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The cooperative Mexican Agricultural Program was initiated in 1943 at the invitation of the Mexican government with the objective of increasing the production of basic food. The program is a joint undertaking of the Mexican Ministry of Agriculture and The Rockefeller Foundation. The achievements in wheat production reported herein are based upon the research information and materials developed jointly by a large number of Mexican and Rockefeller Foundation scientists.

Wheat culture was introduced into Mexico in the early 1520's by the Spaniards shortly after the Conquest. Nevertheless corn, which was already extensively cultivated by the Indians when the Spaniards arrived, until very recently remained the only important bread grain. The *tortilla* which is the daily bread of the Mexican people is made principally from corn. Within the past twenty years, however, the consumption of wheat has increased to the point where it is now about one third that of corn.

Wheat today is consumed largely in the form of hard rolls known as *bolillos*. In recent years pan-type bread, spaghetti, macaroni, and pastry products have grown in popularity. The *tortilla* of the rural areas of the three northern states, Sonora, Chihuahua, and Coahuila, is generally made from wheat rather than corn.

The Problem

When the Mexican agricultural research program was organized in 1943, it was clear that wheat was one of the crops on which a concentrated research effort should be made. At that time more than 275,000 metric tons (10,175,000 bushels), or more than 55 per cent of the total consumption, were being imported (FIGURE 1). This importation cost approximately 100,000,000 pesos (21,000,000 dollars), which was by far the greatest expenditure for food imports. There were many indications that the demand for wheat would grow as more people began to consume bread and, moreover, that the increasing demand would certainly be accelerated by the rapid growth in population.

What was the situation with respect to wheat production when the research program was initiated? Wheat was grown primarily as a winter irrigated crop. It was planted from September through December and harvested from April through June, depending upon elevation. The varieties

*This paper, No. 87 of the Agricultural Journal Series of The Rockefeller Foundation, New York, N. Y., illustrated with lantern slides, was the second of two papers presented at a joint meeting of the Section of Biology and the Division of Mycology on December 9, 1957.

were all of spring habit and, with the exception of two Sonora varieties introduced from California, were of unknown origin. Varieties in the ordinary sense of the word did not exist, but were mixtures of many different types. All varieties were susceptible to stem rust caused by *Puccinia graminis tritici*, the most serious disease of this crop. In years when ecologic conditions were favorable to the pathogen, as was the case in Sonora in 1939, 1940, and 1941 and in the Bajío region in 1948, devastating epidemics brought economic ruin to the wheat producer. Cultural practices were very primitive in every area except Sonora, where mech-

