Long before this Roman aqueduct graced the landscape, durum was North Africa's premier crop, as it is today. Within the last decade, new varieties have brought the promise of higher and more stable yields to durum farmers throughout the developing world.

CIMMYT TODAY No. 2

DURUM WHEAT: NEW AGE FOR AN OLD CROP

CIMMYT's development of short, widely adapted durum wheats has enhanced the food production prospects of durum-producing nations. Scientists at CIMMYT and in national cereal programs are working together to combine high yield potential with disease resistance, adaptation to difficult environmental conditions, and good durum kernel quality. Farmers from Morocco to India already are benefiting.

When North Africa was the bread basket of the Roman Empire, the bread eaten by patricians and plebeians alike was not a light, high-rising loaf made from bread wheat. Rather it was a flat, round loaf made from durum wheat, like the breads still eaten and preferred in the Mediterranean region and much of the Middle East.

Varieties of durum wheat now grown in many developing countries have changed little since the heyday of the Roman Empire. They yield poorly and have a low level of disease resistance. While national populations have soared, farmers have not been able to increase the productivity of traditional varieties. Until the 1960's durum exports earned large amounts of foreign exchange for countries like Tunisia, Algeria, Morocco, and Syria but now they import durum as well as bread wheat (in international parlance, *Triticum aestivum* is known as "bread wheat" while *Triticum* subspecies *durum* is known as durum or "macaroni" wheat. *See box* "Evolution of wheat."

Recognizing the high yield potential and stability of the short Mexican bread wheats that triggered the wheat revolution from India to Turkey, more and more farmers in durum-growing countries (*See box* "Durum production and trade") have switched to new bread wheat varieties. But the tide is changing. In the last 7 years, CIMMYT and national research programs have taken the experience and methods used to develop high yielding bread wheats and brought them to bear on durums. The prospect for improvement is even greater than in the bread wheats. As Norman Borlaug, director of CIMMYT's wheat program says,

> I would just not like to be a bread wheat breeder and make the statement that durum wheats are second rate. Despite present limitations durums probably have the best yield potential among the wheats. This is particularly true when we consider the small amount of work that has been done. If 1 percent of the money which has gone to wheat research as a whole has brought durums up to this level, [bread wheat breeders] should look out.

An example of what Borlaug means by "this level" can be found in the results of the annual international durum yield nurseries. In 1972/73, scientists in 26 countries grew 25 durum varieties in identical trials. Cocorit, a new semi-dwarf durum, was among the five highest yielding varieties at 22 of the 38 locations at which the trials were grown while, in comparison, Cajeme, a new semi-dwarf bread wheat was among the top five at only 15 locations. Cocorit had the highest average yield in the trial, 4.3 metric tons a hectare. Cajeme yielded 4.0 tons a hectare.

Although not without flaws, the high yield potential and adaptability of Cocorit has encouraged several wheat programs in the major durum-growing regions to release it to farmers. And even better durums are in advanced testing by scientists who make up an international fraternity dedicated to increasing the productivity of the world's wheat farmers.

Spread of the new Mexican durums

The two most widely used semi-dwarf durums today are Jori and Cocorit developed by CIMMYT. Jori was named and released by the Mexican government in 1969 and Cocorit in 1971 (CIMMYT develops experimental lines of cereals, but does not release varieties—naming and release of varieties is the prerogative of national cereal improvement agencies).

In trials throughout North Africa and the Middle East, these two varieties have performed well under

Gerbrand Kingma, CIMMYT plant breeder, inspects a head of Maghrebi, a new durum variety released by Tunisia from a cross made at CIMMYT.

EVOLUTION OF WHEAT

The genus *Triticum* contains about 30 types of wheats that have enough genetic differences to be considered separate species or subspecies. About half of the types are cultivated somewhere in the world and the rest grow wild. By far the most land is devoted to the bread wheats, *Triticum aestivum* subspecies *vulgare*. Perhaps a tenth as much land is planted to durum wheats, *Triticum turgidum* subspecies *durum*.

The genetic characteristic uniting all members of the genus *Triticum* is that they have 14 chromosomes (seven pairs) or a multiple of 14 chromosomes. For example, *T. monococcum*, Einkorn wheat, has 14 chromosomes and is known as a diploid (because it has two sets of seven chromosomes); durum wheat has 28 chromosomes and is known as a tetraploid (four sets of seven chromosomes); and bread wheat has 42 chromosomes and is known as a hexaploid (six sets of seven chromosomes).

Durums evolved more recently than Einkorn wheat and bread wheats are more recent than durums. Both durums and bread wheats are the result of evolutionary accidents eons ago.

Tetraploid wheats, of which durum is one, occurred when Einkorn wheat, a diploid, crossed with a diploid grass, *Aegilops speltoides*. Wind carried pollen from one onto the stigma of the other where, despite formidable barriers to crosses between genera, fertilization occurred *and* a seed was formed which produced a plant which in turn had fertile seeds.

