvement are now characterized by a high degree of international cooperation, we have chosen to be conservative in determining the origin of particular varieties. This is especially true in the case of maize, whose ability to outcross enables breeders to incorporate a wide array of materials from different sources into single open-pollinated varieties (OPVs). Consequently, it is sometimes difficult to establish whether a given OPV or hybrid contains a significant amount of our maize germplasm or not. With a self-pollinating crop like wheat, on the other hand, the decision is more clear-cut. Since wheat varieties are the products of deliberate crossing among specific lines, their geneologies, however complex, are more transparent than is the case with maize.

PATTERNS IN THE RELEASE OF WHEAT VARIETIES

Our database currently lists more than 1,300 wheat varieties released by national programs, nearly all of which have been released since 1965. With each five-year interval during that period, the number released has risen steadily, so that by 1985-89 it was double the number in 1965-69 (Figure 10). Prominent among wheat breeding programs in developing countries are those of Brazil and India, each of which has released a total of 180 varieties since 1965. Other countries that have released large numbers of varieties are Chile, Argentina, Mexico, Turkey, and Pakistan. Described below are notable patterns in the release of wheat varieties.

- Over 80% of the varieties released are spring bread wheats, which account for 77% of total wheat production in the developing countries represented in our database.
- The number of varieties released is not closely related to wheat area. Thus, programs in Latin America have released nearly half the total number of varieties, even though the region contributes only 10% of total wheat production in the developing world.
- The proportion of varieties developed for rainfed areas is clearly increasing (Figure 11). Whether varieties tend to be targeted more for irrigated or rainfed environments depends to a large extent on the region. Thus, in Asia most spring bread wheats are shaped to the requirements of irrigated production and in Latin America to rainfed areas.

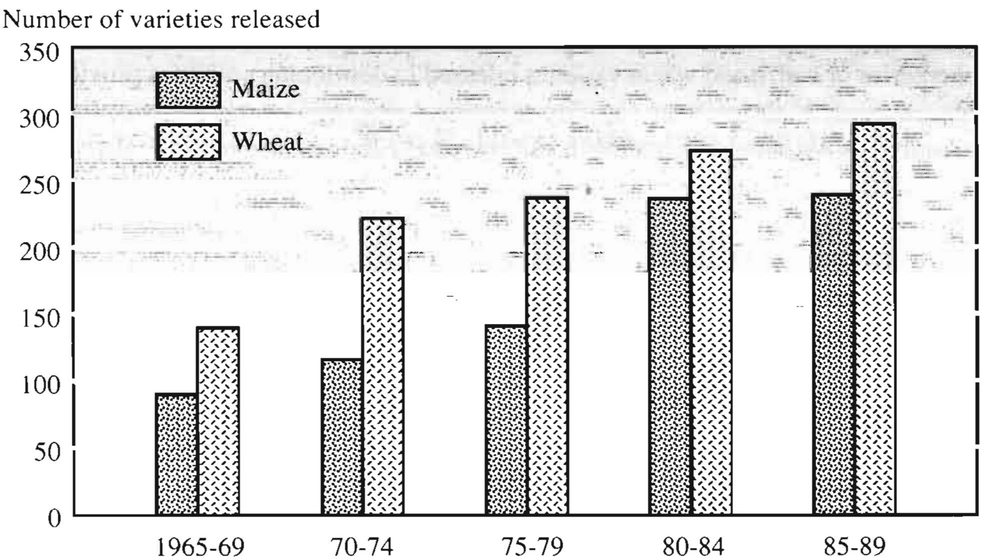

Figure 10. Trends in the number of wheat and maize varieties released, all countries in survey.

The origin of wheat varieties

In documenting the direct utilization of CIMMYT wheat germplasm, we divided all of the released varieties into three categories, those based on 1) Center lines or selections from our nurseries (that is, germplasm resulting from crosses made by our staff in Mexico), 2) crosses made by national programs, in which at least one of the parents was obtained from us, and 3) crosses made by national programs, using no CIMMYT germplasm as one of the immediate parents (often, however, our materials occupy a more distant place in the geneology of these varieties). For future analysis we are currently refining this scheme to better reflect the full range of options available to national programs in using our germplasm. The major findings of our initial effort to establish the origin of released varieties are given below.

- The proportion of varieties resulting from CIMMYT's work (that is, fitting the first or second of the categories described above) increased steadily from 1965 to 1980, levelling off at about 75% for all wheats (Figure 12). By the 1980s nearly half the varieties released were based on crosses made by Center staff in Mexico, a trend that held steady throughout the decade.

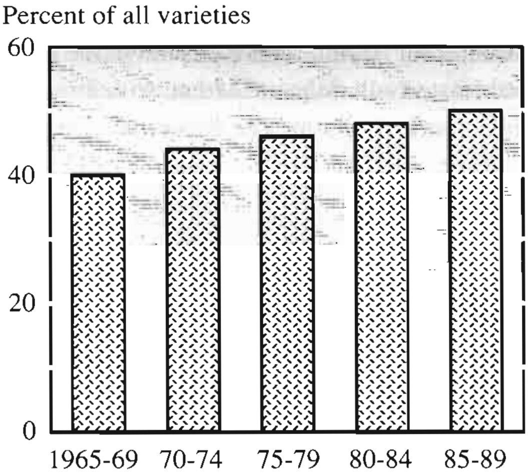

Figure 11. Percentage of wheat varieties developed for rainfed areas.

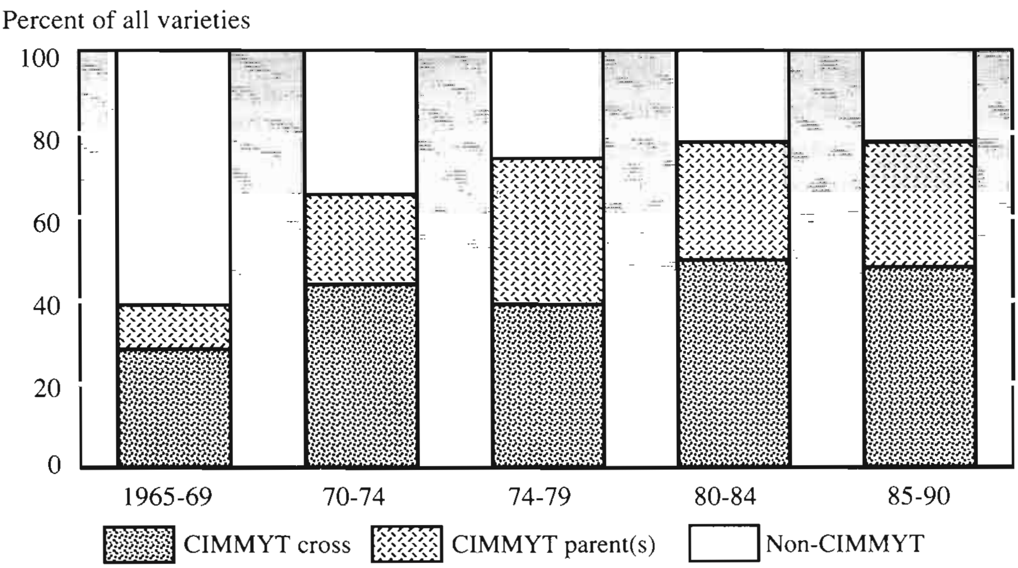

Figure 12. Trends in the origin of wheat varieties released in developing countries, 1965-90.

- Some 90% of all spring wheat varieties released in the 1980s were semidwarfs, nearly all of which have CIMMYT germplasm in their backgrounds.

- Though the Center has worked intensively on improving winter wheat germplasm, per se, only since 1985, over a quarter of the varieties released during the 1980s (not including those in China) are based on our germplasm.

- In the development of spring bread wheat varieties, CIMMYT germplasm has figured most importantly in the West Asia/North Africa (WANA) region, where over 75% of the varieties released contain materials generated at Center headquarters or in our cooperative program with the International Center for Agricultural Research in the Dry Areas (ICARDA). CIMMYT wheats are used least in sub-Saharan Africa, with just over half the varieties released there containing our germplasm. The generally strong national programs in Asia draw heavily on our materials but are more likely to employ them as parents in their own crosses than to use crosses made by Center staff.

- In every region there is a distinct tendency for smaller programs to base their released varieties more on CIMMYT materials than on their own crosses. As expected, stronger programs rely more on their own capacity to develop commercial releases (Table 4).

- The most popular CIMMYT cross is Veery, which has been released 36 times in developing countries during the 1980s, more than double the number of releases for II8156, the cross that spearheaded the Green Revolution in the 1960s. Large-scale crossing of spring with winter wheat (of which Veery is a product) has resulted so far in the release of 72 varieties in the 1980s. Their impact should become evident in the 1990s, as they are distributed more widely among farmers and as the stronger national programs use them more extensively as parents in crosses.

Table 4. Classification of national programs according to the extent of wheat varietal releases from their own crosses

Percent of releases from their own crosses, 1965-90			
< 25%	25-50%	50-75%	> 75%
Algeria	Egypt	Argentina	Kenya
Bangladesh[a]	Iran	Brazil	Peru
Bolivia	Pakistan	Chile	
Burma[a]	Paraguay	India	
Ethiopia	Syria	South China	
Guatemala	Tunisia	Zimbabwe	
Libya	Turkey[a]		
Mexico	Uruguay		
Nepal[a]			
Saudi Arabia			
Sudan[a]			

[a] Country with a significant number of wheat releases from third-country crosses.

Patterns in the release of maize varieties

Our inventory currently includes 1,007 OPVs and hybrids released by national programs, most of which have been released since 1965. As with wheat, the number of releases has risen rather steadily over the past 25 years (Figure 10). There is considerable variation among countries in the number of releases, ranging from 4 in Togo and Uganda to 85 in Mexico. Other noteworthy trends in variety release are described below.

- Among materials released by public-sector institutions, OPVs have predominated, composing about 60% of the total. These organizations have also been active in developing both conventional and nonconventional hybrids, which make up the remainder. A little more than half of all materials released are adapted to the lowland tropics and the rest to the subtropics, midaltitudes, and highlands.

- The number of maize varieties released apparently has little to do with the strength of the national program. Some of the countries that have released the fewest varieties per million hectares (Brazil and India, for example) are among the most accomplished in maize breeding.

The origin of maize varieties

Because of the complex genealogy of most maize varieties and hybrids, we employed a different classification scheme than that for wheat. We divided maize varieties into the following classes: 1) those having no CIMMYT germplasm, 2) those containing some germplasm from the Center, 3) materials from our international trials that have undergone selection for local adaptation, and 4) direct introductions of our experimental varieties. We also attempted to gauge the use of our materials by the private sector through a limited survey of seed companies in developing countries. Our analysis of germplasm utilization had the following outcomes.

- The number of maize OPVs and hybrids released by national programs that contain CIMMYT germplasm rose steadily from 1970 to 1989, when it reached about 75% (Figure 13). Of the varieties and hybrids released since 1965, about half now contain the Center's germplasm (Table 5).

- As indicated in Table 5, our germplasm has been employed most intensively in Latin America (showing up in 55% of all varieties released there) and least in the WANA region (37%). At the national level, there is considerable variability in the use of CIMMYT materials, which apparently has nothing to do with the size of the national program and is related more to the types of materials required, among other circumstances.

- Our materials have been used quite extensively to develop OPVs, which make up about 70% of all releases containing CIMMYT germplasm (Figure 14). Among releases containing the Center's germplasm, materials adapted to the lowland tropics predominate, followed at a considerable distance by those for the subtropics, midaltitudes, and highlands. This trend reflects the high priority the Center has given to lowland tropical materials, based on their greater extent in developing countries. For other germplasm categories, superior materials are now available, and their utilization in national programs can be expected to increase significantly.

- The manner in which national programs use CIMMYT germplasm is related to breeding capacity, much as in wheat. Whereas the stronger programs tend to carry out further improvement of our materials, those with less capacity are likely to release this germplasm with little modification.

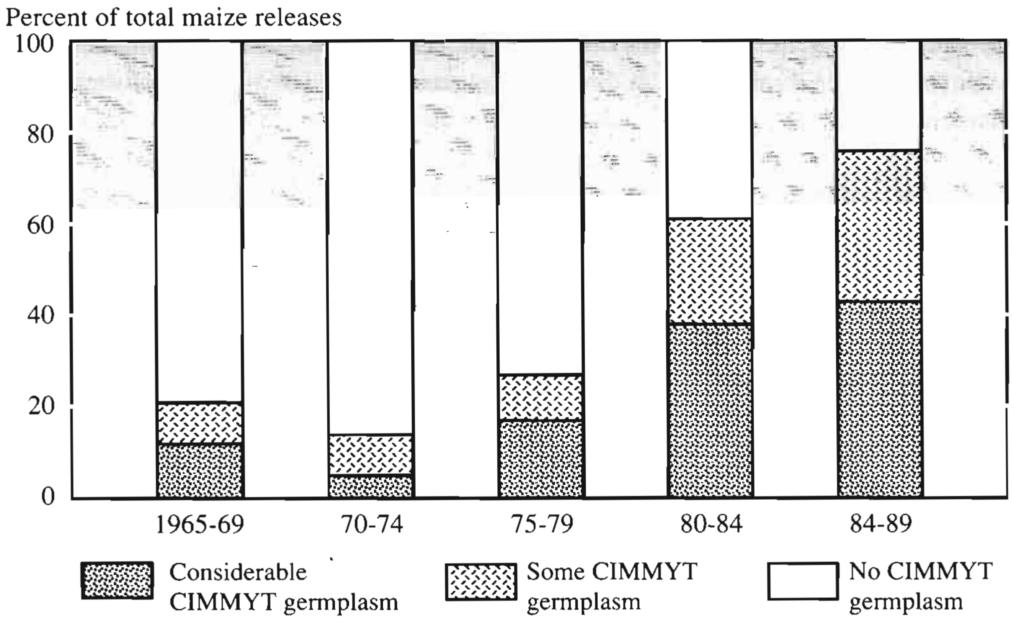

Figura 13. Trends in the origin of maize varieties released in developing countries, 1965-89.