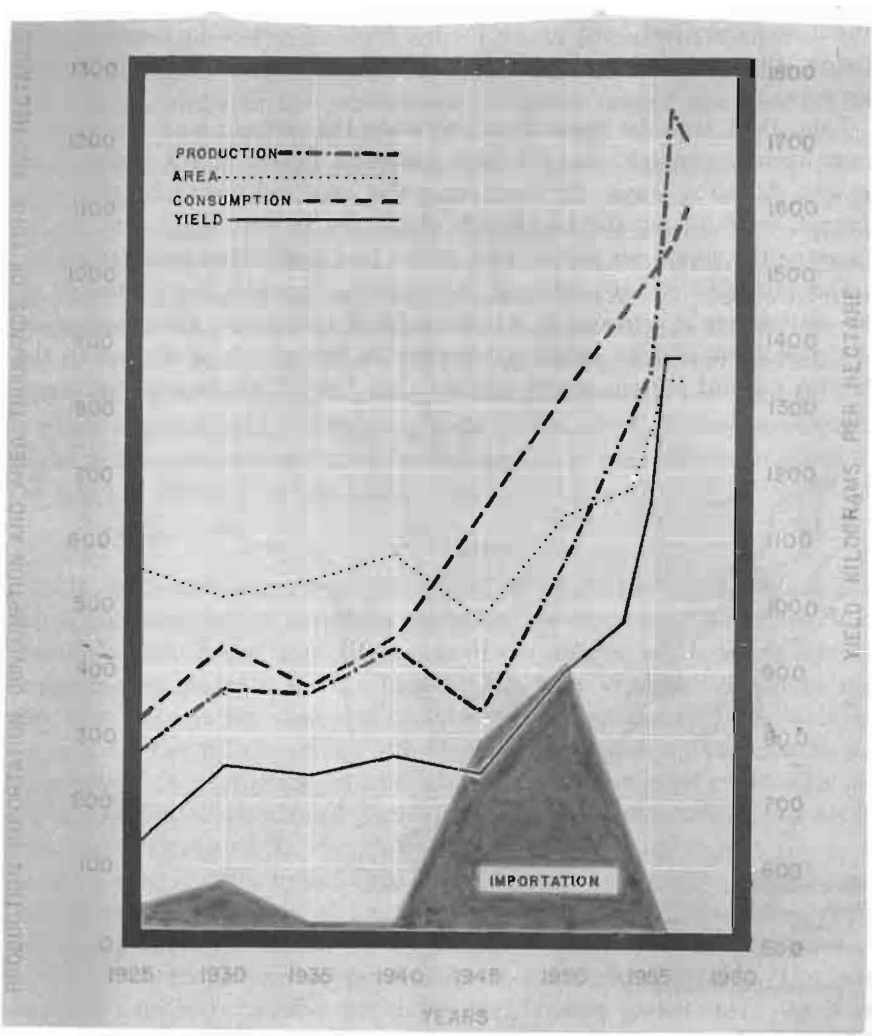

FIGURE 1. Wheat production, importation, consumption, yield, and area in Mexico between 1925 and 1957 (from Dirección General de Economía Rural C.E.I.M.S.A. and other sources of information).

anization and improved methods were well advanced. The Egyptian plow was the only implement used in land preparation and planting operations in most areas, and harvesting was done largely by use of a hand sickle.

During 1944 approximately 480,000 hectares (1,200,000 acres) were planted to wheat, with an average national yield of 750 kilos per hectare (11 bushels per acre). The only bright spot in the production picture was that represented by about 40,000 hectares in the Valle del Yaqui, Sonora, where yields averaged 1500 kilos per hectare (22 bushels per acre). However, this glimmer of hope was greatly overshadowed by the discouragingly low yields in all of the other areas, such as the Bajío, where wheat and corn had been grown for hundreds of years. In these regions yields often varied between 300 and 600 kilos per hectare (5 to 9 bushels per acre).

This, then, was the general picture when the program was initiated. It soon became apparent that the best approach was to attack the problem in two different ways: by increasing the area cultivated to this crop through establishing the feasibility of culture in new areas, and by increasing the yields per unit of area on the land then being grown to wheat.

The principal wheat-producing areas in the republic are indicated on the outline map in FIGURE 2. For the sake of simplifying the explanation of the problem and its solution, discussion henceforth is limited to the Pacific coastal region, which contains the "new" wheat-growing areas

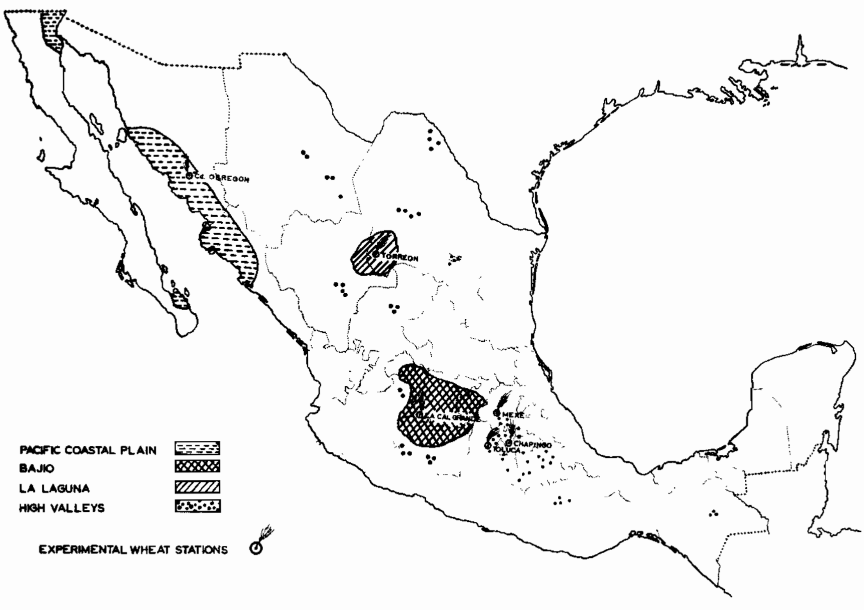

FIGURE 2. Wheat-production regions in Mexico, classified from a breeding standpoint.

of Sonora, Sinaloa, and Baja California; and the Bajío region, which includes the "old" wheat-producing areas of Querétaro, Guanajuato, Michoacán, and Jalisco.

The Approach

An analysis of the causes of low yields and lack of interest in wheat production indicated that through research it would be necessary to develop: (1) improved disease-resistant, high-yielding, good quality varieties that would also possess the agronomic characteristics making them well adapted to improved agricultural methods and practices; (2) basic information on the soil fertility levels of the different principal soil types where wheat was grown and, with this information, suitable fertilization and rotation practices as a stride toward attaining higher yields; (3) improved economical methods for land preparation, planting, and harvesting, which are all-important considerations in reducing costs and increasing yields; (4) the proper irrigation practices necessary for efficient utilization of the benefits expected from the use of improved varieties and fertilizer practices; and (5) basic pathological and entomological information on the important diseases and insect pests, and also to make this information available to the breeding program so that resistance could be incorporated into the new varieties, wherever feasible, or direct biological or chemical control measures devised.