When a diploid plant is crossed with another diploid plant the offspring is diploid, too. That is, the pollen carries one half the chromosome complement of one diploid parent and the egg cell carries one half the chromosomes from the other parent. If the parents are of the same species, the chromosomes from one parent can match up, or pair, with the chromosomes from the other parent and the offspring will be fertile. If the parents are of different genera, as are Einkorn wheat and *A. speltoides*, the chromosomes cannot pair and the offspring will be sterile, like a mule. But in the cross of Einkorn wheat and *A. speltoides* something happened that doubled the chromosomes of the offspring. So instead of being a sterile diploid with seven chromosomes from Einkorn wheat and seven from *A. speltoides*, it was a fertile tetraploid with seven *pairs* of chromosomes from Einkorn wheat and seven pairs from *A. speltoides*.

Cytogeneticists call the seven paired chromosomes of Einkorn wheat the *A* genome and the seven paired chromosomes of *A. speltoides*, the *B* genome. Thus the two sets of chromosomes of Einkorn wheat can be represented *AA* and the two sets of *A. speltoides* chromosomes, *BB*. When the two genera were crossed, the offspring had the chromosome complement *AB* and should have been sterile except that the chromosomes doubled making the offspring a tetraploid: *AABB*.

Nature blinked again when an accidental cross of a tetraploid wheat with another diploid grass, *Aegilops squarrosa*, succeeded in creating bread wheat. The genome of *A. squarrosa* is designated *D*, so bread wheat genomes are *AABBDD*.

Three major barriers stand in the way of natural crosses between genera. First, when a pollen grain of one genus lands of the stigma of another genus, an immunological reaction may occur which prevents the pollen from reaching the ovary. Second if the pollen succeeds in reaching the ovary and fertilization occurs, the resulting seed usually is shriveled, that is, it has little starch which is needed to sustain the growth of the embryo after germination until a seedling with functioning roots and leaves has formed. Finally, if a plant succeeds in growing to maturity it probably will be sterile—it will have no seeds. It will be sterile because half its chromosomes are from one parent and the other half are different chromosomes from the second parent. None of the chromosomes are able to pair. But certain substances can cause the chromosomes to double so that each chromosome will have a counterpart to match up with. In nature, scientists speculate, methane from a nearby swamp, or ozone from a lightning flash may have doubled the chromosomes of the ancestors of durums and bread wheats.

Scientists today are crossing different cereal genera in attempts to create new crops. Among the tools scientists use are immunosuppressive chemicals to help the alien pollen reach the ovary, micro-surgery to remove the embryo from the seed after which it is allowed to develop in a special nutrient gel, and treatment with the drug colchicine which encourages doubling of the number of chromosomes in the cell. Since the late 1960's scientists at CIMMYT and elsewhere have been able to routinely cross wheat and rye to create triticale. Crosses like wheat x barley and wheat x oats have not proved successful yet.

DURUM PRODUCTION AND TRADE

Most of the world's durum comes from four areas: the Mediterranean region, the plains of North Dakota, Saskatchewan, and Manitoba which lie across the USA-Canada border, USSR between the Black Sea and the Caspian Sea, and central India.

Data on durum production in individual nations is not highly reliable and is often non-existent. Most agencies that publish data on cereal production simply lump statistics on bread wheats and durums. Nevertheless, by piecing together data from official sources and estimates from informed observers, durum production in different countries can be crudely compared.

Italy and Turkey are the world's largest durum producers. Each produces about 2.5 million tons a year. Production in the USA and Canada can fluctuate violently from year to year because farmers switch from durum to bread wheat and back depending on the relative prices of the two crops. In some years, production in either Canada or the USA comes close to equaling production in Italy or Turkey.

The USSR and India are considered major durum producers although no data is published. One estimate put durum production in the USSR at 1.5 million tons. India, CIMMYT observers believe, grows perhaps 2.75 million hectares of durum. If this area averaged 1 ton a hectare, then India would be about the largest durum producer in the world. If it averaged as little as a half ton a hectare then India would still rank with the USSR.

The only other country that averages over a million tons of durum a year is Morocco.

Argentina, although known for durum because it is a major exporter, actually grows only a moderate-sized crop. The crops in Ethiopia and Syria usually are larger than Argentina's.

In most countries, the durum crop is smaller than the bread wheat crop. But in Morocco, Algeria, Tunisia, Libya, Ethiopia, Cyprus, Jordan, Syria, and Saudi Arabia, durum is king.

Of the 20 million tons of durum which the world harvests each year, only 2 million tons enter international trade. The rest is consumed in the countries where it is grown.

Nine of every ten tons in international trade originate from USA, Canada, and Argentina. Seven of every ten tons land in Western Europe. Italy is by far the largest single importer, even though its durum crop makes up three-fourths of total European production.

A decade or two ago, Syria, Algeria, Morocco, and Tunisia were exporting 100,000 to 200,000 tons of durum a year to Europe. Their exports withered after 1965 and imports of wheat boomed. These countries now have 40 percent more mouths to feed than they did in 1960. In addition, the populations of cities have exploded. Rapid increases in demand for wheat combined with generally stagnant durum yields have transformed these former exporters into large importers. Tunisia, however, regained self-sufficiency in 1975 and is once again exporting its surplus durum.