Note: Most materials developed at IITA were classified as having some CIMMYT germplasm. A few of those materials, however (such as the TZPB-SR series developed from our Tuxpeño Planta Baja population), were classified as containing a considerable amount of CIMMYT germplasm.

Table 5. Release of maize varieties containing CIMMYT germplasm, by region, 1965-91

Region	No. of varieties released	Containing CIMMYT germplasm	
		Number	% of total
Sub-Saharan Africa	304	135	44
West Asia and North Africa	27	10	37
South, East, and Southeast Asia	184	87	47
Latin America	351	193	55
Total	**866**	**425**	**49**

- From our limited survey of private seed companies, it appears that more than 25% of the materials they have released (all hybrids) contain CIMMYT germplasm (Table 6). The companies that use the Center's materials most extensively include those located in some of the largest maize producers among developing countries (such as Brazil, India, Mexico, and Thailand).

Adoption of Improved Varieties in Developing Countries

That CIMMYT's germplasm is widely used by maize and wheat breeders in developing countries is a logical consequence of the strong links forged between international and national research through decades of close cooperation. More remarkable, perhaps, is that varieties containing this germplasm, particularly of wheat, are so widely grown by farmers. After all, the obstacles to variety adoption in developing countries are numerous and formidable, often including poorly conceived agricultural policies, ineffectual seed industries, and weak extension services.

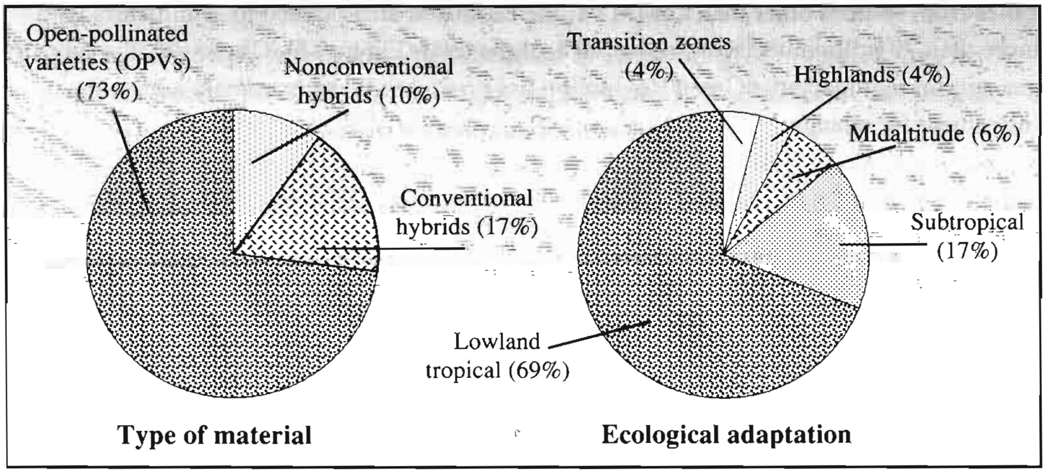

Figure 14. Maize releases containing CIMMYT germplasm.

Table 6. Private company maize releases containing CIMMYT germplasm

Region	Number of companies responding	Number of releases	Percentage with CIMMYT germplasm
Sub-Saharan Africa	6	92	11
Asia	10	58	55
Latin America	18	141	28
Total	**34**	**291**	**28**

Effective seed production is an especially important prerequisite for wide dissemination of improved maize but is slightly less critical for wheat. Both crops are very much affected by government policy. In Egypt, for example, the adoption of semidwarf wheats was discouraged for some years in part by a combination of low prices for wheat and high prices for livestock products. The value of wheat straw, a major source of fodder, came to exceed that of grain, and this, along with other factors, provided farmers with a compelling incentive to continue growing tall varieties with low harvest index (ratio of grain to stover). During the 1980s, however, the government altered its commodity pricing policies, with the result that over 75% of its wheat area was sown to semidwarfs by 1990, up from about 10% in 1979.

The spread of semidwarf wheats

By 1969, just a few years after CIMMYT's founding, semidwarf varieties occupied 8.4 million hectares in the Third World. This alone was sufficient to establish the Center's reputation as an agent for revolutionary change in wheat production. Since then semidwarfs have continued to spread steadily at a rate of about 2 million hectares per year. In the 1980s alone, an additional 20 million were planted to these varieties in developing countries. And by 1990 the area they covered was close to 50 million hectares in developing countries, not counting China. If we include China, which used dwarfing genes from sources other than CIMMYT, the estimated area planted to semidwarfs is more than 70 million hectares or over 70% of the total (Figure 15). Obviously, the type of germplasm that made the Green Revolution has proved to be an extremely adaptable instrument for change.

Semidwarfs have been most successful among spring bread wheats. Of the total area covered by this category of wheat in developing countries, over 80% is planted to short varieties, accounting for more than 90% of the Third world's entire production of spring bread wheat (Table 7). Semidwarfs have been adopted to a lesser degree in sub-Saharan Africa and the WANA region. For other categories of wheat, especially winter-habit materials, the area occupied by semidwarfs is notably less than for spring bread wheat. In the case of durums, the area planted to semidwarfs is also slightly disappointing, considering that such materials have been available since the 1970s. Even so, more than half the durum wheat area is now planted to semidwarfs; their adoption has been especially extensive in Latin America and is increasing.

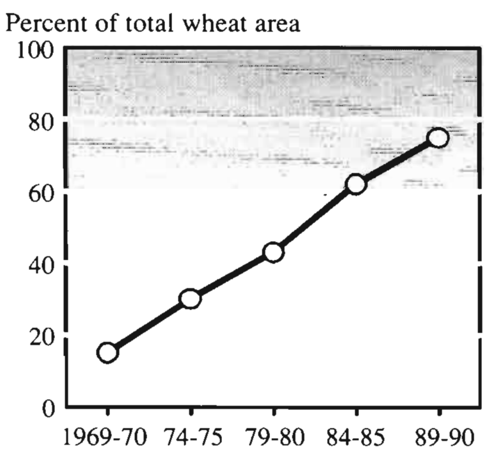

Figure 15. Trend in the adoption of semidwarf wheat varieties, developing world.

In studying the continued spread of semidwarfs since the early days of the Green Revolution, it is instructive to examine separately the record in irrigated and rainfed areas. Both environments provide good examples of on-going adoption into the 1980s. Much of the developing world's production of spring bread wheat takes place in irrigated environments, about which we note the following points.

- By 1980 practically all of South Asia's irrigated spring bread wheat area (a sizeable share of the developing world's total) was sown to semidwarfs. In 1990 these materials covered more than 28 million hectares of irrigated land in the region.

- Across all irrigated wheat environments, farmers have replaced earlier generations of semidwarfs at least once and usually twice, though rather slowly in some areas. In Pakistan's Punjab, for example, the first widely grown semidwarf, Mexipak (from the cross II8156), was exchanged in the 1970s for Yecora (from Bluebird) and WL711 (a cross made by Indian scientists). Those varieties in turn were replaced during the late 1980s by Pak81 (a Veery cross). Varietal turnover has also taken place in India's Punjab and in Bangladesh. Mexican farmers have abandoned old semidwarfs for new ones, on average, every two to four years, mainly because of the rapid rate at which rust pathogens evolve.

In general, semidwarf wheats have been adopted to a lesser degree in rainfed than in irrigated environments (Table 8). The major impediments in the former are the smaller yield gains achieved with modern varieties under less than optimum rainfall and the greater risk to production in these areas, which discourages fertilizer use, among other effects. Additional deterrents are the price premiums often paid for grain of the older, tall varieties and the importance in many rainfed areas of straw for fodder. In spite of these obstacles, there is ample evidence that since the 1970s semidwarfs have advanced slowly but steadily into areas characterized by less than optimum moisture conditions. The findings given below indicate both the extent of the progress and of the challenges that remain.

Table 7. Percentage of wheat area planted to semidwarfs for different regions and wheat classes, 1990

Region	Spring bread	Spring durum	Winter bread	Winter durum	All
Sub-Saharan Africa	46	18	-	-	35
West Asia/North Africa	69	50	17	14	39
Asia	89	-	-	-	87
Latin America	81	64	100	-	81
All	**83**	**44**	**19**	**14**	**75**

- In the rainfed areas of Pakistan, farmers first began to adopt semidwarfs around 1975 and by the late 1980s had taken them up quite widely in medium- to high-rainfall areas but less so in low-rainfall environments (Figure 16).

- Evidence from other countries also suggests that the adoption of semidwarfs in rainfed areas is still incomplete. In Syria and Tunisia, for example, where these varieties have spread gradually in the 1980s, about 30% of the rainfed area is still planted to tall varieties. In general, semidwarf spring bread wheats have enjoyed far greater success under rainfed conditions (because they are generally grown in the areas with higher rainfall) than have semidwarf spring durums and winter bread wheats.

- The pattern that emerges from available evidence is that in rainfed areas semidwarf wheats spread from higher rainfall, temperate locations to drier and often colder or hotter areas. It is primarily in these more difficult environments, where winter bread wheats or durums often predominate, that adoption of semidwarfs is still limited.

- It seems likely, however, that even the frontier of very dry areas will gradually be occupied by semidwarf varieties. In low-rainfall areas of Pakistan, for example, Pak81 (from a Veery cross) is now being adopted.

Table 8. Percent of wheat area under semi-dwarfs, by moisture regime, 1990

	Percentage of area	
Wheat class	**Well-watered**	**Dryland**
Spring bread	100	54
Spring durum	84	19
Winter bread	96	15

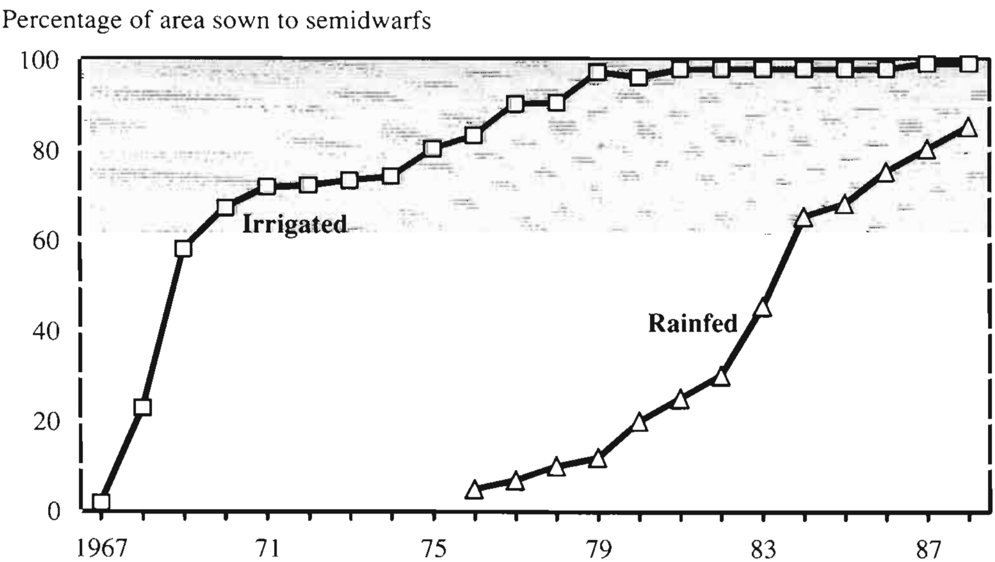

Figure 16. Adoption of semidwarf wheat varieties in Pakistan.

Similarly, varieties of bread and durum wheat, based on germplasm supplied by the CIMMYT/ICARDA breeding program, have been released in the WANA region and are showing promise in dry areas. In time these relatively recent products should be taken up on a fairly large scale, as has happened in dry areas of Australia.

Adoption of CIMMYT-based wheat varieties

Though not the only source of semidwarfs, the Center is undoubtedly the most important one in developing countries, and this fact is clearly reflected in the area planted to varieties derived from our germplasm.

- Overall, varieties to which CIMMYT has contributed directly cover 37 million hectares in the developing world (Table 9), plus another 10.5 million occupied by semidwarf varieties with our germplasm in their ancestries. Of the resulting total of 47 million hectares, about 23 million are occupied by varieties based on crosses made by Center staff.

- By far, the most popular cross, based on area planted, is a fairly old one, Sonalika, which still covers more than 6 million hectares and probably once occupied at least 9 million (Table 10). Even II8156, made available in the early stages of the Green Revolution, is still grown on an estimated 1 million hectares mostly in South Asia. The second most popular cross is Veery, currently sown on 3.4 million hectares out of a total of 4.0 million now occupied by varieties from crosses of spring with winter wheats.

- Apart from Veery no other recent bread-wheat cross has been adopted over a large area. The tendency now, as indicated in Table 10, is for more numerous varieties from various crosses to be taken up over more limited areas. It is unlikely then that a single cross will come to dominate wheat production, as was the case in the early years of the

Table 9. Area planted to CIMMYT-based wheat germplasm, 1990

Wheat class	CIMMYT cross	Immediate CIMMYT parent	No immediate CIMMYT parent: Semidwarf*	No immediate CIMMYT parent: Tall	All
			million ha		
Spring bread	20.6	12.9	9.3	7.9	50.7
Spring durum	2.1	0.1	0.0	2.8	5.0
Winter bread	0.0	1.1	1.1	8.9	11.1
Winter durum	0.0	0.0	0.2	0.9	1.1
All	**22.7**	**14.1**	**10.6**	**20.5**	**67.3**
		47.4			

*Nearly all with CIMMYT ancestry.

Green Revolution. We see this is an important and healthy trend, contributing to the genetic diversity in farmers' fields.

- The countries with the largest areas sown to varieties derived from CIMMYT crosses are India, Pakistan, and Argentina. If we consider only those varieties released since 1980, then Pakistan is the clear leader.