Plant breeders, soil scientists, plant pathologists, and entomologists began a concentrated and coordinated attack on the various aspects of the problem during 1944 and 1945.

The Results

A broad breeding program was begun, which in the initial stages utilized for commercial purposes varieties developed by selection from materials introduced from other countries. Better varieties developed from crosses made in Mexico between the best "native" varieties and the best introduced stem-rust-resistant varieties became available to farmers for the first time in 1949. Despite two upsetting changes in the stem-rust race population in 1951 and 1953, this program produced varieties capable of increasing yields and providing protection from stem-rust losses (FIGURE 3).

The soil scientists began detailed studies of the nitrogen, phosphorus, and potash requirements of soils in each of the principal regions where wheat was grown. These and supplementary experiments revealed that in almost every area a deficiency of nitrogen limited wheat yields. The land recently cleared of desert vegetation in the new irrigation districts of Sonora and Sinaloa is the only area where lack of nitrogen is not a factor in limiting wheat yields (FIGURE 4). In the older areas, such as the Bajío, nitrogen must be applied in large quantities – up to 120 pounds per acre – in order to obtain yields of 45 to 60 bushels per acre. The

FIGURE 3. Field and greenhouse experimentation, both essential phases in the development of new varieties. (a) Wheat nursery in Toluca Valley, one of seven such nurseries where thousands of new lines are evaluated. (b) Greenhouse at Chapingo, where hundreds of the most promising lines are tested to determine their reaction to each of the prevalent races of the stem-rust pathogen.