The same pressures, of course, have been at work in most developing countries. When short Mexican bread wheats became available many durum farmers switched out of durum. The substantially higher yields promised by short bread wheats more than made up for their slightly lower price (in some countries prices of durum and bread wheat are the same, which means that high-yielding bread wheats have even more of an advantage over traditional durums). Now, however, through the work of CIMMYT and its collaborators, durum varieties are reaching farmers that can match the yields of the best bread wheats.

Nations which annually produce 250,000 tons or more of durum, or in which over half the total wheat crop is durum.

favorable growing conditions as well as in low rainfall areas where diseases are not a severe problem. Jori is being planted by farmers in Algeria, Iraq, and Lebanon, and is being multiplied for release in Afghanistan, Cyprus, Egypt, Saudi Arabia, and Jordan. Cocorit is being planted by farmers in Turkey, Lebanon, and Algeria, and is being multiplied for release in Cyprus, Egypt, Iraq, Saudi Arabia, and Jordan.

Iraq and Algeria introduced Jori by making massive imports of seed. Iraq imported 10,000 tons of Jori (enough to plant 100,000 hectares) from Mexico in 1971. Algeria imported 15,000 tons in 1973.

Turkey released Cocorit for southeastern Turkey under the name Dicle I in 1974. Three sister lines of Cocorit are being considered for release under the names Dicle II, Dicle III, and Dicle IV. Gediz I has been released for western Turkey (Izmir area). This variety was developed from a cross made at CIMMYT.

Tunisia probably has a higher proportion of its durum area in new varieties than any other nation. In 1975, a quarter of the Tunisian durum plantings were Bedri and Inrat 69. Both these varieties are improved, but tall types that were bred and developed by the Tunisian cereal program. In 1972 Tunisia released Amal and Maghrebi, semi-dwarfs that were developed from crosses made at CIMMYT. Under good management Amal, in particular, outyields Inrat 69, which in turn is better than Bedri.

Although Mexico is not a major durum producer, farmers in the main bread wheat region in 1974 switched 10,000 of the area's 600,000 hectares into Cocorit because of its high yields. Mexicali, a durum variety released in 1975, promises to be an even greater attraction to Mexican wheat growers, and to farmers elsewhere.

Lodging and a heavy infestation of wild oats will give the farmer a meager durum harvest. By helping to develop widely adapted, lodging-resistant durums and new farming systems that suppress weeds, CIMMYT is giving durum growers weapons to combat chronically low yields.

Traditional varieties

Few farmers in developing nations planted semi-dwarf durums before 1969. As a result, even today most durum being grown are traditional varieties. Historically, traditional durums were probably better adapted than traditional bread wheats to the harsh conditions of the areas in which durums are now grown. Some scientists believe that durums as a class are more successful than bread wheats in filling the grain during the scorching weather that characterizes the end of the growing season in durum areas. Probably the best characteristic of traditional durums is the quality of their grain for making pasta, couscous, and bulgur (*See box* "Durum quality").

Nevertheless, although traditional durums have survived thousands of years with little change, they have surprising weaknesses. One is disease resistance. Many traditional varieties have satisfactory resistance to one disease or another (and plant breeders use such varieties as sources of resistance in crossing programs), but none have broad resistance to the main diseases. In durum areas the weather pattern and consequently the disease complex change sharply from one year to the next (*See box* "Climates in durum-growing areas") so yields of traditional varieties are reduced first by one disease and then by another.

Another weakness of traditional durums is that they mature late. One motivation for farmers' switch into semi-dwarf bread wheats in durum areas is that the modern bread wheats mature 1 or 2 weeks earlier than most traditional durums.

Finally, traditional varieties do not respond well to good growing conditions. In years when temperature and rainfall patterns are very favorable, traditional durums do not produce spectacular yield increases. Moreover when farming conditions are improved through better soil preparation, weed control, application of fertilizer, or irrigation (*See box* "Better farming methods"), traditional varieties are not capable of responding with a yield increase that makes these improvements highly rewarding to the farmer.

Later maturity and lack of broad disease resist-

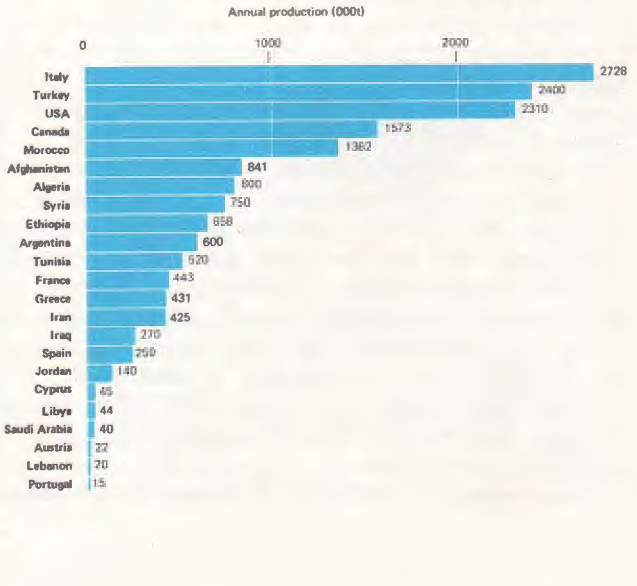
Face to face with Santiago Fuentes, CIMMYT pathologist, and a thousand durum lines, a trainee from Algeria, right, learns to rate rust resistance.

ance are of course important reasons that traditional durums are not responsive to better conditions. But in addition, because traditional durums are tall and have weak stems, they lodge easily—they fall over before harvest. Lodged plants do not intercept sunlight efficiently, photosynthesis and translocation slow down; and they produce fewer and less plump grains. Use of fertilizer increases the tendency to lodge so that anything but small doses of fertilizer are often counterproductive with tall varieties. As a result, the prospects for raising yields of traditional durum varieties to feed evergrowing populations are bleak.