Obviously, farmers are satisfied with the improved wheat varieties resulting from our combined efforts with national programs. Nonetheless, we are concerned that, even though older varieties are being replaced by new ones, the rate of turnover appears to be slow. This is particularly true among the larger wheat producers of Asia, where the average variety age (weighted by the area under each variety) is more than 12 years. Given that it can take 8 to 10 years to develop and release an improved variety, the overall lag between peak expenditures on variety development and widespread adoption in the region can reach 20 years. Such a slow rate of replacement is a hindrance to maintaining disease resistance and reduces the benefits of wheat breeding considerably. In Latin America varieties are replaced more rapidly, commonly within 8 years or less, a rate comparable to that for the industrialized countries and approximating the average longevity of rust resistant varieties.

Slow varietal turnover has reinforced CIMMYT's habit of exploring all possible sources of genetic diversity in germplasm development. This approach contributes to genetic diversity in wheat production and limits vulnerability to disease epidemics and other stresses. In the early years of the Green Revolution, this vulnerability was very real. With surprising speed a small number of semidwarf varieties, having a relatively narrow genetic base, displaced a greater quantity of improved and local tall varieties. Since then, however, many new semidwarfs have entered the field, and these are based on a larger

Table 10. Area under popular CIMMYT crosses, 1990-91

Cross	First released	Area (000 ha)	Country/region
Sonalika	1968	6,250	South Asia
Veery	1981	3,370	Pakistan, Turkey, Iran, Chile
II8156	1965	1,070	India
Marcos Juárez	1971	860	Argentina
Bluebird	1970	840	Saudi Arabia, Egypt
Anahuac	1975	800	Brazil
Bittern (durum)	1979	500	Morocco, Turkey, Tunisia
Frigate (durum)[a]	1983	480	Syria, Algeria
Cisne (durum)	1971	460	Morocco, Turkey
Others		8,170	

[a] CIMMYT/ICARDA.

number of successful crosses than the original semidwarfs. Moreover, as explained above, there has been a marked tendency toward adoption of greater numbers of genetically distinct varieties over smaller areas.

Thus, the era in which just a few popular materials almost completely dominated the wheat landscape is rapidly disappearing. The newer generations of superior crosses and those now in the making are products of a deliberate and longstanding effort at CIMMYT to create genetic diversity in modern varieties. The key elements of this work (including crosses of spring with winter wheats, wide crosses research, and other initiatives) are described in other sections of this publication.

Adoption of CIMMYT-based maize varieties

The danger of genetic uniformity in the maize production of developing countries is far less grave than it ever has been in wheat. The populations from which CIMMYT generates maize germplasm products are already genetically diverse, and our maize scientists, like their counterparts in wheat, are actively seeking new sources of diversity for key traits. A further consideration (one that will eventually change, however) is that unimproved local varieties continue to predominate in many areas of the developing world. As recently as 1985-87, about 68% of the maize area in sub-Saharan Africa was planted to such materials, 50% in the WANA region, 38% in Asia, and 49% in Latin America, excluding areas, such as northern China, that lie in the temperate zone.

Based on survey results provided by national programs in 45 countries (encompassing more than 95% of the developing world's maize area outside the temperate zone), we draw the following conclusions about adoption of varieties based on our materials.

- Overall, nearly 8.0 million hectares or 13% of the maize area in developing countries (excluding the temperate zone) is planted to varieties containing CIMMYT germplasm (Table 11). This area constitutes a significant proportion (nearly 30%) of the area planted to improved varieties.

Table 11. Area planted to varieties and hybrids containing CIMMYT germplasm, 1990

Region	Maize area in 1990 (000 ha)	Area under CIMMYT-derived varieties (000 ha)	Area under CIMMYT-derived varieties (% of maize area)
Sub-Saharan Africa	14,427	1,460	10
West Asia/North Africa	1,224	476	39
South, East, and Southeast Asia	19,038	1,776	9
Latin America	23,807	3,884	16
Total	**58,495**	**7,596**	**13**

- CIMMYT germplasm has so far had the greatest impact in the lowland tropics; fully 85% of the area planted to varieties derived from our materials lies within this zone. Excellent materials are now available for other major ecologies, however, and should be widely utilized during the 1990s.

- Even though national programs in the WANA region have employed our germplasm least extensively (as a percentage of varieties released), that is where CIMMYT-based varieties have been most widely adopted (as a percentage of the region's total area).

These conclusions rest on estimates provided by researchers in national programs. Though we consider this information to be reasonably accurate, we suspect that it understates the adoption of improved maize germplasm. Our impression derives from the quite restrictive definition we used for variety coverage. In view of the ability of maize varieties to outcross readily with other genotypes, we included (at least theoretically) only those areas planted to OPV seed purchased within the last three years; for hybrid seed the limit was one year. Thus, our estimated total represents only those areas planted to improved seed that is true to type. It does not take into account the many genotypes in which improved germplasm has assumed a kind of disguise by mixing with local materials.

The Benefits of Improved Varieties

Farmers obviously would not adopt improved varieties unless they expected to realize tangible gains. For that reason patterns in adoption give clear signals about the magnitude of the expected benefits and about the conditions under which these are most likely to accrue. From the evidence given above, we can draw two fairly obvious conclusions about the payoff from improved varieties. First, it has so far been greater for wheat than for maize. And second, well-watered environments are more conducive to benefits than are drier rainfed areas, although gains to farmers in the latter appear to be growing.

It is easy to account for these trends. In the well-watered wheat areas, appropriate crop management (in some cases approaching that of experiment stations) and favorable moisture conditions allow improved varieties to express much of their genetic potential. Wheat is generally monocropped in these environments, reflecting the high priority farmers assign to it, which in turn helps explain their commitment to good crop management. Combined with the relative homogeneity of the well-watered zones, these circumstances are ideal for rapid and widespread adoption of improved varieties. Conditions are less conducive to such dramatic change in many rainfed areas. They tend to be more variable; moisture is sometimes less than optimum; and multiple cropping is common. As a result, it is often less apparent to farmers that the benefits of improved varieties outweigh the costs. Since most of the developing world's maize area is characterized by such conditions, it should come as no surprise that improved maize has spread more slowly and yielded fewer benefits than wheat.

As mentioned earlier, other factors come into play as well. Where farmers lack information about improved varieties, policies discourage their adoption, and high-quality seed is not available (a particularly common problem in maize), the most basic conditions for varieties to generate benefits go unfulfilled, and farmers never even get the chance to consider whether the new genotypes are better.

To catalogue and determine the relative importance of these problems, however, is not our aim here. Rather, it is to examine the available evidence on the benefits of improved varieties. In the case of wheat, we have sufficient data to compare the contributions of particular factors that create these benefits. Much as we suspected, the evidence largely confirms the conclusions that we can surmise from the rates of variety adoption.

Gains in wheat yields

Farmers in developing countries are not concerned exclusively with grain yield. Other items on their list of priorities are yield stability, maturity, grain quality, and straw yield. Even so, most producers weigh grain yield quite heavily in their choice of genotypes and recognize increases as an important source of benefits. As with patterns in the spread of semidwarf varieties, it is helpful to divide the evidence on their yield benefits according to production environments. We must also seek to verify the extent to which gains in yield potential, measured in experiment station and on-farm trials that precede variety release, are translated into comparable improvements under typical farm conditions, as determined from surveys and farmer-managed trials. Most of the data available pertain to irrigated wheat, about which we make the following observations.

- It is now well established that the adoption of semidwarfs in irrigated environments during the early years of the Green Revolution gave average yield gains of 35 to 40% over the tall varieties they replaced. A lesser known point is that during the two decades since then the yield potential of semidwarf varieties under irrigation has continued to increase by about 1% annually for a total of about 20% (Figure 17).

- We have every reason to believe that farmers in irrigated areas have captured a large share of the gains in yield potential. Their high levels of crop management and slow but steady replacement of old varieties with new ones have virtually guaranteed this outcome.

- Yield progress has perhaps not been as rapid where wheat is planted late. This practice is common in many cropping systems, particularly in South Asia, where nearly half of the irrigated wheat is sown after 1 December, usually following rice or cotton.

Information on yield gains in rainfed environments is scarce but provides evidence of some progress.

- In dry areas of Pakistan, modern varieties have not until quite recently offered farmers' a sufficient yield advantage to compensate them for the lower price of grain of these varieties and for a perceived loss of straw. New materials, derived from crosses between spring and winter wheats, promise to alter this equation significantly. The variety Pak81, for example, shows a yield advantage of at least 15% over local materials in the dry areas and is starting to be adopted there.

- Under the very harsh conditions of Western Australia's drylands, semidwarfs in farmers' fields are giving modest jumps in yield of 5 to 10% over the performance of tall varieties.

Notable progress has been achieved in warmer regions, where conditions are generally far from ideal for wheat production.

- Results from trials conducted in Brazil and Paraguay indicate that gains in fairly warm, rainfed environments are on the order of those achieved in more favorable areas under irrigation. But since these experiments were conducted without fungicide treatment, it is likely that some of the gains observed were due to improved disease resistance.

- In Bangladesh the variety Kanchan, a cross made by Indian scientists using a CIMMYT parent line, consistently outyielded Sonalika, the variety most farmers grow, by 17% in 3,000 on-farm demonstrations over a five-year period. This yield advantage is only slightly less than that observed in variety trials.

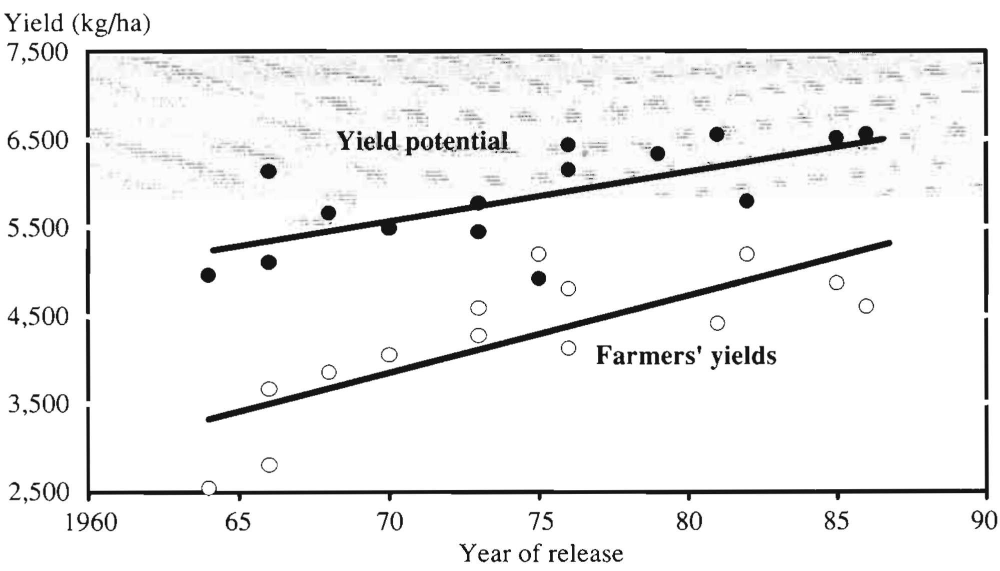

Figure 17. Yield gains in popular varieties (data from northwest Mexico).

Based on evidence from rainfed and warmer areas, it would appear that even in less than optimum environments farmers tend to capture a sizeable share of the yield advantage offered by new varieties. In Pakistan, for example, it was estimated that in mountainous areas the Veery-based variety Pak-81 gives farmers a yield gain of 35% over the tall local variety and 13% over previously released semidwarfs. Elsewhere in the country, farm surveys have consistently shown that Pak-81 outperforms other semidwarfs by 10 to 20%.

Gains in maize yields

The modern maize varieties being distributed in developing countries show considerably higher yield potential at experiment stations and in on-farm trials than the local alternatives. The evidence for maize can be divided into two categories: data from on-farm trials managed by researchers and that from experiments under the farmers' own management. The former are often conducted under different levels of fertilizer, including none or very little, the treatment that is most representative of conditions in farmers' fields. Though the results of these trials are rather variable, the reported yield gains are significant (Table 12). In trials managed by farmers, yield gains tend to be smaller than in on-farm trials managed by researchers (Table 13). Commonly, improved varieties show a yield advantage of 5 to 15%, approximating that of semidwarf wheats in rainfed environments.

Given the variable performance of improved maize in farmers' fields and the difficulty of determining accurately the area planted to it, we feel that additional analysis is required before average annual rates of gain in yield can be estimated with confidence.

Table 12. Yield of improved maize materials in researcher-managed trials on farmers' fields

Country	Mean yield, improved material (kg/ha)	Mean yield, local check (kg/ha)	Yield gain (%)
Nigeria	2,700	3,050	- 12
Indonesia	4,450	4,322	3
Morocco	2,190	1,990	10
Malawi	1,758	1,456	21
Philippines	1,565	1,255	25
Zaire	2,330	1,780	31
Guatemala	4,227	3,075	37
Ghana	4,045	2,543	59
Burundi	2,973	1,721	72
Togo	1,918	1,080	78
Average of 19 sets of researcher-managed on-farm trials			**28**

Maintaining disease resistance in wheat

As early as the 1940s, the scientists whose work led to CIMMYT's establishment viewed disease resistance as a vital complement of high yield potential. In the semidwarf wheats they created, it was the combination of these traits that accounted for widespread adoption. Built-in protection against rust epidemics provided farmers with a kind of agricultural insurance, greatly reducing the risk that they would lose their investments in the new seed and other inputs. Conversely, lack of resistance to the septoria diseases in early semidwarfs effectively halted their spread in North Africa until resistant genotypes were made available.

CIMMYT's Wheat Program has begun to work on other diseases as well, and we have achieved satisfactory progress in developing resistance to most of them. To assess the impact of this more recent work, though, would be premature, since our resistant materials are either still at the experimental stage or only now reaching farmers in varieties developed by national programs. The work on septoria diseases is a better candidate for our impact study, but we are still in the process of gathering data.