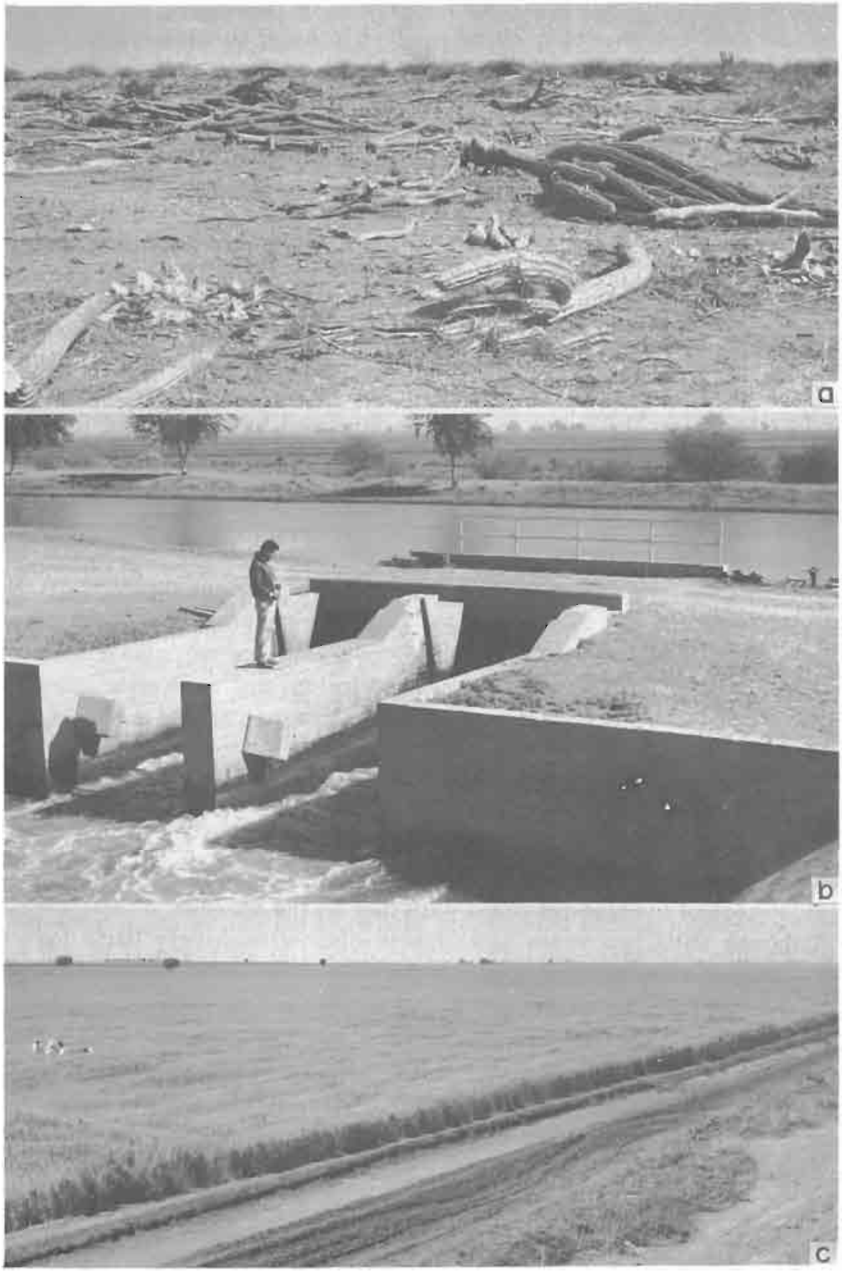

FIGURE 4. Expansion of wheat culture in Sonora and Sinaloa. (a) Desert vegetation being cleared to open new land for wheat production. (b) New government irrigation projects, providing water essential to the conversion of desert to productive wheat land. (c) Vast expanses of wheat replacing the desert vegetation in the past six years.

soils of the Bajío region are also deficient in phosphate, and this element as well as nitrogen must be applied in order to assure satisfactory yields. The soils of Sonora and Sinaloa do not respond to phosphates. All of the soils where wheat is grown have adequate quantities of available potash.

More recently the soil scientists have determined the most efficient method and time of application for the different fertilizers on each of the principal soil types. They have also studied the effect on yield of the interaction between the amount and the time of application of irrigation water at different levels of nitrogen fertilization. Their findings have been formulated into fertilizer and irrigation recommendations for each of the major soil types that are now followed by many wheat farmers.

The two most important developments in the improvement of wheat production in the Bajío region and similar areas have been the introduction of improved varieties and the use of chemical fertilizers. The introduction of these two factors into commercial wheat farming made it economically feasible for the first time to mechanize wheat production and thereby automatically initiate many other improvements in the culture.

Through the information developed by the agronomic research, it has become economically feasible to introduce successfully new land preparation, leveling, and planting techniques that reduce planting costs, achieve uniform distribution of irrigation water, and assure the adequate plant populations necessary to full utilization of varietal and fertilizer potentials.

The plant pathologists have provided information on stem-rust race populations and have evaluated many thousands of lines of promising wheats developed in the breeding program for their resistance to the various rust races. This information and assistance are invaluable in the development of disease-resistant varieties by the breeder.

Although until two years ago insects caused relatively little loss in the commercial crop, the entomologists have provided information and proposed controls for insect pests that might become destructive. One of the most potentially dangerous insects is the English grain aphid, *Macrosiphum granarium,* which became destructive in the Bajío region within the past three years. Prior to 1955 it had not been a problem in this area. The increased threat of this insect in recent years is correlated with the development of a more favorable microclimate within the grain field. This more favorable microclimate is created by the lush, rank vegetative growth of the wheat plants when heavy fertilization and adequate irrigation practices are followed.

How have the research findings affected wheat production? Their full impact has become felt only within the past three years. Although prior to that time advances had been made along certain fronts, it was not until 1954 that all the necessary information, materials, and methods were both available and in sufficiently wide use among farmers to reveal their influence on production and yield. The results have exceeded even the most optimistic original expectations (FIGURE 1).

Effect on Cultivated Area

The area cultivated to wheat has increased from 500,000 hectares (1,250,000 acres) in 1946 to 840,000 hectares (2,100,000 acres) in 1957. A considerable part of this increase, approximately 250,000 hectares, has occurred in Sonora and Sinaloa where wheat has become the most important crop in several new large irrigation districts opened during the past five years. This area now accounts for 60 per cent of the national production of this cereal.

The early-maturing disease-resistant varieties that are efficient in the use of irrigation water and well adapted to combine harvesting have been the catalyst for the increase in the cultivated area of wheat in Sinaloa and Sonora. Since the land is largely "new," soil fertility levels are much higher than in other areas and the use of additional chemical fertilizers is of secondary importance. It should be emphasized that this expansion could not have been accomplished with the old native varieties without encountering devastating losses from rust epidemics.

Most of the remaining expansion has taken place in areas that have been cultivated for several hundreds of years and where yields were until recently extremely low. This increase is in many ways the most spectacular and gratifying change that has taken place. Yields have doubled, tripled, and, in some cases, even quadrupled in recent years through the application of the research findings. With these increased yields wheat has again become a profitable crop and the cultivated area has grown rapidly.

In areas such as the Bajío, where yields were formerly extremely low, the use of heavy rates of chemical fertilizers has been the primary catalyst. The use of improved varieties and improved cultural practices has been of secondary importance (FIGURE 5).