The beginnings of durum improvement

Throughout the world much less research time and money has been invested in durum than in bread wheats. And the research that has been done, until very recently, was concentrated in developed countries.

Major durum producing nations, circa 1974 (India and USSR omitted). Source: Developed countries and Argentina—International Wheat Council; other countries—survey by George Varughese.



Although the USA and Canada bred a number of superior varieties, they were daylength sensitive (*See box* "Sensitivity to daylength") so they would not grow successfully in countries nearer the equator. North American varieties had good stem rust resistance but no resistance to stripe rust, a scourge of the Mediterranean region. Furthermore, the grains of recent North American durums are small so that if the bread wheat grains were mixed with durum grain, the two types would be difficult to separate.

In the Mediterranean region, Italy has had the most active durum research work. But until the 1950's Italian durum improvement consisted only of selecting superior plants from existing varieties—no crossing of one variety with another was done. In the 1930's, the Italian variety Senatore Capelli was planted in several North African and Mediterranean countries, mostly in areas that had irrigation or high rainfall.

In the early 1960's many varieties from the Italian crossing program were tested in the region and Capeiti 8 was found to be adapted and to give fairly good yields.

The bread wheat revolution affects durums

Later in the 1960's the green revolution which started in India and Pakistan began to spill into the Middle East and North Africa. The high yield potential of the semi-dwarf Mexican bread wheats encouraged many durum farmers to plant them. Some countries imported seed of the Mexican bread wheat from India and Pakistan, others got seed directly from Mexico. Since then the bread-wheat area in most North African and Middle Eastern countries has continued to increase at the expense of durum.

In Turkey, which grows both "spring" and "winter" durums, dramatic changes were caused in coastal areas by the Mexican spring bread wheats, and in the plateau region by Bezostaya, a short Russian winter bread wheat (winter wheats require a cold period during the growing season to induce flowering). Polat Solen, a Turkish plant breeder, told a regional meeting of wheat workers in 1975 in Tunis:

> In Turkey in the last few years there has been a shift from growing durum to bread wheat, and the introduction of high-yielding bread wheat has been largely responsible for this shift. In the coastal areas, Penjamo 62 and Lerma Rojo 64 [Mexican bread wheats] have replaced most of the native durums grown in the [coastal] valleys, but native durums are still being grown on the hilly and more marginal lands. In Thrace, Bezostaya currently occupies approximately 80 percent of the total wheat area, whereas 5 years ago the region was 60 percent durum. In the Southeast the situation is much the same. Eight years ago the region grew probably 70 to 80 percent durum wheat but now Penjamo 62,

DURUM QUALITY

In Jordan durum is used almost exclusively for bread, in India durum makes chapatis, in North Africa durum is traditionally eaten as couscous, but when plant scientists and cereal chemists discuss durum quality they mean the physical and chemical characteristics needed for making pasta products such as spaghetti and macaroni.

Western Europe is the world's largest importer of durum, and almost all of the durum there is used for pasta products. Italy alone is projected to import 1 million tons of durum a year for the next decade. For exporters like Argentina and former exporters like the North African nations and Syria, sales of durum to Western Europe are the pot of gold at the end of the rainbow. They must strive to develop varieties that have good pasta-making quality as well as high yields.

The single most important quality characteristic is color. Manufacturers want macaroni that is deep amber or golden. Durum kernels may range in color from white to orange-yellow. Manufacturers often blend different durums to get the color they want, but they reject durums that are white or gray or that have mottled colors. The desirable yellow color is caused by a high percentage of carotene. This can be destroyed by a high level of the enzyme lipoxidase. Hence varieties must have high carotene content and low lipoxidase content.

Semolina output is another important characteristic of durum kernels. To the layman, semolina is simply the meal that results from grinding the durum kernel after removing the bran layer. But the manufacturer distinguishes between semolina and flour both of which can be milled from durum kernels—semolina will pass through a 30-mesh sieve but not a 100-mesh sieve. Flour will pass through a 100-mesh sieve. In other words, semolina has larger particles than flours.

One influence on semolina output is the size of the durum kernel. A large kernel has a higher proportion of endosperm (which when milled is semolina) to bran than a small kernel. Thus with large kernels, for each ton of semolina, the miller handles less than he would if he were milling small kernels.

Another influence on semolina output is the amount of "yellow berry"—a peculiar name since it refers to a pale or while discoloration in the kernels of some varieties resulting from the development of floury starch rather than vitreous starch. The more yellow berry a kernel has, the higher the proportion of flour and the lower the proportion of semolina it will yield.

The quantity and nature of gluten—a form of protein—in the kernel affects the cooking quality of pasta products. Manufacturers like a high percentage of strong gluten so that pastas don't disintegrate if they are overcooked.