The conclusions we present here about the benefits of disease resistance are therefore based on experience with germplasm resistant to the rusts of wheat, particularly leaf rust, which is a severe and widespread hazard to the crop. Efforts to contain the threat have been complicated by rapid evolution of the disease pathogen, which greatly shortens the useful life of resistant varieties. Our response has been to develop new generations of germplasm with different combinations of resistance genes, a task often referred to as "maintenance research," which seems an oddly mundane epithet for such a vital function. At the same time, we are searching for means of achieving durable resistance to leaf rust

Table 13. Yield of improved maize materials in farmer-managed trials

Country	Mean yield, improved material (kg/ha)	Mean yield, local check (kg/ha)	Yield gain (%)
Malawi	1,300	1,400	- 8
Mexico	8,400	8,000	5
Nigeria	1,720	1,590	8
Pakistan	5,580	5,050	10
Ghana	2,460	2,180	13
Cameroon	2,980	2,620	14
Benin	1,880	1,620	16
Zaire	1,710	1,360	26
Nigeria	1,990	1,560	28
Average of 9 sets of farmer-managed on-farm trials			**12**

(as opposed to single-gene resistance, which is subject to rapid breakdown as the disease pathogen evolves), and this goal now seems to be within our grasp.

In the absence of a more permanent solution, the system of developing and disseminating new varieties has generally proved adequate for warding off major leaf rust epidemics. Two important exceptions are the outbreaks that occurred in Mexico and Pakistan during 1978. In these cases the problem was primarily local. New varieties had already been released to replace the old ones whose resistance had broken down, but their adoption was delayed by slow production and dissemination of seed and inadequate extension efforts. Although this experience provided a sobering reminder of the costs of negligence, there is still evidence, as we point out above, that in some areas the replacement of old varieties is long overdue. Hence our urgency in developing genotypes with durable resistance to rust.

In the numerous places where variety replacement has proceeded more rapidly, the benefits of rust resistance depend on the yield losses that would have occurred if germplasm carrying this trait had not been available. Many studies indicate that leaf rust can cause yield losses of 25 to 45% at specific sites during years when climatic and epidemiological conditions are exactly right for an epidemic. Average losses in farmers' fields are usually much lower, ranging from 5 to 20% in favorable environments according to planting date and other factors. Assuming that average yield losses without resistant germplasm are 10% and that the expected life of the variety is seven years, then the yield losses avoided through maintenance research are a little more than 1% per year. In the developing world's favorable wheat areas alone, the value of this contribution amounts to about US$150 million and now exceeds even that of annual additions to yield potential.

The overriding importance of rust resistance is supported by the first year's results from a CIMMYT study conducted on the experiment station at Ciudad Obregón, Mexico, during 1990-91. Semidwarf varieties developed over the years were compared under heavy leaf rust infection, both with and without fungicide treatment. In the absence of chemical control, varieties released before 1973 suffered losses of nearly 50% in this experiment, compared with virtually none for more recent varieties now in commercial production and under 20% for varieties that appear to show durable resistance. The overall gains through breeding—for both yield and leaf rust resistance—were on the order of 2.9 to 5.3%, depending on the varieties included and the planting date. When these same varieties were treated with fungicide, we observed a 1% average rate of gain in yield potential. It is thus apparent that rust resistance accounts for the remaining and much larger share of the overall gains (Figure 18).

Tolerance to acid soil conditions in wheat

From our experience with leaf rust, it is clear that a sustained assault on the major stresses that reduce crop yields can generate huge returns far exceeding the investment in research. Though it is hard to imagine a more emphatic demonstration of the point, even more encouraging evidence comes from CIMMYT's cooperative work with Brazilian scientists, focusing mainly on tolerance to aluminum toxicity in acid soils. This condition is widespread in Brazil's wheat-producing regions and is generally accompanied by other problems, including various diseases that thrive under warm, humid conditions. The poor performance of older semidwarfs under these stresses largely kept them out of the country's wheat area on acid soils until well into the 1980s. Farmers logically preferred locally developed tall varieties, in spite of their lower yield potential, because they were better adapted to the prevailing conditions.

By the early 1980s, attractive alternatives had been developed through a breeding program begun during the early 1970s in which selections were made alternately in Brazil and Mexico (see page 29). The unique products of this work were semidwarf varieties showing the tolerance to aluminum toxicity and disease resistance of the older varieties but with 15 to 25% higher yields. Between 1982 and 1990, more than 30 new semidwarfs were released, and by 1990 they occupied 64% of the country's total wheat area. In Brazil's two most important wheat-producing states, the yield potential of released varieties climbed at a rate of 2 to 3% per year from 1970 or so to 1990, and much of the increase can be attributed to the new semidwarfs. This rate of progress rivals gains achieved in the far more favorable environments of Asia during the early 1970s.

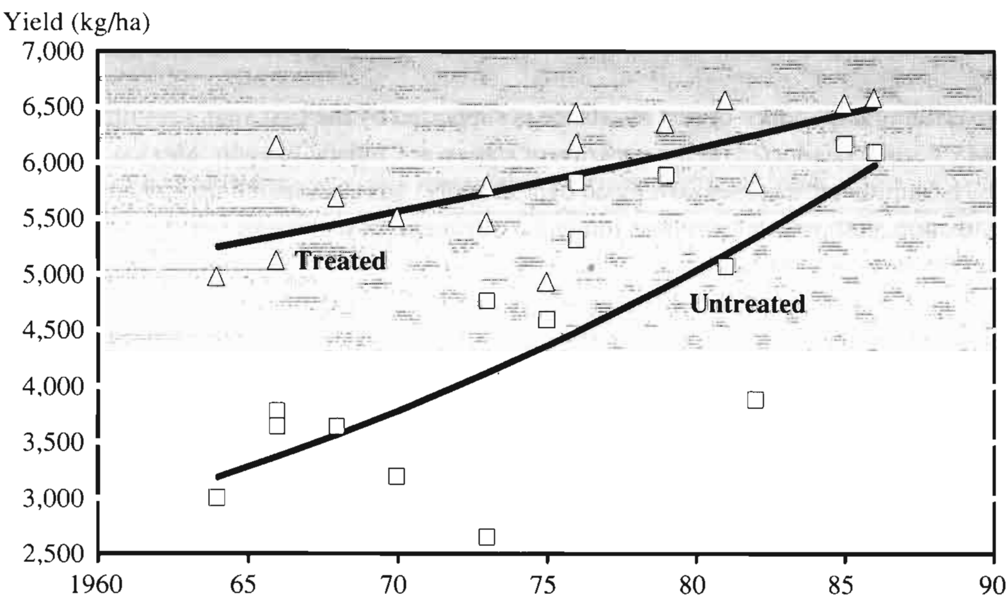

Figure 18. Yield of varieties released since the 1960s, with and without fungicide, northwest Mexico, 1990.

WHO BENEFITS FROM IMPROVED VARIETIES?

When the benefits of any enterprise become larger, the question of who receives them assumes greater importance. The issue is especially pertinent to a humanitarian endeavor like that in which CIMMYT is engaged, because its express purpose is to help a specific group—the poor in developing countries. As the Green Revolution got underway in the late 1960s, these considerations gave rise to a vigorous debate, in which it was asserted that well-to-do farmers received the lion's share of the benefits from semidwarf wheats. A large amount of research, including studies conducted by CIMMYT, demonstrated that this was not the case. Although large-scale farmers tended to adopt the new varieties first, small-scale producers joined the feast soon afterwards. There were large discrepancies in the rates of adoption, but our own studies showed that they were related to agroclimatic and other differences among environments, not to farm size. Moreover, in spite of slow adoption in some areas, consumers across all environments benefitted from the spread of semidwarf wheats through lower food prices.

More recent experience further confirms the view that semidwarf varieties are essentially scale neutral. A comparison of developments in Brazil and Egypt dramatically illustrates the point. In both countries semidwarfs were adopted extensively in the 1980s. The rates of adoption were comparable, even though in Brazil wheat is produced mostly by commercial farmers with relatively large holdings (averaging about 80 ha in Paraná, the country's major wheat-producing state) and in Egypt farms are among the smallest in the world, averaging less than 1 ha.

Even the large imbalance between optimum and less favorable environments seems to have diminished some since the 1970s, as semidwarfs have slowly but steadily advanced into areas characterized by drought, soil problems, and other stresses. Nonetheless, adoption of these varieties is far from complete. In numerous places, including Ethiopia, dry areas of the WANA region and of central and southern India, and highland zones from Turkey to Afghanistan, farmers have yet to enjoy the benefits of wheat research. The difficult circumstances of these people call for a continuing commitment to the development of hardier genotypes and to improved management of crops and agricultural resources.

As farmers in the less favored regions do obtain improved germplasm, they will not be its only beneficiaries. In fact, under certain circumstances consumers receive a larger share of the gains than producers, mainly through lower food prices. In India, for example, which is close to self-sufficiency in wheat production, real wheat prices paid to farmers have fallen by more than 3% yearly since 1970, and those for consumers have dropped at an annual rate of over 2% (Figure 19). This trend has benefitted the rural and urban poor in particular, since they spend a sizeable proportion of their income on wheat products (about 20% in the Indian Punjab, for example). A similar situation has prevailed in Pakistan, though increases in real land prices there have enabled farmers to make up for some of the losses in real grain prices. In smaller countries that import large quantities of wheat, producers and in some cases the government have probably been the major beneficiaries. Regardless of overall trends in producer and consumer prices, it is important to remember that many small-scale farmers must purchase wheat once their homegrown supplies have been exhausted. As net consumers of this commodity, farmers in any region, but particularly in the marginal environments, can capture some of the benefits generated by technological change in favored areas.

Environmental benefits

CIMMYT is convinced that many further benefits can be generated for the developing world's poor by extending the productivity gains achieved over the last 25 years. But we are also committed to working toward this aim in ways that are consistent with the need to conserve natural resources. Fortunately, much of what we have been doing for years to increase productivity has also had positive environmental payoffs.

Gains in the productivity of maize and wheat, especially in favorable production environments already under cultivation, have had a considerable "land saving" effect. In India, for example, had yields of wheat and rice stayed at mid-1960s levels, it would have taken 115 million hectares of land to produce 1990's output of these crops. In fact, that level of production was achieved on only 68 million hectares. In effect yield increases saved 47 million hectares of land by reducing the pressure to expand cultivation. Much the same thing has occurred in other developing countries.

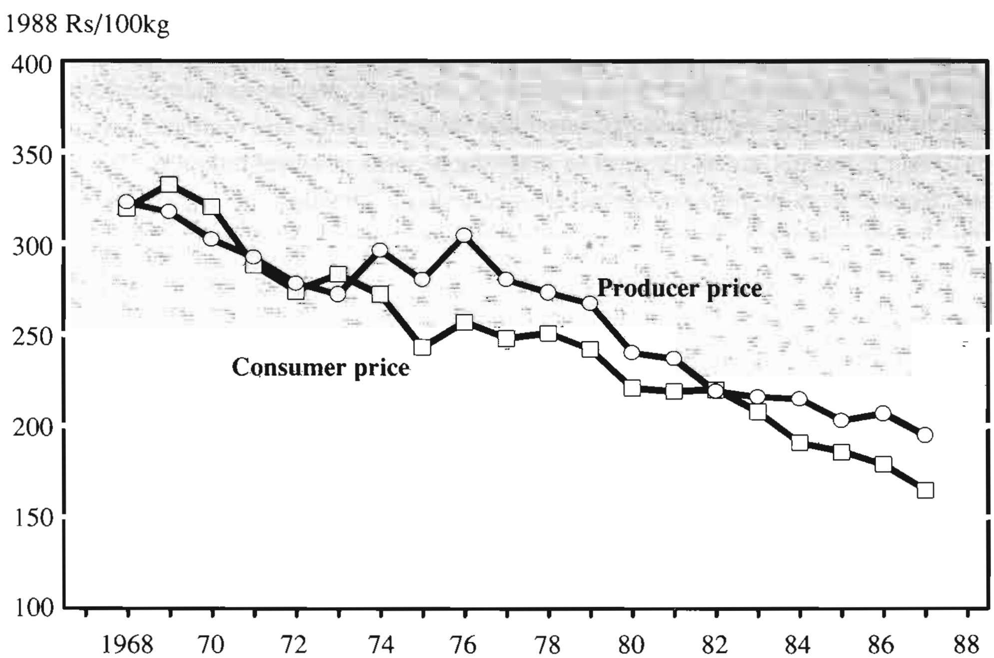

Figure 19. Trends in the price of wheat (Punjab, India).

An additional benefit of modern varieties is that their improved resistance to diseases and insects has reduced the need for potentially harmful chemicals. As part of its effort to maintain and strengthen this resistance, CIMMYT has acquired and preserved sizeable collections of maize and wheat genetic resources, including materials whose value may not yet be apparent. We consider these to be a kind of low-cost insurance against potentially devastating epidemics and a foundation for future progress in germplasm improvement.

The Center is also pursuing new lines of research that relate directly to the conservation challenge. By improving the efficiency with which maize and wheat use available nitrogen, for example, we are addressing the widespread constraint of poor soil fertility, which will grow in severity as cropping intensity increases. More intensive cropping will also give rise to greater demand for genotypes that are uniquely suited to intensive and conservation-oriented cropping systems. We are addressing this challenge in various ways, for example, by seeking genetic variability in maize and wheat for improved performance in rotation or in combination with other crops and by evaluating some of our materials under minimum tillage.

Both this system and the rice-wheat rotation practiced widely in Asia figure importantly in our crop management research, which is focusing increasingly on the long-term productivity of major wheat and maize cropping systems. This work is largely strategic in nature, with results having broad applications in a number of countries, and it emphasizes the development of diagnostic tools and research methodologies. In conjunction with these new initiatives in research, CIMMYT is modifying its training programs to ensure that participants are sensitized to environmental issues and learn about the impact of various practices on the quality and productivity of the natural resource base of agriculture. For a comprehensive treatment of this theme, see the CIMMYT 1990 Annual Report, which focuses on the contributions of the Center's research to sustaining agricultural resources in developing countries.