A third increase in the area grown to wheat was made possible by the introduction of wheat as a summer crop grown at elevations of 5500 feet and above during the rainy season that usually occurs between May and September. Formerly wheat could not be grown successfully during this season of the year because of losses caused by stem and stripe rusts and weeds. The use of rust-resistant varieties solved the former problem, and the use of 2,4-D-type weed killers removed the second obstacle. Although the area planted with summer wheat is still small, only 50,000 hectares, it can be expanded as more production is needed.

Effects on Yield

The over-all effect of the general application of research on wheat production from the grower's point of view is best shown by the changes

FIGURE 5. Rehabilitation of impoverished land. (a) Centuries of continuous cultivation with inadequate measures to maintain fertility produced wheat like this in many areas of the Bajío in 1945. (b) Response of impoverished land in the Bajío to fertilization, proper irrigation, and improved cultural practices. The plot on the left received an application of 150 kilos of nitrogen; the plot on the right received no nitrogen. (c) Soils in the Bajío rehabilitated under commercial conditions through the application of heavy fertilization and good cultural practices.

in yield per hectare. The average national yield in 1945 was 750 kilos per hectare (7½ bushels per acre), whereas by 1956 it had risen to 1370 kilos per hectare (21 bushels per acre). This has made wheat production profitable again despite a number of adverse economic factors. Within the past six years the wheat farmer has absorbed increases in machinery costs of 65 per cent, fuel costs of 60 per cent, fertilizer costs of 40 to 60 per cent, and labor costs of 40 per cent, while receiving only a 10 per cent increase in the price of grain. The farmer's ability to absorb these increased costs has been made possible by increases in yields per unit of cultivated area.

Effect on National Production

The combined effects of increases in cultivated area and yield per unit of area are summarized in FIGURE 1. The production increase can be summarized as follows:

Year	Production in metric tons
1945	400,000
1950	575,000
1955	875,000
1956	1,250,000
1957	1,200,000

This rapid increase in production within the past two years has made Mexico self-sufficient in wheat for the first time in its history. Moreover, it has created a surplus of 200,000 tons that will be of great assistance in offsetting the corn shortage and the reduction in wheat acreage during the forthcoming season caused by a very extensive and severe drought.

It is impossible to assign relative importance to the different research results that have contributed toward making Mexico self-sufficient in wheat production. It is sufficient to point out in a general way the contribution of each project.

The new varieties have been the principal "catalyst" in increasing production in some areas. In others they have been the "insurance policy" against crop losses. They have made possible more efficient use of both fertilizers and irrigation water. They are better adapted to mechanization and possess better quality characteristics for industrial purposes. The cumulative effect of all these advantages has been the cultivation of the improved varieties on approximately 90 to 95 per cent of the total area.

The soils research information has had tremendous impact, especially on the older agricultural areas. As late as 1950 virtually no chemical fertilizer was being used in Mexico. Only a few wheat farmers had begun to apply fertilizer by 1953, but by 1957 a very large percentage were using some fertilizer in those areas where the need was apparent. Some farmers applied up to 120 lb. of nitrogen per acre on their 1957 crop, probably a heavier rate than was used anywhere else in the Americas. The investments in fertilizers on some wheat farms in the Bajío went as high as 600 pesos per hectare (19 dollars per acre) during 1957, but nevertheless proved to be sound investments. Some farmers are now harvesting 3 to 4 tons per hectare (45 to 60 bushels per acre) on the same land that yielded 400 to 700 kilos per hectare (6 to 10 bushels per acre) only four years ago.

Indirect or By-Product Effects of the Research Program

Certainly one of the most significant by-products of the program has been the awakening of the farmer to the values of agricultural research. Ten years ago Mexican farmers in general were not convinced of the value of research as a tool or aid in increasing their production and consequently improving their standard of living. A great gulf of misunderstanding and distrust separated the farmer from the agricultural scientist. The results obtained and the benefits derived by the farmer from the research program have in recent years brought about a completely new understanding soundly based upon mutual respect between farmer and agronomist. This new understanding has resulted in the elevation of the professional agronomist to the same rank of prestige formerly reserved for engineers, architects, lawyers, and members of other comparable professions.

A number of important businesses or industries have arisen and developed rapidly as research information has been applied commercially. These business enterprises could not grow and prosper until wheat yields had been increased. The introduction of new varieties and the use of chemical fertilizers were the keys that unlocked the door to the development of the farm machinery business in the Bajío region. Ten years ago, with very few exceptions, the only implements used in wheat cultivation were the Egyptian plow and the hand sickle. Today virtually all wheat planting in this area has been mechanized. Tractors, plows, disc harrows, land-leveling equipment, grain drills, and self-propelled combines are employed on most wheat farm operations. Thus the mechanization of this region has advanced from the Egyptian plow and hand sickle, which date back more than three thousand years, up to the most modern tractors and self-propelled combines of the twentieth century, all in a period of only ten years (FIGURE 6).