In North Africa and the Middle East, only 20 percent of the durum is consumed as pasta products. George Varughese, a CIMMYT durum breeder stationed in Tunisia, says, "The quality for couscous and bulgur may be similar to that of pastas...,however the main use of durums in many countries of the region is for different types of bread. I am sure that bread-making quality and spaghetti or pasta quality are not the same." Varughese believes that wheat scientists must begin developing definitions and screening methods for quality of durum products other than pasta.

Bezostaya, and other improved [bread wheat] varieties are grown on most of the area and durums occupy only 30 to 35 percent of the total wheat area. In the Central Plateau and winter wheat region, the shift is not as dramatic, but Bezostaya and other improved varieties have displaced some durum wheat acreage.

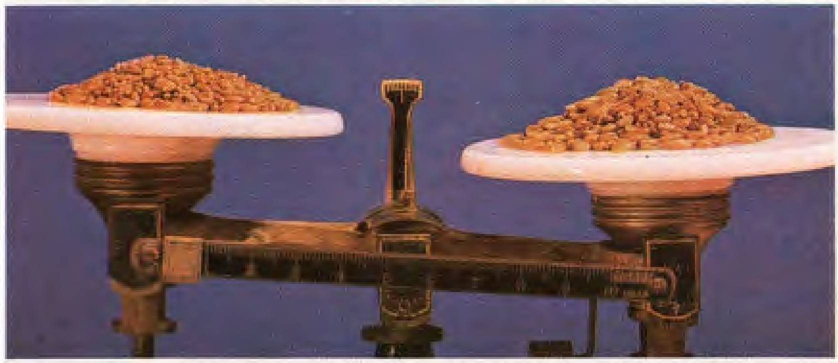
CIMMYT's early durum research

The foundations of CIMMYT's work on durum wheat were laid in the Office of Special Studies, a branch of the Mexican Ministry of Agriculture which operated between 1943 and 1961. The Office of Special Studies was a cooperative venture between the Mexican government and the Rockefeller Foundation aimed at increasing the production of maize, wheat, beans, and potatoes in Mexico. When CIMMYT was founded in 1966 it took over many of the personnel of the Office of Special Studies and formally internationalized the programs (between 1959 and 1966 The Rockefeller Foundation employees in Mexico informally assisted other nations with wheat and maize improvement).

Since durums were insignificant in Mexican agriculture compared with bread wheats, they were a side interest of the Office of Special Studies. Nonetheless, methods developed for improving bread wheats were used for durums, but on a smaller scale.

In the 1950's the scientists emphasized breeding resistance to the rusts which devastated the Mexican wheat crop almost every year. Breeding for rust resistance produced several durum varieties, culminating in Tehuacan in 1960. This variety has remained resistant to the three major rusts in Mexico until the present. Tehuacan is however sensitive to daylength and because it is tall, it lodges. The beginning of the breeding of semi-dwarf wheats soon resulted in durums that yielded much more than Tehuacan.

Durum grains are larger and heavier than grains of bread wheat.



The first semi-dwarf durums

In 1954 the Office of Special Studies began crossing tall Mexican bread wheats with bread wheats carrying a gene for short stems that was originally found in Norin 10, a Japanese wheat. The goal was to produce varieties that would resist lodging, especially when high rates of fertilizer were used. The story of the Mexican semi-dwarf bread wheats and their ability to catapult yields in numerous countries has been told many times. But it is less well known that durums were being improved through the same system.

Scientists in the Office of Special Studies crossed tall durums with bread wheats carrying the Norin 10 gene. Then the progeny were selected in generation after generation, retaining only those that were short and had good durum characteristics. In addition, like the bread wheats, the durums were grown twice a year, allowing what in other breeding programs would be 10 years work to be done in 5 years. One generation was planted near sea level in northern Mexico at 27°N and the following generation was planted at 2600 meters elevation near Mexico City at 19°N. This annual movement of segregating lines had great advantages in developing widely adapted wheats. First, it made it easier to spot and eliminate daylength-sensitive plants. Second, only lines that could yield satisfactorily under the environmental conditions and disease complex of a low-altitude desert as well as those of a cool, humid high plateau were retained.

In 1965, Mexico released the first semi-dwarf durum, Oviachic. This variety resulted from a cross of Tehuacan and a bread wheat that carried the Norin 10 genes. Unfortunately, the Norin 10 gene for short stems was linked with genes for sterility, so many florets (wheat flowers) did not produce grain. A tendency towards sterility is especially undesirable in durums because drought and high temperatures which are common in durum-growing areas, accentuate the amount of sterility. Nevertheless, Oviachic gave good yields because its short height and strong stems made it resistant to lodging, because it responded well to fertilizer, and because it tillered profusely (tillers are auxiliary stems, each of which usually bears grain).

CLIMATES IN DURUM-GROWING AREAS

Durum is grown under several different ecological conditions and the breeders of durum must take these conditions into account. The fundamental denominators of these conditions are the temperature pattern and the rainfall pattern during the growing season. In the Indian durum area, for example, durum is planted when the monsoon rains stop. Durum varieties there must grow and fill their grains relying only on the moisture of the soil. If the soil moisture is used up or evaporates before the crop is ripe, the harvest is puny. But since little rain falls during the growing season, many diseases are less troublesome than in more humid areas.