Measuring the Impact of Crop Management Research

If measuring the impact of improved maize and wheat presents complex challenges, then quantifying the contributions of crop management research (CMR) is unquestionably even more difficult. Nonetheless, the complementarity of modern varieties and improved crop management compels us to pursue vigorously the relationships between CMR and increased agricultural productivity.

Sources of complexity

One complicating factor is the intangible nature of the products of CMR, which consist almost entirely of information, such as recommended fertilizer rates or application methods. To deliver such products is inherently more difficult than the dissemination of germplasm. Moreover, once new information has arrived at a given destination, we cannot easily chart its further progress. If a product as discrete as an improved maize variety can lose its identity fairly quickly in farmers' fields, then what chance does a technical message have, even if it is in print, of remaining completely intact as it spreads throughout the countryside? As one CIMMYT scientist put it, though farmers do not generally "half-adopt a variety," they often modify cultural practices, applying perhaps only half the recommended rate of fertilizer.

Even so, we can still identify cases in which developing country farmers have changed their practices on a large scale as a result of researchers' recommendations. Moreover, though it is often difficult to separate the effects of improved crop management from those of new varieties, there is ample evidence that innovations of the former type contribute importantly to increased yields. Various studies, conducted mostly in industrialized countries, suggest that improved practices account for about half of the total gains in maize and wheat yields; the proportion is even higher in marginal environments.

Despite the intangible and highly mutable character of information pertaining to crop management, we can still identify cases in which developing country farmers have changed their practices on a large scale as a result of researchers' recommendations.

In reviewing such findings, however, we must avoid the mistake of crediting research organizations with all of the yield increases brought about through improved crop management. Their work is undoubtedly an important contributor to change, but it is not the only one. A great deal of useful information about crop management is generated by the extension services and by farmers themselves through trial and error. Moreover, inputs and mechanical innovations are usually provided by the private sector, and both the availability of these items and farmers' incentives to adopt them are conditioned to a large extent by the government's agricultural policies. In the case of improved germplasm, it is far easier to determine the exact contribution of research. Since there is generally little doubt as to the source of a given variety, the causal connection between the institution that developed the material and the benefits accruing to farmers who adopt it is fairly clear.

Defining the patterns of change

Given these complexities, we cannot employ means as straightforward as our germplasm survey for gauging the effects of CIMMYT's support of CMR in national programs or for estimating farmers' adoption of products resulting from this research. Even so, as we embark on a more systematic study of CMR impacts, we find ourselves asking some of the same questions that have arisen in our efforts to document the effects of improved germplasm. What, for example, are the notable patterns of change in farmers' practice, and how do these inform our appraisal of impact? In analyzing the effects of semidwarf wheat varieties, we noted the importance of variety turnover in keeping one step ahead of rapidly evolving rust pathogens. This requirement has very much influenced the direction of wheat breeding and is therefore central to the study of its impact.

Similarly, our examination of crop management practices in land-intensive agriculture (the predominant type in much of Asia) suggests that change occurs in a sequence of four phases:

1. *Pre-Green Revolution:* Increased production results largely from expanded area.

2. *Green Revolution:* A technological breakthrough (such as the development of high-yielding, fertilizer-responsive varieties) creates the potential for a dramatic increase in the productivity of the land.

3. *First post-Green Revolution:* After widespread adoption of modern varieties, farmers begin to intensify their use of inputs, especially fertilizer, which serves as a substitute for increasingly scarce agricultural land.

4. *Second post-Green Revolution:* Once input use has reached high levels, farmers search for ways of using inputs more efficiently, allowing managerial skill to substitute increasingly for input use.

The last two of these phases have quite distinct implications for the role of CMR, for the specific innovations on which it focuses, and for the kind of impact these have. In the third phase, the challenge for CMR is to develop and demonstrate broad recommendations for input use. This research contributes to rapid yield gains, accompanied by increasing production costs per hectare. By the fourth phase, farmers turn their attention to technologies such as reduced tillage, more precise timing and methods of fertilizer application, and integrated pest management. CMR should lead the way by generating information about these more complex practices and by starting to examine long-term trends in the productivity of major cropping systems. These are, of course, extremely worthwhile pursuits, but their impact, expressed as modest gains in yield and perhaps reduced production costs, may be less noticeable than that in phase 3.

The flow of products from crop management research

Another parallel between our efforts to measure the impact of improved germplasm and of CMR is that in both cases it is necessary to trace the flow of products and to examine their effects at each stage, focusing on different indicators of impact. This is where the similarity ends, however. Whereas the products of plant breeding are fairly distinct and their path from researchers to farmers more or less direct, the information generated by CMR is less tangible and its flow more complex, consisting of divergent streams with quite different destinations and modes of delivery.

For the purposes of studying impact, it is convenient to divide CMR into four categories. Two of these are concerned with adaptive research aimed at generating recommendations for farmers — the type of work in which CIMMYT scientists have been most closely involved. One category consists of adaptive CMR in national programs and the second of the various ways in which we support this work. Our primary means of doing so are consultation, training, and information, focusing mostly on research methods. To determine the impact of this work is a matter of gauging the demand for our services and use of the procedures that we promote, among other indicators.

As with plant breeding, though, we are unlikely to make a very convincing case for impact unless we extend the analysis beyond utilization of our products. To measure impact thoroughly at this stage demands that we carefully monitor changes in recommendations, in agricultural policies, and ultimately in farmers' practices. In selected cases, we might also calculate the economic returns to innovations in crop management.

A third category of research that we have turned to in fairly recent years is strategic CMR. This work addresses topics that are less site-specific than those dealt with by adaptive CMR; most are regional in scope, such as the parasitic weed Striga in sub-Saharan Africa and erosion control in the hillside agriculture of Central America. Though obviously it would be premature to measure the impact of this work, we will eventually need to make assessments comparable to those for adaptive research.

It is less apparent how we should weigh the effects of a fourth category of CMR, namely its support to plant breeding. Nonetheless, we are quite confident that this work has increased the efficiency of breeding for increased yield potential and anticipate a significant payoff from its contribution to the development of genotypes with drought tolerance.

EXPERIENCE WITH ON-FARM RESEARCH

From our initial examination of published and informal literature and from leads provided by various CIMMYT staff, it is obvious that the outcomes of CMR conducted during the 1970s were rather poorly documented and that our prospects for demonstrating impact are much better as we examine work that took place in the 1980s. This is the period in which our joint efforts with national programs to develop methods for on-farm research (OFR) came to fruition and in which this approach found wide application in the developing world (see pages 51-52). Though we are still in the early stages of measuring the impact of OFR in ways suggested above, one of our staff has just completed a detailed study of experience with this methodology. From that book (which is currently in press), we have gleaned the following highlights, which indicate at least the location and type of impact, though without precise measurements of its magnitude.

- One of the earliest countries to demonstrate the possibilities of OFR was Panama, whose national program tested this method in the Caisan region. Surveys and on-farm experiments led to the development of improved practices for weed control, planting, and reduced tillage. The majority of farmers adopted these practices, and a subsequent study showed high returns from the investment in research. On the strength of this experience, the national program introduced OFR as an integral part of its research strategy at the national level.

- Around the early 1980s, CIMMYT made a considerable effort to develop OFR capacity in the Andean zone, particularly in Ecuador. A special program was established for adaptive research, and OFR teams were assigned to 10 areas of the country. Among the first challenges taken up by scientists in one of these areas was to incorporate early maturing maize varieties into the predominant farming systems of the highlands. Though research demonstrated that the new varieties were appropriate and beneficial, their spread was limited by poor infrastructure and the prevailing agricultural policies. Nonetheless, the country's OFR program has gained increasing respect and is now recognized as a primary source of information on Ecuador's varied and complex farming systems.

- CIMMYT also actively promoted the OFR approach in Mexico during the 1980s, with support from the French government. The national program proposed that these procedures be tested in maize-based farming systems in southern Mexico, where the majority of the country's rural poor reside. Through a combination of research projects and training activities, scientists identified some of the principal limiting factors in maize production and gained a new appreciation of the value of farm-level data for shaping research priorities. In the state of Chiapas, OFR not only led to the development and adoption of improved technologies but gave rise to an innovative extension program and a reorientation of fertilizer distribution policy.

- In eastern and southern Africa, CIMMYT staff have worked for more than a decade, with funding from the US Agency for International Development (USAID) and the Canadian International Development Agency (CIDA), to support various OFR initiatives. As a result, national programs in the region have strengthened their adaptive-research capacity, and we have achieved a better understanding of the conditions for OFR to fulfill its potential. In some countries, including Ethiopia, adoption studies demonstrate that OFR has led to the diffusion of new technology.

- OFR has featured importantly in a long-term, CIDA-supported project in Ghana, where CIMMYT has worked with the International Institute of Tropical Agriculture (IITA) to strengthen local research institutions. Two central achievements of the project have been to integrate the efforts of researchers and extension agents throughout the country and to create a nation-wide system for on-farm testing of new technology. A recent evaluation shows that farmers have widely adopted the project's recommendations, which emphasize improved maize varieties, better plant population, and fertilizer application.

- In Asia CIMMYT staff have focused on incorporating OFR into some of the region's relatively well-developed agricultural research programs. In the Philippines and Indonesia particularly, the method has been applied successfully and with great imagination. In the Malang district of the latter country, research on insect control and management of plant stands helped increase the efficiency of maize production on small farms and encouraged growers to take advantage of new varieties. In Pakistan's Northwest Frontier Province, maize OFR has given researchers a better grasp of the basic rationality of farmers' crop management and pointed to ways of accommodating a new variety in the unique farming systems of this area. OFR activities in the country's major wheat-producing zones have demonstrated the potential of this research as an aid to setting priorities in the national wheat program.

In spite of this fairly long list of positive experiences, OFR has not in general met the high expectations set for it in the early 1980s, particularly if we confine our definition of impact to the successful transfer of improved technology to resource-poor farmers. The reasons for this outcome are many, including poor implementation and inadequate support to research and extension. Moreover, OFR programs have frequently been isolated from other research services, denying them access to the technical support required to address the complex problems of small-farm agriculture. Clearly, the development of an OFR capacity alone does not lead automatically to effective technology development and dissemination. In the future OFR programs must acquire a more integral role in strong, stable research establishments that are capable of using information from the field to set priorities and choose objectives. In many cases it is evident that national programs' experience with OFR procedures has helped them move in precisely that direction.

Assessing the Impact of Research-Related Activities

Practically all of CIMMYT's research activities have prominent training and information components. These activities are two of our primary means for strengthening the capacity of national programs in plant breeding and CMR. For that reason our assessment of impact cannot be complete without adequate means of measuring progress in the Center's various efforts to train and inform cooperators.

A good start toward determining the impact of these activities is to document the number of people trained and the demand for information products. But obviously we must do more. Training and information work ultimately have an impact at the farm level, and in the future we must attempt to measure these effects systematically. This will be a difficult task, however, because they are so thoroughly embedded in the outcomes of plant breeding and CMR.

Training

This circumstance has not prevented at least one researcher from attempting to relate gains in maize productivity to the "capacity of maize researchers," among various other factors. In that study the number of national program staff trained at CIMMYT was used as a proxy for researchers' capacity. Though we must interpret with caution the results of econometric studies like this one, it is still interesting to note one of the conclusions: Every 5% increase in the number of trainees a given developing country sent to the Center for training over the last 25 years is associated with a 1% increase in national maize yields.

Our confidence in the power of training, however, is based less on quantitative results of that sort than on observations of its effects. Particularly valuable are insights provided by the participants themselves and by experts who have been invited to review our training activities. Over the years both groups have consistently endorsed the content and underlying philosophy of CIMMYT's four- to five-month, in-service courses on maize and wheat breeding and CMR, which form the core of our overall training effort.

The crux of our approach in these courses is an emphasis on learning by doing (see page 61). In-service trainees generally spend about 50% of their course time engaged in field activities, and they are expected to demonstrate learning through competence in specific tasks. The courses are strongly oriented toward accurate identification of farmers' needs and well-planned research for addressing them. We were thus pleased to find in the results of a survey of past participants in CIMMYT's wheat improvement course (completed in 1990 by one of our training officers) that the proportion who said they had frequent contact with farmers was 83% after training, compared to 59% before. The survey data also suggest that course participants are more strongly disposed than before to engage in interdisciplinary cooperation. This latter finding is perhaps related to another key feature of our in-service training, namely the close and prolonged contact with other participants and with the experienced scientists who conduct the courses. Surely it is self-evident that training is conducive to research impact if it emphasizes practical skills, a focus on farmers' problems, and the value of collaboration. Of course, in order for training of this type to translate into greater research effectiveness, scientists must also have adequate operating funds, infrastructure, and incentive systems.

Information

Surveys are also a common means of testing the effectiveness of particular publications, and we have employed this approach in soliciting feedback on one of our recent annual reports and selected training materials. To gain a more general idea of the impact of CIMMYT publications, we recently investigated their availability in major international databases as well as the degree to which they have been cited by others over the last 10 years or so.