The chemical fertilizer business was nonexistent ten years ago. The first modern domestic ammonium sulfate production plant was opened in 1952. By the middle of 1953 demands for fertilizer had outgrown this plant's production capacity, and the consumption of fertilizers has continued to increase at a fantastic rate. Within a short span of five years, the manufacture of chemical fertilizers has grown into an industry with sales running into several hundreds of thousands of tons. Demand long ago outstripped domestic production and large quantities of fertilizers are currently being imported. Meanwhile the infant domestic chemical

FIGURE 6. Revolution in the mechanization of the wheat harvest in the Bajío region. (a) Common method of harvesting grain in 1945. (b) Grain being threshed in 1945 by treading animals. (c) Self-propelled combines now being used to harvest nearly all of the area.

fertilizer industry is frantically trying to expand its production facilities in an attempt to catch up.

Although this discussion has been confined to the impact of research on wheat production, many of the methods, techniques, and developments have a large "carry-over" value to other crops in the same area. The revolution in wheat production methods is thus of far wider implication and value than is evident only in production.

The increases in wheat yields in the Bajío region have also had other broad effects. Land rental values have increased sharply as wheat yields have risen. All rentals are now for cash, whereas ten years ago they were nearly always on a "share-of-the-crop" basis. Cash rentals have grown as investments in the crop have increased. In the Bajío region today it is common to find farmers investing from 1200 to 1500 pesos per hectare in a wheat crop. With such large investments, cash rentals are obviously more desirable than share rentals. Land prices have similarly risen sharply as wheat yields have increased.

Another intangible value that has evolved as a by-product of the research program is the establishment of close cooperation among scientists working on wheat in the different American republics. Some problems, such as the stem-rust epidemics, where the inoculum is airborne for hundreds of miles, are truly of an international nature. The outbreak of race 15B of stem rust in North America in 1950, which first became widespread in the United States, one year later had become equally disconcerting and dangerous to the wheat farmers of Mexico and Canada. As an outgrowth of the emergency created by this outbreak, there was developed a cooperative project coordinated by the United States Department of Agriculture, which is known as the Cooperative International Wheat Rust Nursery. Currently the uniform sets of seed collected for this nursery are being grown by cooperating scientists in more than twenty different countries. Data on diseases are taken and later compiled into a comprehensive report that is made available to agricultural scientists throughout the world. The Mexican research program has cooperated closely in the development of this project; through this and related projects, Mexico's young scientists have become personally acquainted with many of their counterparts in the other American republics.

The most significant and fundamental achievement of the entire research program is the development of an excellent corps of young Mexican scientists trained in the different sciences related to wheat production. This group, a number of whom have already received their doctorates, ranks high when compared with any other group of scientists working on wheat anywhere.

Not only have wheat research scientists been trained but, as the need has arisen, government-sponsored extension programs and seed distribution programs have been created. Many of the young men who are now part of these organizations received their original training in research with the Mexican program.

Another valuable by-product of the Mexican program has been the training of young scientists from other Latin American countries. Scientists from nine different countries have spent from six months to more than a year in training with the Mexican program. When their training was completed they returned to their own countries to initiate or expand research work on wheat.

The Future

The research information and the methods and materials now available are adequate to supply wheat needs for the next ten years if they are extended to all areas where wheat is now grown. Since wheat is primarily an irrigated crop, it would appear advisable to carry over grain reserves of 10 to 20 per cent of annual consumption to provide for reduced production in those years when abnormally low precipitation in the watersheds of the principal reservoirs causes a shortage of irrigation water.

The production potential visualized with the information and materials now available takes into consideration the increased demand that will occur as a result of the increase in population and an even greater increase in per capita consumption of wheat. At the present time the population of Mexico is growing at a rate of 3.1 per cent per year. Wheat consumption now appears to be increasing at the rate of 9 per cent per year. The increase in per capita consumption undoubtedly reflects a rising living standard for many people.

Another factor that must be taken into consideration in formulating wheat production policy, if the production goals are to be met, is the need to provide compensation in price increases commensurate with increases in the cost of production. Although the grower has largely absorbed the increase in production costs during recent years, a point will soon be reached where this is no longer economically feasible, and where acreage now planted to wheat will be diverted to cotton.