In contrast, in much of North Africa, durum is planted in late autumn when the rains begin. Varieties must flower when the temperature rises in the spring and then ripen quickly before hot desiccating winds blowing off the desert can shrivel the grains. In coastal areas, because of the humid climate, diseases do much damage.

The third general type of durum area exists in, for example, parts of Turkey and the high plateau of Algeria. Durums are planted in the autumn, and they must survive the cold winter. Because the climate is cool during the growing season, certain diseases are a serious hazard here too.

In most durum areas, the climate is highly variable from year to year. Algeria, for example harvested only 630,000 tons of durum and bread wheat in 1966, while in 1968, a year of better weather, it harvested 1,530,000 tons. Periodic droughts and unseasonably hot or cool weather not only affect yields directly, they also change the disease complex. Thus while the varieties grown in a locality may have some resistance to the prevalent diseases or races (strains) of diseases, if the season is cooler or wetter than usual, other diseases or races may predominate and destroy the crop.

George Varughese, CIMMYT durum breeder stationed in Tunisia, describes durums being developed at the Beja research station to a gathering of wheat researchers from the Mediterranean region, the Middle East, and CIMMYT.

In 1967, the year after CIMMYT was founded, Mexico released Chapala, and Chile released Quilafen, a variety selected from a cross made at CIMMYT. Chapala was semi-dwarf and insensitive to daylength, but had sterility problems. Quilafen was sensitive to daylength, but for Chile which is not close to the equator, the daylength sensitivity of Quilafen was no drawback. Chilean farmers still grow it today.

New durums challenge bread wheats

Two momentous events occured in 1969: the first international durum yield nursery was sent out and the variety Jori was released in Mexico. The acid test of a variety's adaptability is its performance at locations throughout the world where it will be exposed to many different diseases and growing conditions. In 1969 CIMMYT assembled packages containing 12 durums from five countries including four CIMMYT advanced semi-dwarf durum lines. Inia 66, a semi-dwarf bread wheat known to be high yielding from Mexico to India was included as a check—a standard by which to measure the other entries in the test. The nursery was grown in 32 locations, most of which were in the Middle East and North Africa. When the results were compiled, the four CIMMYT-bred durum lines finished first, second, third, and fifth. The results

Large plump grains fill the heads of Mexicali, a variety bred by CIMMYT and released in Mexico in 1975.

were convincing evidence that short, daylength-insensitive durums were widely adapted and substantially more productive than tall, daylength-sensitive durums. And, astonishingly, the semi-dwarf durums showed they could challenge and even exceed the yields of the semi-dwarf bread wheats. In the first international durum yield nursery, Jori yielded 10 percent more than Inia 66.

Breaking the sterility barrier

Jori was capable of higher yield levels than previous semi-dwarf durums because it had less sterility. Jori gave the first hint that, through painstaking selection, the linkage in short durums between the Norin 10 gene and genes for sterility could be broken.

In 1971, Cocorit was released by Mexico. In this variety the sterility linkage was broken further so yields were higher than those of Jori. It was also insensitive to daylength, and it had improved resistance to several diseases. Four international durum nurseries have been conducted since 1970 and in each one Cocorit has been the highest yielding entry.

The bright future for durums

Jori and Cocorit are far from the end of the road in durum improvement. While high yielding, these varieties do not have the high-quality grain demanded by durum importers. Countries that regain self-sufficiency will need durum with good pasta-making quality if they are to penetrate world durum markets.

Both Jori and Cocorit tend to be late maturing. Many areas need high-yielding varieties that have special maturity characteristics to fit unusual growing seasons. Cold tolerance is needed for high plateaus where durum growing is important.

Better and broader disease resistance must be incorporated in new varieties to combat the highly changeable disease complexes that are characteristic of many durum-growing areas.

These goals and others have been pursued by the three scientists directly responsible for CIMMYT's durum breeding program since 1968. George Varughese, an Indian plant scientist, was CIMMYT's first full-time durum breeder. Since 1971, he has been CIMMYT's durum breeder in Tunisia which has one of the most vigorous durum improvement programs in the developing world. Marco Quiñones, a Mexican plant breeder, headed CIMMYT's durum work from 1971 to 1974. He is now one of the leading cereal breeders of the Mexican national program. Gerbrand Kingma, a young Dutch scientist who was a wheat breeder in Lebanon currently is responsible for CIMMYT's durum development in Mexico.