In reviewing our own annual reports and in-house databases, we first determined that the number of CIMMYT contributions published per year (including those carrying the Center's own imprimatur and those appearing in refereed journals and other scientific publications) has risen from 100 in 1980 to 269 in 1990, with most of this increase occurring in the last five years (Figure 20). The upward trend was particularly marked among journal articles. CIMMYT contributions are well represented in the international databases. Between 1984 and 1990, CAB Abstracts reported 386 items by Center staff and 226 with CIMMYT's imprimatur; the same figures for AGRIS during 1984-1991 are 471 and 846 and for AGRICOLA during 1970-1991, 684 and 428. The Science Citation Index

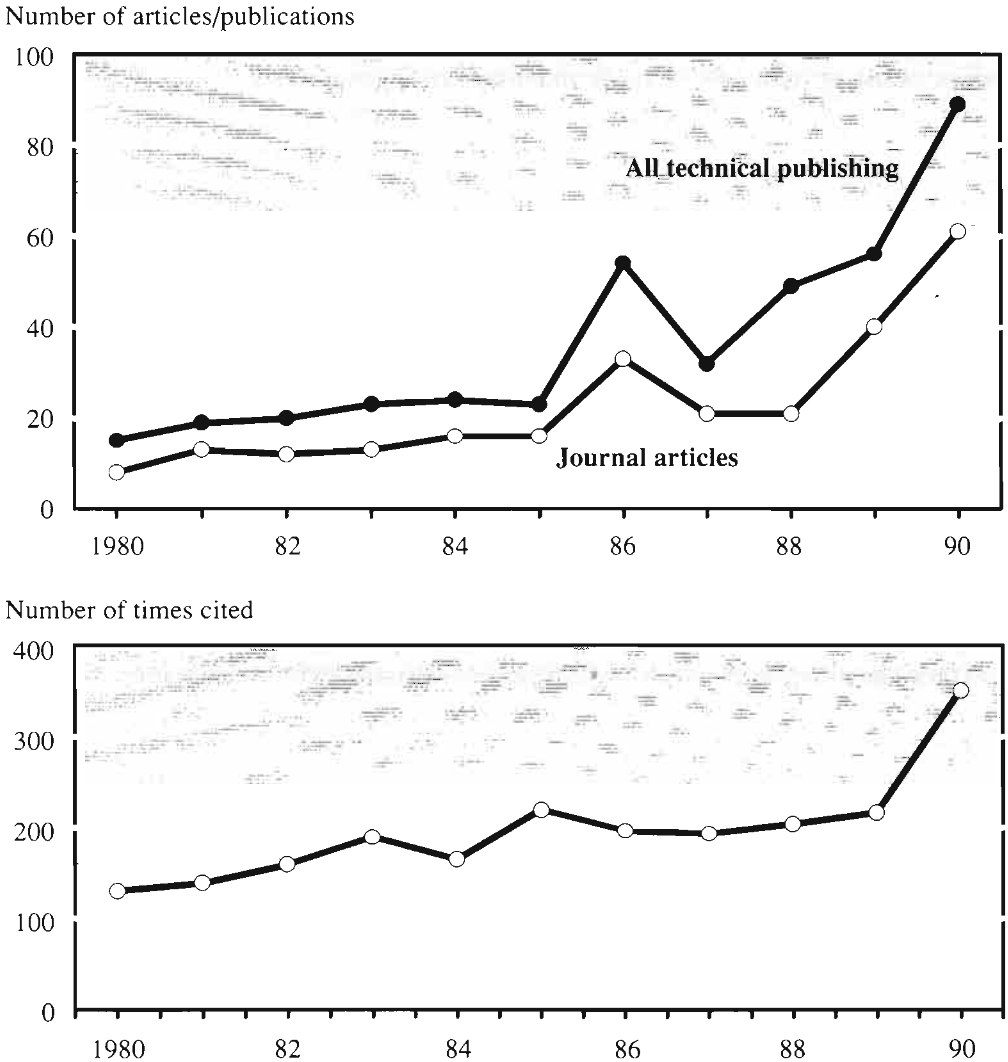

Figure 20. Trends in technical publishing by CIMMYT staff and citation of the Center's work, 1980-90.

reports over 2,300 citations to items published by current and former CIMMYT staff, a quite large number considering that our scientists often agree to appear as coauthors of publications prepared jointly with colleagues in national programs and thus are not included in the citation count.

Though we can draw only tentative conclusions from such citation analyses about contributions to science, we are pleased with the results. It appears that we are doing a better job now than 10 years ago of reaching the worldwide scientific community with useful information.

For the Future

This account of CIMMYT's research and impact has focused on important changes in our work over the past 25 years and how those changes are linked to impact. We have also observed that much about the Center has not changed; there is a core of enduring values and practices that form its culture and account for much of CIMMYT's vitality and effectiveness. The ethos of the Center today is very much the same as at its inception: an emphasis on field work, on the importance of direct researcher involvement, on a pragmatism based on the needs of farmers, on evenhandedness in dealing with clients, and on the benefits and obligations of an open association with a worldwide network of practitioners sharing the same principles. Recently added to this list is a growing sensitivity to the advantages of contributing to science, and wider concern for benefits relative to costs in pursuing specific activities. These are the hallmarks that condition virtually all aspects of CIMMYT's institutional life.

CIMMYT's mission: To increase the productivity of resources committed to maize and wheat in developing countries while protecting natural resources, all through agricultural research.

In looking to the future, we affirm the continuing importance of these hallmarks. We also note that healthy organizations like our own are responsive to changing circumstances and new opportunities. In the past few years, significant energy has gone into evaluating our operational realities, weighing opportunities, and charting a course to the next century. The process we used, our reasoning, and the outcomes of our effort are detailed in *Toward the 21st Century: CIMMYT's Strategy,* published in 1989; that effort and the resulting document provides the basis for much of what follows.

ONE VISION, BUT AN EVOLVING MISSION

CIMMYT's institutional vision still holds — we exist to help the poor of developing countries. This vision has been expressed in various ways over the years and the means for implementing it have changed in fundamental ways, yet at its heart lies the notion that international agricultural research can open new options for the poor, with the potential for dramatically improving the welfare of hundreds of millions of people.

At its founding, CIMMYT's purpose was succinctly expressed in a forceful mission statement:

> *To increase the quantity and quality of maize and wheat production in the developing countries of the world.*

At a time when widespread starvation and malnutrition threatened millions in the developing world and when knowledge about the development process was limited, an emphasis on producing more grain was entirely appropriate. A sense of urgency pervaded our work and the heady success of our early efforts helped to motivate hundreds of agricultural scientists around the world in the struggle against poverty and hunger.

Since then, a growing understanding of agriculture's dynamic role in economic development and of the potential contributions of international research to advances at the farm level led us to refocus our attention. By the mid-1980s, we had shifted our emphasis to the productivity of resources committed to maize and wheat; our preoccupation with outputs was supplanted by concern for the input side of the equation. We formalized this new view of CIMMYT's purpose in our strategic plan with the following mission:

> *To help the poor of developing countries by increasing the productivity of resources committed to maize and wheat, whether in research or on the farm.*

This formulation seemed sufficiently broad to accommodate a host of relevant opportunities, yet narrow enough to keep us focused on important problems. Still, one of those problems — the potentially negative effects of agriculture on the environment — is of such fundamental importance in our work that it too requires explicit recognition. We have therefore reformulated CIMMYT's mission once again:

> *To increase the productivity of resources committed to maize and wheat in developing countries while protecting natural resources, all through agricultural research.*

Note that our vision of helping the poor in developing countries remains intact, as does the conviction that international agricultural research provides an efficient means of doing so. The forceful rallying cries of an earlier day, however, have given way to more subtle calls to action, and the immediacy of the early challenge to "fill hungry bellies" has been augmented with emphasis on the future and on a broader range of objectives.

Future Directions: Charting the Next Decade

Strategic planning provided us a clearer sense of new opportunities and the changing needs of clients. Assessments of six major external "environments" strongly influenced our planning decisions: The CGIAR's mandate and concerns; the state of science; the circumstances of national programs; alternative sources of supply, including national programs; the economics of the maize and wheat sectors; and the state of the global environment. About every two years we revisit these environments to see how well our predictions are tracking emerging events and with the idea that we will reexamine priorities and resource allocations as needed to accommodate significant deviations.

> **During the 1990s, we will increase our allocations to research by some 40%. Germplasm improvement will remain CIMMYT's main line of work . . . and we will increase our efforts in strategic crop management research, giving more emphasis to protecting natural resources while increasing productivity.**

In the near term, we are revising — sometimes in significant measure — the resources allocated among major enterprises and activities. These changes are being phased in over time, and are themselves responsive to new information and budget realities.

During the 1990s, we will increase our allocations to research by some 40%. Germplasm improvement will remain CIMMYT's main line of work. We envision a growth in demand for advanced germplasm products and for sources of special traits that national programs can rapidly convert to useful products for farmers.

We will increase our efforts in strategic crop management research, giving more emphasis to protecting natural resources while increasing productivity. Our strategy in this realm involves focusing on problems that relate to major maize and wheat cropping systems and are international in scope. We will use new tools to extrapolate and extend results.

We will do relatively more social science research over time, especially as it pertains to generating new technologies, evaluating policies that impinge on maize and wheat production, and to the efficient allocation of research resources by CIMMYT and by national programs. We will be involved in considerably less on-farm research as others take up the activity.

We will also increase resources devoted to information work, especially that which improves the efficiency of research but as well that aimed at keeping the patrons of international agricultural research better informed of its payoffs.

We will allocate less to administration and direct support to national programs (reductions of about 10% and 30%, respectively). While giving more emphasis to midcareer education, we will give less to entry-level training. Consulting will become more structured, less ad hoc, and occupy less of our energy.

Our planning effort yielded not only the broad directions noted above but as well a rich array of operational strategies, the "meat on the bones." What follows here are but some of the highlights. Interested readers should see either our strategic plan or its supplement, *Toward the 21st Century: Strategic Issues and the Operational Strategies of CIMMYT.*

Germplasm research

National programs either release CIMMYT germplasm directly as final products or incorporate it into their own breeding programs. Both approaches will remain important, though their use as intermediate steps to final products has become more common in better endowed national programs. While our Maize and Wheat programs will continue to produce many of their current products, both are adding emphasis to special trait populations that can serve as donor stocks. Both programs generate materials that are broadly adapted within large, relatively homogeneous "mega-environments," a fundamental strategy that we apply in all our germplasm improvement work. We then rely on national programs to select for specific adaptation, frequently assisting less advanced national programs in this task.

We are using a wide range of sources in a deliberate effort to increase the genetic base of maize and wheat. The spread of CIMMYT-related wheats over so vast an area makes it imperative that we actively expand its genetic diversity. While most of the variability required to sustain genetic gains until the year 2000 will come from crosses within the same species, some will be obtained from near relatives by means of wide-cross techniques. Although they will be relatively small in number, such genetic transfers are expected to play a particularly important role in wheat breeding.

We will maintain our recently expanded responsibilities in germplasm evaluation and conservation. CIMMYT's role in the latter rests on two objectives: easier access to genetic resources to solve known problems, and ensuring the availability of those resources to solve problems that may arise in the future. Clearly, the latter objective should be seen as part of our commitment to conserving natural resources. We will continue with our global responsibility for conservation and evaluation of maize landraces. We will do the same for bread wheat and for triticale, as well as provide backup storage for the base collection of durum wheat and wheat's wild relatives maintained by the International Center for Agricultural Research in the Dry Areas (ICARDA). In evaluation we will concentrate on the search for specific traits for which there is insufficient genetic variability in advanced germplasm. To improve the efficiency of evaluation, our bank managers are forming core collections representative of the major genetic complexes thought to exist in each species. This collection will be available to national programs. Special emphasis in maize is being given to building stronger relationships with national germplasm banks so as to ensure that materials are properly handled, and that relevant information about bank accessions is widely available.

In our "maintenance" research — that aimed at defending genetic gains by developing resistances to constantly evolving pathogens — added emphasis will be given to increasing the durability of resistance. This is of greater concern to the Wheat Program, which currently invests some 50% of its research resources to maintaining and expanding effective disease resistance. Their efforts in this arena are treated more fully earlier in this publication (see pages 18-20).

While the transfer of single genes from one genus to another holds considerable promise, it also poses scientific, legal, and economic challenges. Because of their high cost, we will not undertake to develop the techniques of transgenosis ourselves. Rather, we see CIMMYT as a user of tools developed elsewhere, and as a conduit of useful methodologies to others. Thus, our strategy calls for close monitoring of progress in this field, and for research aimed at testing and adapting specific tools for use in our circumstances and, eventually, the circumstances of national programs in developing countries. Even so, as in the case of our important work on nonradioactive probes, we will seize relevant opportunities as they emerge. We are pleased with our initial efforts and our ever stronger interactions in this arena. To further implement our strategy and to speed our breeding work by taking advantage of other efficiencies promised by new science, we anticipate growth in this area.

Finally, while we recognize that crop improvement will often not be the best option in addressing marginal environments, we will pursue improved drought tolerance in both maize and wheat, tolerance to acid soils in maize, and heat and cold tolerance in wheat.

As a part of all these efforts, we envision greater contributions to science, especially in pathology, physiology, and the disciplines related to crop and natural resource management. It is expected that interaction across programs will continue to increase.

Strategic crop management research

In this sphere we are shifting our emphasis to explicitly include the protection of natural resources, and we are broadening our perspective to include natural resource management and the use of crop modelling and geographic information systems as a complement to the traditional CMR and economics research that was featured in this work. We expect this expanded view to enhance the international extensions of our efforts and to better incorporate CIMMYT's concern for the environment. While doing this we recognize that there will still be great scope for refinements to meet local needs, which reinforces the role of national programs in this work. In support of their role, we will develop diagnostic tools and methodologies, and serve as integrators and distributors of agronomic information generated by us and by others.

There are at least two broad approaches to crop and resource management aimed at increasing productivity while protecting the environment. One emphasizes an ecoregional view. Ours treats large, well-defined maize and wheat cropping systems, with the major commodities serving as vehicles for opening research on the dominant production system. There is a question as to which of these approaches can best meet the twin challenges. To improve understanding, we will pay close attention to documenting the course of our work and its impacts in this domain.

We will do relatively more social science research over time, especially as it pertains to generating new technologies, evaluating policies that impinge on maize and wheat production, and to the efficient allocation of research resources.