The appearance of a new physiologic race of the stem-rust pathogen capable of attacking the commercial varieties could greatly jeopardize wheat production plans for the future. Several times during the past twenty-five years new races of stem rust have suddenly appeared in North America. When a new race arises, either through hybridization of preexisting races or through mutation, and becomes widely distributed, the whole structure of wheat production in North America is endangered. Whenever climatic conditions favorable to the pathogen coincide with the appearance and widespread distribution of a new rust race, serious regional epidemics develop and result in tremendous economic losses. Such was the case with race 15B in the United States and Canada from 1950 through 1954 when epidemics caused losses running into hundreds of millions of dollars.

Self-pollinated crops, such as wheat, oats, and barley, when bred by the conventional method, are extremely vulnerable to changes in races, since the entire population of a variety has identical characteristics for resistance. This danger is magnified even more by the fact that generally all the popular commercial varieties in any large geographic region carry the same type of rust resistance. Consequently, when a new race of the stem-rust pathogen develops that is capable of attacking that type of resistance, it finds a vast area of perfect culture medium upon which to increase. The result is a disastrous epidemic that literally explodes, in much the same way that a prairie fire explodes once a spark ignites in a vast expanse of dry grass.

The research program is now attempting to develop composite varieties that will be so constituted as to have several different types of resistance. It is highly improbable that a new stem-rust race would have the genetic make-up enabling it to attack all of the different genotypes present in the composite variety. Consequently the increase in inoculum will be slowed, and this in itself will delay the development of the epidemic to such a degree that the grain of even the susceptible components of the variety will mature. Such a variety has the added advantage that it can be modified quickly to meet shifts in the race population (FIGURES 7 and 8).

The composite variety is being developed by a modification of the backcross method. The best commercial variety in each region is being crossed independently to varieties containing all the known types of stem-rust resistance. Subsequently, each cross is backcrossed a number of times to the commercial variety. Eventually lines can be isolated that are phenotypically similar to the commercial parent or recurrent parent, but which are genotypically different for resistance to stem rust.

The composite variety that the farmer will grow will be a mechanical mixture of eight to ten lines that phenotypically are similar but genotypically are different for resistance to stem rust. Pure seed of each line incorporated into the composite is maintained in reserve. New lines can be developed as new sources of resistance are discovered. With this new approach the plant breeder can reform or reconstitute the composite variety rapidly whenever dictated by the shifts in the race population. If the development of composite varieties is to be successful, it must be based on accurate knowledge of the current rust race population, extensive greenhouse testing with various "tester" rust races to identify the best lines from each backcross, and maintenance of viable inoculum of all races of the pathogen collected in the area.

This new approach is designed to bring about a more permanent solution to a shifty and often frustrating biological problem. The research was initiated three years ago; within the next three years the feasibility of the new method should be either established or disproved.

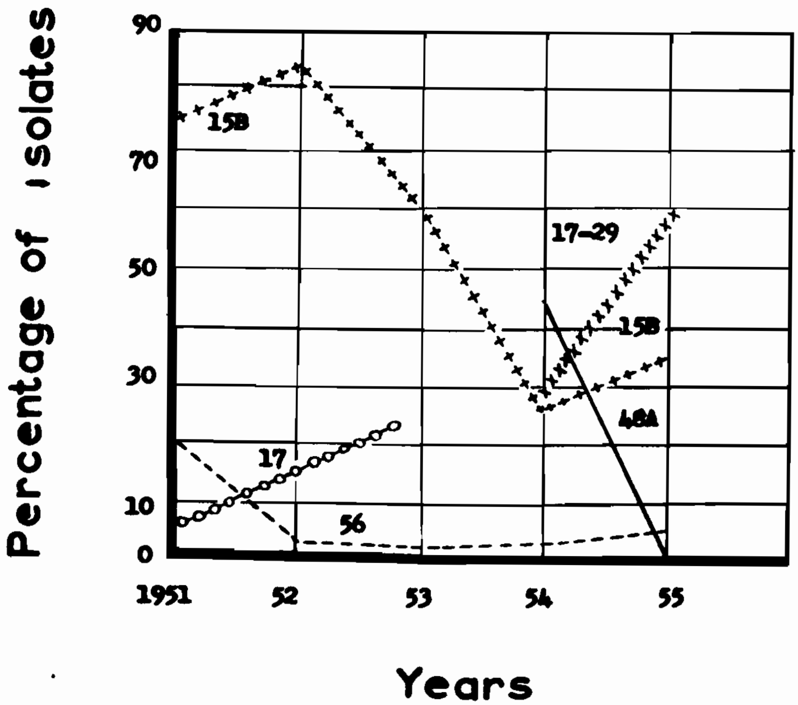

FIGURE 7. Shift in the race population of *Puccinia graminis tritici* in Sonora and Sinaloa from 1951 to 1956.