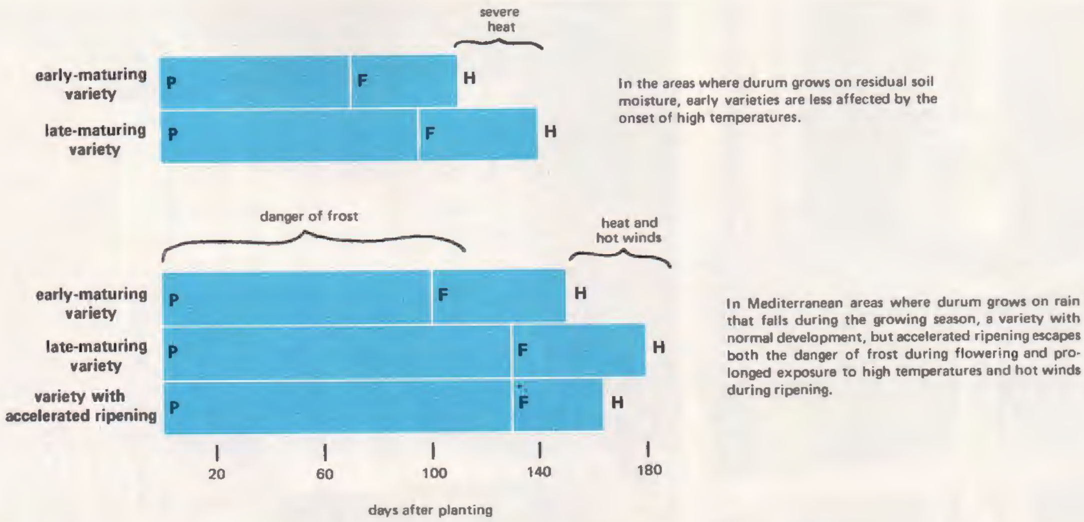
Here are some of the changes that are being made in durums now in CIMMYT's experiment fields.

- *Plant height.* The first semi-dwarf durums had one gene for short stems. Newer lines have two or three genes for shortness. The effects of the genes are additive so plants with two of the genes are shorter than plants with only one gene, and plants with three genes are shorter than those with two genes. The sterility problem tends to increase as the number of genes for shortness increases. In new two-gene and three-gene semi-dwarf durums, the linkage has been severed so these lines have a yield potential 15 to 20 percent greater than that of Cocorit. Mexicali, a two-gene semi-dwarf durum, was released by Mexico in 1975.

Thus the durums CIMMYT is developing have a range of heights. The shortest ones tend to have the highest yield potential: they can respond to good growing conditions—abundant moisture and high soil fertility—without lodging. The taller ones, while having an adequate degree of lodging re-

Since all lines in CIMMYT's experimental fields are deliberately inoculated with rusts, teams of technicians, far left, work from dawn to dusk scoring resistance to rusts.

Stem rust is one of several fungus diseases which can severely reduce durum yields.



Schematic example of the advantages of durums with early maturity or accelerated ripening in certain areas. (P = planting; F = flowering; H = harvest).

sistance, are able to compete better with weeds in areas that have heavy weed infestations.

• *Quality improvement.* Quality in durum means suitability for pasta making. A mottling, called yellow berry (*See box* "Durum quality") in grains of Cocorit is one reason some farmers prefer Jori although Jori is lower yielding. Growing durums with little or no nitrogen fertilizer tends to increase the percentage of grains with yellow berry.

To ensure that new durum lines have acceptable quality, CIMMYT has begun testing for semolina color, the most important aspect of pasta quality. CIMMYT's cereal chemist, Arnoldo Amaya, measures the carotene content (carotene gives the semolina a desirable yellow color) in all durum lines that reach the third, fourth, and fifth generation of selection.

Because CIMMYT grows two crops a year the carotene tests must be completed in the brief period between the harvest of one crop and the planting of the next. To make this possible, Amaya has refined the carotene test so that it takes 30 minutes instead of 18 hours to complete.

In 1974, grains from 4000 plants were tested. The average carotene content was nearly twice as high as that of materials tested in 1972—encouraging evidence that the quality shortcomings of Cocorit will be solved in newer varieties.

In addition, macaroni is made at CIMMYT from all high yielding lines and from all lines being used frequently as parents in the durum program. The macaroni is graded for color and cooking quality.

• *Maturity and growth habit.* CIMMYT is developing durums with different maturity patterns—early maturing durums, durums with rapid grain filling, and semi-winter durums—and is contributing to development of winter durums.