Economics research

CIMMYT and its national program clients must carefully rationalize decisions about the allocation of increasingly scarce research resources. Decision makers need to understand longer term trends in the maize and wheat economies at the global, regional, and national level, and to see the implications of trade in inputs and product. They must also better appreciate the interactions among local markets, farming systems, and farmer decisions. Our economists will augment efforts to provide research managers with better information and improved methods and procedures for analyzing allocations and assessing progress. Beyond that, we will add to a comprehensive database on utilization of improved germplasm; on maize and wheat production, consumption, and prices; and on the use of inputs. We are giving more attention to the consequences for CIMMYT and for national programs of the trend toward privatization of research. Finally, we will devote more efforts to interactions with strategic crop management research, particularly that related to natural resource management.

Training

We are transforming our training in two fundamental ways: by increasing the array of specialized and advanced training opportunities and by gradually reducing our involvement in entry-level training in crop management research. While continuing to provide in-service training in crop improvement and, as resources permit, experiment station management, we are now offering more specialized and advanced courses for midcareer researchers. In CMR training for entry-level participants, we are well along the path toward regional training managed by national programs. Finally, our visiting scientist program is more focused, with greater emphasis being given to those who can profitably work for longer periods on well-defined research projects relevant both to their institutions and to our own work.

Information

Information products and services are becoming more important to the Center and its clients. Largely through the use of new information technologies, we are increasing the availability of scientific information to our own staff and to colleagues in national programs. We have added emphasis to publishing information of a more technical nature, much of this in refereed journals. We will continue to publish practical guidebooks and manuals under CIMMYT imprimatur to enhance the research and training capabilities of others, especially of national programs. We are increasing resources aimed at keeping donors and their constituents better informed about CIMMYT's work and the impact of agricultural research.

Consulting

At the specific request of national programs, our consulting work now features less frequent but more structured forms of interaction. The results of such interactions are proving to be more useful to national programs and to CIMMYT, with the added benefit of requiring fewer resources to implement.

Changing Relationships with National Programs

While we are reducing some of our work in direct support of national programs (consulting and entry level training), we are expanding other efforts that provide important, though more indirect benefits. As well, we are exploring new paradigms to facilitate interaction and support, and to more effectively draw on the talents and skills of colleagues in national programs.

One example of this strategy is the work focused on sustaining Asia's vast rice/wheat rotation, which features national programs in the research agenda. Note, too, that as we move further into the realm of strategic research, especially that aimed at protecting natural resources (as exemplified by the rice/wheat work), the collaborative network must be extended beyond national programs to include sister institutes in the CGIAR and other research centers of excellence. We anticipate considerable efficiencies through the application of these collaborative strategies.

In describing our near-term plans, we have presumed that funding will be available to meet the basic demands for our work. This presumption rests on the belief that concern for the developing world's poor and for the environment will remain high, that agriculture will still be regarded as an effective way to deal with those two problems, that research remains central to the search for solutions, and that alternative sources of supply (whether private or public) for the products CIMMYT generates will increase but still be notably limited.

Charting a Course Beyond 2000

In thinking about CIMMYT's more distant future, we should first consider the probable role of international agricultural research as changing circumstances redefine the world. It is well to remember that the CGIAR System, of which CIMMYT is a part, was founded 20 years ago with the expectation that the System and its centers would soon work themselves out of business; 15 to 20 years was the longest horizon that the founders contemplated. Twenty years later for the CGIAR and 25 years later for CIMMYT, and after successful undertakings of great benefit to the developing world, the System and CIMMYT are contemplating the next two decades, out well beyond 2000.

Our impression is that, ebbs and flows of the short run aside, support for international agricultural research will remain high if we can demonstrate its effectiveness in dealing with important problems or opportunities.

International research after 2000

Beyond 2000, we must see the demands for international agricultural research — defined as research that draws resources, whether private or public, according to anticipated multicountry benefits and costs — in the context of changes so dramatic as, perhaps, to change the very character of the CGIAR.

Most observers are less than sanguine about the capacity of developing countries to cover their food needs toward the future, either through domestic production or through unsubsidized imports. They point to the small anticipated gains through expansions in area or irrigation, where additions could be offset by productivity declines in existing systems and to the difficulties of further raising yields while attending to the environment. Most claim that the way forward must involve improved technologies and that these are dependent on agricultural research. Two major remaining questions relate to the likely source of that research — private or public, national or international.

Our impression is that, ebbs and flows of the short run aside, support for international agricultural research will remain high if it can be demonstrated that such research provides an effective way to deal with important problems or to gain from opportunities. It is clear that as long as developing country national programs are weak, international research is an efficient way to assure the continuing flow of useful technologies to farmers; this was a primary consideration in launching the CGIAR.

Beyond that, however, as Donald Winkelmann has argued in a paper presented in October 1991 at a World Bank conference ("Agricultural Technology: Current Policy Issues for the International Community and the World Bank"), international research can play an important role even when national programs are strong. That argument goes on to list seven arenas in which such research can offer advantage because of the effects of economies of scale. The seven are: germplasm improvement; germplasm collection, evaluation, and storage; crop and natural resource management; specialized training; collation and dissemination of information; development of research methodologies and procedures; and assessing the needs of global agriculture. As well, the argument continues, where there are high costs in maintaining proprietary interests (the public goods case) and where benefits will not be financial (aiding the poor and maintaining the environment), there is a strong case for financing such international research publicly.

Consider just two of these arenas as examples: germplasm improvement and crop management research. The experience of the last 25 years shows categorically that plant breeding need not be done locally to have advantage locally. For maize and wheat, and probably for all cereals, it appears that over half the gains in yield and yield stability latent through plant breeding can be achieved with materials that meet the important demands of large, relatively homogeneous environments (mega-environments), with less than half, then, remaining to be derived through breeding aimed at local or micro needs. (Maize appears to offer more to local breeding than does wheat, which is to say that maize suffers more losses to small or local causes than does wheat.) Moreover, it appears that such environments include a very high percentage of the developing world's maize and wheat production.

Maize and wheat mega-environments comprising at least a million hectares and including vast areas in more than one country are amenable to international research. There is, then, potential advantage in conducting research in only a few locations within a mega-environment (risk considerations usually call for some redundancy) and then reproducing successful materials for the remaining users in the environment, as compared with paying the full cost incurred in separately developing materials locally. The further payoff associated with meeting local needs will depend on the added gains in doing so and the extent of the area over which those gains prevail. We add that the argument is really much like the one that keeps each farmer from developing her or his own germplasm. Thus, in assessing economies of scale the relevant questions are: over what reach do the important similarities extend and what does it cost to attend to them?

The same kinds of considerations apply to crop management research. Here, however, it seems clear that the value added through local research is a greater portion of the total than in plant breeding, especially when the research is aimed primarily at deriving recommendations for farmers. In CIMMYT, this consideration led us to move away from traditional approaches to CMR toward strategic research and then further, by broadening the disciplinary base for this work and adding to array of techniques used. We believe that, by combining crop and natural resource management with crop and environmental modelling and geographic information systems, we can increase the area over which particular research can be applied and raise the proportion of gains that can be attributed to non-local research. The effect would be one of raising the platform from which local research takes off, lowering its costs and hastening its results. Again, to the extent the reach can be extended, there is promise for economies of scale and scope for international research.

Having stressed the case for international agricultural research, there is a question about who will finance it (for more on this, see the Winkelmann 1991 World Bank paper referenced above). Our view is that, where proprietary interests can be secured and where returns are adequate, the private sector will finance and undertake international research. Some of the opportunities in germplasm improvement will meet these conditions, some will not. In strategic CMR, especially that pertaining to natural resources, there appears to be less opportunity for the private sector and more cause for public financing. The extent of such balances will say much about CIMMYT's future.

CIMMYT after 2000

Against that background of potential returns to international agricultural research, what can we say about CIMMYT after 2000? Not surprisingly, we can say little that is specific, but we can identify the considerations that seem likely to influence the arenas in which our work will still promise an effective way forward. Each consideration, and perhaps others, merits more attention by CIMMYT, by its clients, and by its donors. For now, the most likely elements identified are: advances in science, advances in the creation of new markets through changes in attitudes and institutions, extensions of proprietary interests, and gains in farmers' yields through the application of more intensive practices. These, along with developments within the national programs of developing countries, will be important parameters in shaping our more distant future.

Clearly, advances in science will have a widespread impact on how we do our work. However, to the extent that through science it becomes possible to extend the domain of proprietary interests, advances there will be critical in deciding what work we do. Suppose, for example, that it becomes possible to dramatically lower the cost of hybrid wheat seed, or to identify categorically the product of a particular open-pollinated variety. Then, other things being equal, private firms can be expected to enter more markets, increasing the alternative sources of supply. In the past, where the private sector has been active CIMMYT has curtailed its own investments; we would expect to follow that strategy in the future unless new thinking suggests otherwise.

In another dimension, advances in science leading to more effective modelling and to opportunities for applying geographic information systems will open new opportunities for international work in strategic crop management research. Since the results of that research will be information, difficult to make proprietary, and as much of it will apply to conserving natural resources, this case favors public financing and an expansion of CIMMYT's work. And, to the extent that such advances facilitate multi-country research on, say, tillage, residue management, and crop rotations, there will be greater scope for international research and, because of limits on proprietary claims, more work for CIMMYT.

The creation of new markets oriented around extending plant breeders' rights or varietal protection will change our role, other things equal, to the extent that they expand opportunities for proprietary claims. They will also change our role to the extent that there emerge enforceable contracts for the delivery of research products, such as improved germplasm, from one party to another. These will have the effect of reducing the importance of "evenhandedness," the guarantee of delivery without contract and an important part of CIMMYT's current advantage over other would-be suppliers of the products of international research. The possibility of such contracts could bring selected national programs into international research, adding to alternative sources of supply.

Other things (such as contracting) being equal, the growing concern for reducing the costs of research should enhance our role. Mega-environment-based work in breeding and management, with the accompanying opportunities for economies of scale, brings advantages to internationally focused work like that undertaken by CIMMYT. Followed far enough, the argument involving advances in science, proprietary interest, and concern for efficiency suggests a relative shift of total cereals research resources (national and international, but not necessarily those of CIMMYT) toward crop and natural resource management and away from plant breeding.

Gains in farmers' yields in maize will open up new terrain for hybrids. We posit that, with management practices that give rise to yields of under 2.5 tons/ha, there is little advantage in seeding unsubsidized hybrids, given their greater cost. As yields pass that level, hybrids seem more likely to offer advantage, even with their greater cost. So, with the spread of more intensive practices and higher yields, there will be a greater area in which hybrids offer promise and a concomitant reduction in open-pollinated varieties. This implies more scope for the private sector and a different role for CIMMYT.

In general then, and again with other things being equal, those developments that add to alternative sources of supply — through advances in science or institutional changes that favor capturing the gains from research and contractual forms that bring national programs into international research — will tend to limit our role. An increasing concern with efficiency in research will tend to expand our role, as will progress in science that favors the extrapolation of research results on "public goods." Finally, as national programs strengthen, other things equal, the alternative sources of supply consideration will encourage us to shift more energies into strategic research.

The context for this discussion relates heavily to the interests of those who finance the various activities in which CIMMYT engages. It is our perception that they are ever more concerned with efficiency and ever more open to the role of private sector activities. As well, it appears that the balance of sentiment in the developing countries is encouraging a greater role for the private sector. Our advantage lies in that arena where public goods predominate, where the private sector will not go because the nature of the goods precludes the taking of profits. Given the context and in particular the concerns of those who finance our work, in the longer term CIMMYT's role shifts as does the arena for public goods, tending to expand with public goods and refocusing with private goods.

Managing the Future

And how will we manage the future? Perhaps the best summary statement is that management of the Center's resources will aim at effectiveness. We develop that idea in our strategic plan, and again refer the reader to that document for additional detail.

The influential elements

In shaping our priorities and assigning our resources we are guided by the goals of the CGIAR — to be efficient in helping the poor and in sustaining natural resources. Efficiency for CIMMYT is ensuring that we are doing the right things and doing things the right way. Judgements about this are influenced by our external and internal environments.

The single most critical element affecting our future success is the quality, energy, and dedication of our staff.

The external environments are those six listed earlier (see page 98). The reader will notice that much of the previous section's discussion hinged on two of those: developments in science and alternative sources of supply. As well, our six external environments were important in determining the changes reflected in the section dealing with our strategies for coping with the near-term future. Staying in touch with these environments is one part of staying efficient.

Internally, and indeed overall, the single most critical element affecting our future success is the quality, energy, and dedication of our staff. Getting it right rests on an effective staff. A host of considerations go into achieving that effectiveness. A few are recounted here, all of them are most relevant to developments over the next decade.

We invest ever more in staff training, mainly through programs offered at CIMMYT (most of these for support staff) and for study leaves (most of those for post-graduate scientific staff). Both efforts aim at keeping staff abreast of new developments, of expanding their knowledge in areas of importance to CIMMYT, and at revitalizing interest in the activities of the Center.

In the recent past there has been new emphasis given to disciplinary research and to publishing research results in professional journals. The idea here is not to encourage a disciplinary-focused institution but rather to ensure that we stay abreast of relevant developments in an ever faster moving science while we expand ways to learn more quickly through the contributions of professional peers. Too, the useful contributions we make to science expand the opportunities open to staff while enhancing the reputation of CIMMYT as a place to work.

We have added more decision points within the management structure of our research programs. These open opportunities to those interested in the management of science and offer more efficacious routes for interaction among those with similar interests. At the same time we have expanded the role of several of the supervisors within the support staff; again offering greater opportunity to staff and putting decision making closer to the action. One result is that all staff feel more involved, more a part of the enterprise. These changes, while pertaining to structure, have a positive influence on staff effectiveness and were made for that purpose.

The independent, free-standing Boards of Trustees that govern the operation of the CGIAR centers comprise one of the System's hallmarks. Over its 25-year history, CIMMYT's Board has played a critical while ever-changing role. New relationships with the Board have brought new sources of expertise to management of the Center and, through Board participation in various search and review processes, have added new dimensions there. Most significant has been added Board participation in finding and recruiting senior management and in our newly established, internally managed, external reviews of the quality and relevance of our science. These roles reinforce the Center's capacity to recognize and seize opportunities.