A second potentially valuable research project was begun two years ago in an attempt to develop a high-yielding, dwarf wheat variety with resistance to lodging (FIGURE 9). With dwarf wheat, it should be possible to apply higher rates of nitrogen fertilizer and increased numbers of irrigations without waste from lodging or from overproduction of stalk and leaf. If a good variety can be developed, it should then theoretically be possible to increase wheat yields by 30 to 40 per cent. Preliminary tests with lines that carry the Japanese Norin dwarf factor have been extremely promising. A breakthrough on this research front could add greatly to potential wheat production capacity.

Within the near future the transfer of over-all responsibility for future research on wheat will be made to Mexico's new corps of young, highly qualified scientists. The future success of this group will hinge primarily upon the ability and willingness of their government to provide them with adequate facilities and an environment conducive to scientific research. New problems will arise, as is always the case when dealing with biological phenomena, but this team of scientists, given proper conditions under which to work, will cope with them successfully.

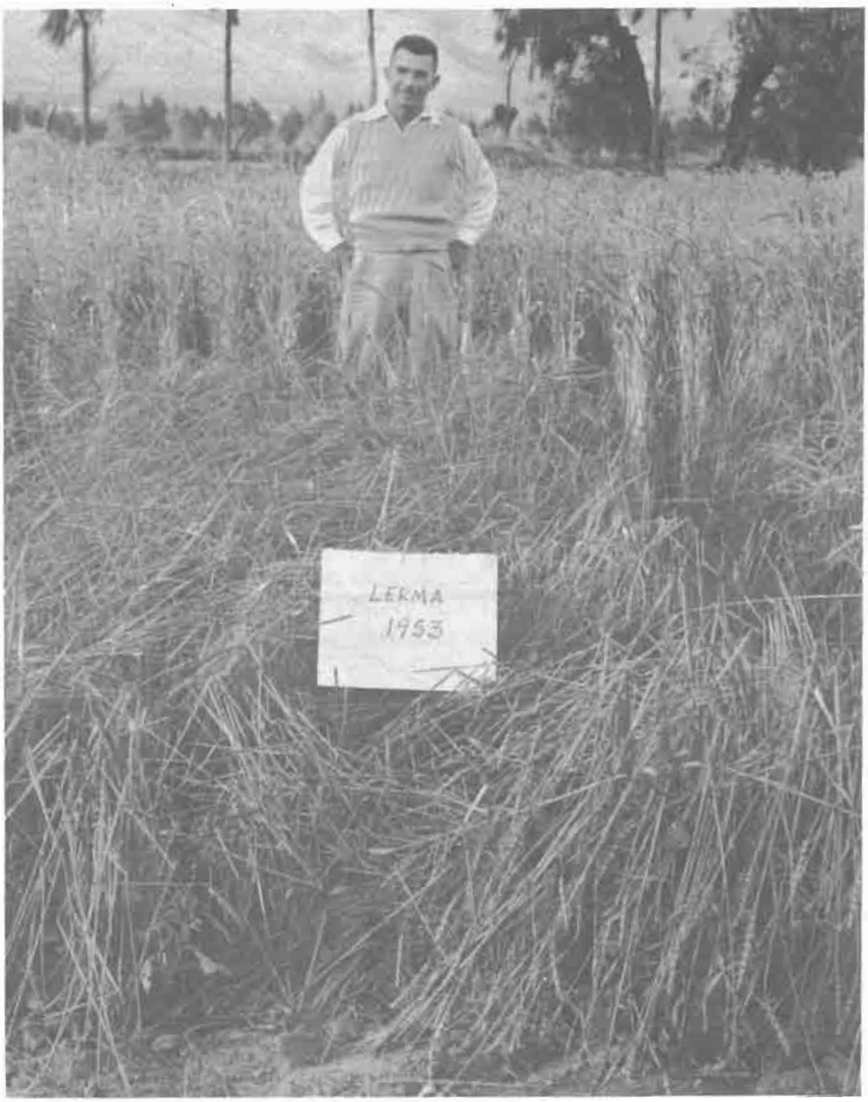

FIGURE 8. Result of the appearance of a new rust race. Lerma 50 was resistant to stem rust until 1953, when it was killed by race 29.

As one of many scientists participating in this adventure in cooperative research, an adventure that was designed specifically to solve a food production problem and that has successfully achieved this objective, I have found the experience personally both extremely enjoyable and gratifying.

FIGURE 9. Development of dwarf varieties. The successful production of a commercial dwarf variety would prevent lodging and, with heavier fertilization, result in higher yields. The agronomist holds a plant of the popular commercial variety, Lerma Rojo, next to a promising dwarf line to indicate relative heights.

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