As we continue to strengthen and reorient our research, investments in facilities need to be made. Several of our current laboratories will be upgraded. Some of our experiment stations, heavily used over the years, require attention. As well, to more efficiently fulfill our commitments in the area of genetic resources, a new maize/wheat cold storage facility will be constructed. All in all, however, CIMMYT facilities have been well maintained over the years and, with the modest exceptions noted here, we are adequately prepared for the future.

The Road Ahead

Given increasing populations and rising incomes, we expect to see developing country utilization of maize and wheat roughly double over the next 25 years. While we would not suggest that countries pursue a policy of self-sufficiency, we do insist that this vast expansion in utilization represents an opportunity to promote dynamism in the agricultural sector, which will further promote economic growth.

To seize this opportunity will require ever more intensive production strategies and, perhaps, an expansion in the area under the two crops. Each avenue for increase carries with it the potential for further threats to natural resources. While the cost to the global environment of developing country agriculture is low as compared to all nonagricultural activities, its effects are important and are notably visible. The rising concern about the health of the environment will add immensely to the challenge of meeting the levels of cereals utilization envisioned. The task for agricultural research is certain and daunting.

We expect wider recognition of the various interactions between productivity and protection of natural resources. In particular an awareness that productivity increasing technologies for favored environments make a dramatic contribution to protecting natural resources in more fragile areas as gains in the first reduce the need to expand into the second. Beyond that, of course, we must find ways to protect those natural resources involved in productivity increasing technologies, whatever the environment.

In the course of the next decade or so, we project only modest improvements in the circumstances of national research programs. Budgetary and institutional constraints seem destined to continue limiting their productivity. Private firms will add to the availability of maize hybrids for some areas but will, as we see it, contribute little else to improved germplasm for maize and wheat. Beyond that, given the limited possibilities for financial gain, firms will invest little in most aspects of research aimed at protecting natural resources. In the terms of the earlier discussion, then, we see little expansion in alternative sources of supply and infer that the effective demand for CIMMYT's products will remain high.

Finally, as we see it the circumstances of our staff, our physical infrastructure, our management structure, and our culture harmonize well with the needs of today; and mechanisms are in place to guide us in adapting to change. The record shows that CIMMYT has been a remarkably productive institution over the past quarter of a century. The challenges of the future — the needs of millions of poor in developing countries, the requirements of the environment, the urgency for a more profound understanding of the dynamics relating productivity and the environment, realizing the potential contributions of research — are evident. Within the context of our resources, CIMMYT is ready to meet those challenges. We look forward to a lustrous future.

Appendix 1:
Key Events in CIMMYT's History

Institutional developments

1943	Office of Special Studies (OSS) established.
1944	Norman Borlaug joins Rockefeller team in Mexico.
1960	Mexico's National Institute for Agricultural Research established.
1963	CIMMYT created as a cooperative program of the Mexican government and Rockefeller Foundation.
1966	CIMMYT founded under a new charter, with an internationally representative board of trustees and Edwin J. Wellhausen as its first director general.
1970	Norman Borlaug receives Nobel Peace Prize for his contribution to the Green Revolution.
	CIMMYT and IRRI receive the UNESCO Science Prize.
1971	CGIAR system created.
	Construction of CIMMYT's current headquarters completed.
	Haldore Hanson appointed director general.
1976	First Quinquennial Review conducted by the CGIAR's Technical Advisory Committee (TAC).
1978	Robert D. Havener appointed director general.
1980	First long-range plan published—*CIMMYT Looks Ahead: A Planning Report for the 1980s.*

1983 Second TAC Quinquennial Review.

1984 Robert D. Osler appointed acting director general.

First comprehensive study of the CGIAR system's impact.

1985 Donald L. Winkelmann appointed director general.

CIMMYT's mission reoriented from increasing maize and wheat production to raising the productivity of resources committed to these crops.

1986 CIMMYT celebrates its 20th anniversary in conjunction with inauguration of the Norman E. Borlaug Training and Information Building.

Concept of sustainability incorporated into the goals of the CGIAR system.

1988 CIMMYT receives the King Baudouin Award of the CGIAR in recognition of its development of Veery wheats.

1989 First strategic plan published—*Toward 2000: CIMMYT's Strategy*.

CGIAR/TAC External Program and Management Review.

1990 Laboratory for applied molecular biology research inaugurated.

CIMMYT impact study launched.

Maize research

1967 Recurrent selection for reduced plant height begun in the maize population Tuxpeño Crema I.

Puebla Project initiated.

Initiation of research at CIMMYT on quality protein in maize.

1970 Experiment station acquired at Poza Rica, Veracruz, for development of lowland tropical germplasm.

Maize agronomy courses begun, with emphasis on on-farm experimentation.

1973 Wide crosses (maize x *Tripsacum* spp.) initiated.

1974 Maize breeding program reorganized and international testing system established.

First regional maize programs set up in Asia and the Andean zone.

1975 Mass rearing of maize insect pests started.

Work begun on drought tolerance in maize, focusing on recurrent selection in the population Tuxpeño Sequía.

Corn stunt project initiated in cooperation with El Salvador and Nicaragua.

1979 Study of Tuxpeño Crema I demonstrates the relationship of reduced plant height to better harvest index and higher grain yield.

1980 Maize streak virus project begun in cooperation with IITA in Nigeria.

1980 Downy mildew project begun in cooperation with Thailand.

1984 Maize Program develops its first special-purpose population, with resistance to mutiple insect species.

1985 Midaltitude maize research station established at Harare, Zimbabwe.

Hybrid maize program begun at Center headquarters.

Highland maize program reoriented from floury and *morocho* to semident grain types.

Facilities for long-term storage of maize genetic resources completed.

1987 Study of Tuxpeño Sequía establishes importance of anthesis-silking interval for improving maize performance under drought.

1988 Regional maize agronomy trials initiated in Central America for on-farm evaluation of erosion control practices.

Maize Program joins a network of European organizations to study the use of restriction fragment length polymorphisms.

1991 CIMMYT and Kenya create a regional training course on crop management research for eastern and southern Africa.

Quality protein maize breeding program phased out.

Wheat research

1945 Scientists in Mexico begin to employ the technique later named shuttle breeding.

1950 International Spring Wheat Rust Nursery begun.

1953 Norman Borlaug introduces Norin 10 dwarfing genes into the wheat breeding program in Mexico.

1956 Mexico achieves self-sufficiency in wheat.

1961 Scientists from the Middle East and Pakistan travel to Mexico for practical training.

1962 First semidwarf, stem rust resistant wheat varieties (Pitic 62 and Penjamo 62) released in Mexico.

1965 Large-scale demonstrations of semidwarf wheats organized in India.

All-Pakistan Wheat Research and Production Program launched under the leadership of the nation's president.

1967 Release of Sonalika, the most widely grown Indian wheat variety in the 1970s and 1980s.

Triticale breeders discover Armadillo, a fortuitous outcross showing improved grain quality and fertility.

1968 Crossing of spring with winter wheat started.

1969 International triticale and durum wheat trials established.

1972 Shuttle-breeding project to improve aluminum tolerance in wheat begun in cooperation with Brazilian scientists.

Barley breeding program initiated.

1973 First regional wheat program established, focusing on disease surveillance.

1974 Screening of wheat germplasm for resistance to helminthosporium leaf blight and heat tolerance begun at Poza Rica.

1975 Wheat agronomy courses begun, with emphasis on on-farm experimentation.

Lines with good resistance to septoria diseases distributed internationally for the first time.

Wide crosses between wheat and its wild relatives initiated.

1978 International testing of Veery lines begun.

1979 Slow rusting response confirmed in the varieties Pavon and Torim.

1981 First Veery-based varieties released in Mexico.

Facilities for medium-term storage of wheat germplasm established.

1982 Project on wheat for warmer environments initiated.

Wheat virology research begun.

1984 First diagnostic surveys of the rice-wheat cropping pattern conducted in Pakistan.

1986 Winter wheat research intensified with the establishment of a cooperative project with Turkey's national program.

1987 Cooperative project initiated with China to develop wheat germplasm resistant to fusarium head scab.

1988 CIMMYT accepts responsibility for maintaining a global base collection of bread wheat and triticale.

1989 Project begun in collaboration with Cornell University, USA, to develop a wheat genome map.

1991 CIMMYT and Argentina initiate a regional course on crop management research for Latin America.

Economics research

1971 CIMMYT adds its first economist to the staff.

1972 Technology adoption studies initiated in eight developing countries.

1975 First commodity sector/policy studies begun, focusing on wheat economies in the Andean countries.

1976 First economist posted to an outreach program (eastern and southern Africa).

Publication of *From Agronomic Data to Farmer Recommendations: An Economics Training Manual.*

1979 First call-system course conducted in Ecuador.

1980 Economics Program created.

Publication of *Planning Technologies Appropriate to Farmers: Concepts and Procedures.*

1981 First issue of the CIMMYT World Maize and Wheat Facts and Trends series published.

First study of wheat-growing environments, a precusor of current work on mega-environments.

1982 A major effort begun to institutionalize OFR in national programs in eastern and southern Africa.

1983 A study conducted on the returns to OFR.

First in a series of comparative advantage studies done, focusing on the potential for wheat production in irrigated versus rainfed areas.

1984 First diagnostic surveys of the rice-wheat cropping pattern conducted in Pakistan.

1988 Major revision of *From Agronomic Data to Farmer Recommendations.*

1989 Various activities initiated to consolidate and reevaluate experience in OFR.

The Planning Stage of OFR: Identifying Factors for Experimentation published jointly by CIMMYT and CIAT.

1990 The start of CIMMYT's first extensive study on the impacts of its research.

APPENDIX 2:

CIMMYT'S ANNUAL EXPENDITURES AND NUMBER OF SENIOR INTERNATIONAL STAFF, 1967-91

Year	Nominal expenditures (000 US$)	Index (1980=100)	Real (1980) expenditures (000 US$)	Senior international staff		
				Headquarters	Outreach	Total
1967	790	37.7	2,095	17	8	25
1968	1,336	39.2	3,408	26	9	35
1969	2,868	41.1	6,978	24	12	36
1970	3,325	43.4	7,661	32	16	48
1971	5,918	45.6	12,978	37	20	57
Average	**2,847**		**6,624**	**27**	**13**	**40**
1972	6,492	47.8	13,582	41	20	61
1973	7,682	51.4	14,946	41	19	60
1974	7,474	58.2	12,842	46	20	66
1975	9,118	64.8	14,071	44	24	68
1976	11,949	70.2	17,021	47	24	71
Average	**8,543**		**14,492**	**44**	**21**	**65**
1977	11,637	76.2	15,272	58	23	81
1978	15,244	81.8	18,636	51	28	79
1979	17,564	89.3	19,669	56	25	81
1980	19,251	100.0	19,251	52	28	80
1981	21,832	110.2	19,811	51	29	80
Average	**17,106**		**18,528**	**54**	**27**	**80**
1982	21,830	118.5	18,422	47	32	79
1983	21,613	124.8	17,318	54	35	89
1984	26,141	130.6	20,016	56	38	94
1985	27,679	136.1	20,337	52	44	96
1986	29,611	139.3	21,257	55	47	102
Average	**25,374**		**19,470**	**53**	**39**	**92**
1987	28,924	143.4	20,170	58	43	101
1988	32,031	148.3	21,599	58	42	100
1989	33,905	154.8	21,902	57	44	101
1990	32,433	162.6	19,946	59	39	98
1991	34,992	168.8	20,730	56	37	93
Average	**32,457**		**20,869**	**58**	**41**	**99**

Notes: All figures are for core and special project expenditures and staff. Index is the International Monetary Fund industrial country consumer price index. 1991 data are estimates.

Appendix 3:
About the CGIAR

Established in 1971, the Consultative Group on International Agricultural Research — the CGIAR — is an association of nearly 50 countries, international and regional organizations, and private foundations dedicated to supporting a system of international agricultural research centers and programs. The purpose of the research effort is to improve the quantity and quality of food production in developing countries, while protecting and preserving the productivity of natural resources. The World Bank, the Food and Agriculture Organization of the United Nations (FAO) and the United Nations Development Programme (UNDP) are cosponsors of this effort. The World Bank provides the CGIAR's chairman and secretariat. The CGIAR is advised by a Technical Advisory Committee (TAC) whose secretariat is provided by the three cosponsors and located at FAO headquarters.

CGIAR-Supported International Agricultural Research Centers

CIAT Centro International de Agricultura Tropical. Cali, Colombia.

CIMMYT Centro Internacional de Mejoramiento de Maíz y Trigo, El Batan, Mexico.

CIP Centro Internacional de la Papa. Lima, Peru.

IBPGR International Board of Plant Genetic Resources. Rome, Italy.

ICARDA International Center for Agricultural Research in the Dry Areas. Aleppo, Syria.

ICRAF International Council for Research in Agroforestry. Nairobi, Kenya.

ICRISAT	International Crops Research Institute for the Semi-Arid Tropics. Hyderabad, India.
IFPRI	International Food Policy Research Institute. Washington, D:C., United States.
IIMI	International Irrigation Management Institute. Colombo, Sri Lanka.
IITA	International Institute of Tropical Agriculture. Ibadan, Nigeria.
ILCA	International Livestock Center for Africa. Addis Ababa, Ethiopia.
ILRAD	International Laboratory for Research on Animal Diseases. Nairobi, Kenya.
INIBAP	International Network for the Improvement of Banana and Plantain. Montpellier, France.
IRRI	International Rice Research Institute. Los Baños, Philippines.
ISNAR	International Service for National Agricultural Research. The Hague, Netherlands.
WARDA	West Africa Rice Development Association. Bouake, Cote d'Ivoire.

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