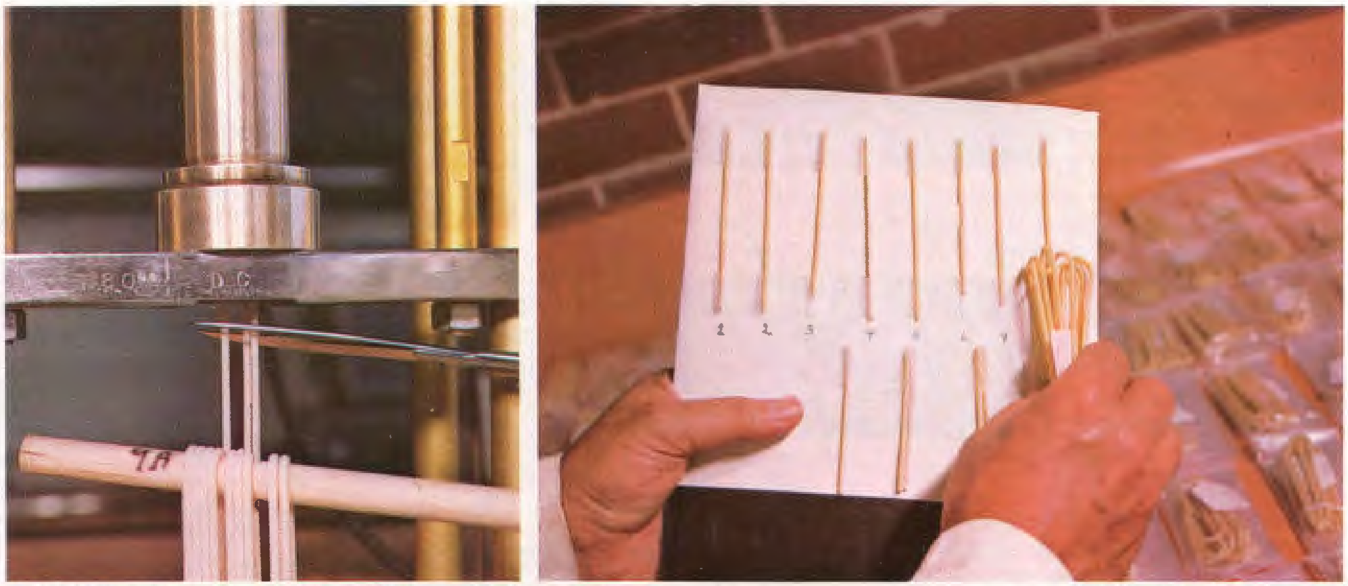
For areas like central India where durums are planted after the monsoon rains end and grow on residual soil moisture, CIMMYT is making crosses with short-season varieties. Progeny of these crosses complete their growth quickly, before soil moisture is exhausted, and they can be harvested before the scorching temperatures of the dry season shrivel the grain.

For areas like North Africa which have mild winters, but where the period between the last frost and the onset of high temperatures and hot winds can be brief, CIMMYT is developing varieties that have rapid grain filling. These varieties have a normal vegetative period so that they can be planted when the rains begin in the autumn, yet flowering (the beginning of the reproductive period) does not occur until the changes of frost are slight. While brief nighttime frosts during the vegetative period do not harm the plant, frost during flowering would make the plant sterile so it would not produce grain.

Once flowering occurs in these durums, the grains form and fill quickly, avoiding the hot winds (sirocco) which begin to blow off the desert in June. Varieties that are still ripening during the sirocco tend to have shriveled grain, which reduces both the crop yield and the quality of the semolina (the raw material of pasta) produced from the grain. In addition, varieties with a normal ripening period are likely to be in the field longer after the last rain and thus are more vulnerable to drought.

Semi-winter durums are types that will not flower unless they are first exposed to a period of low temperatures and, for some, long daylengths. These durums can be planted in the autumn in areas that have cool but not cold winters. Sensitivity to daylength prevents flowering during the short days of winter.

Semi-winter durums and winter durums are being created by crossing spring durums with winter durums. Mexico does not have suitable conditions for winter durums—a moderately cold winter with snow—so selection for winter types is done by



CIMMYT evaluates macaroni-making quality in advanced durum lines.

scientists at Oregon State University (USA) and in Turkey by CIMMYT scientists and the staff of the Turkish cereal improvement program.

The crossing of spring durums with winter durums has never before been done on a massive scale. CIMMYT scientists discovered in 1972 that the climate at CIMMYT's high altitude station (2600 meters) near Toluca, Mexico, permits planting both winter wheats and spring wheats. The winter wheats are seeded in November and cold weather during the following 6 weeks is sufficient to induce flowering later. The spring wheats are planted after the middle of January. With this planting schedule, both types flower during May and June so that hundreds of crosses can be made. In 1975, 250 winter durum varieties were planted at Toluca for use in crosses with spring durums.

• *Disease resistance.* Most durum varieties grown by farmers in the Mediterranean region and Middle East today have poor resistance to the major diseases. In a few areas, like central India and portions of Turkey, the growing season is dry so a high level of disease resistance in durums is not critical. But in most durum areas, the growing season is humid. In humid climates, stem rust, stripe rust, and septoria leaf blotch are the most important enemies of durum. Leaf rusts, smuts, and bunts can also reduce yields substantially in some locations.

Because the weather varies greatly from year to year, the major disease problem may change, too—one year the durum fields may be crippled with septoria, the next year stem rust may batter the crop. In addition, of course, the prevalent races of the three rusts change over time. Since the disease complex in any locality is so unstable, varieties with resistance to only one or two diseases are quite vulnerable. Varieties with broad disease resistance are urgently needed.

The weakness of durum varieties now grown are apparent from the Regional Disease and Insect Screening Nurseries conducted annually in 100 to 150 sites from North Africa to India. The RDISN is coordinated by Gene Saari, a CIMMYT pathologist stationed in Lebanon and Mike Prescott, a CIMMYT pathologist stationed in Turkey. Saari and Prescott told the regional wheat workers conference in Tunis in 1975 that the RDISN's conducted from 1972 through 1974 showed that, as a class, traditional varieties "do not have adequate resistance for the three rusts and...they could sustain heavy damage whenever the conditions for an epidemic are suitable." They said that improved varieties—tall varieties that were released in the late 50's and early 60's—have barely adequate resistance and should be replaced quickly. The semi-dwarf durum varieties available "have good resistance to stripe rust, but merely adequate resistance to stem and leaf rust." The semi-dwarf bread wheats, Saari and Prescott found, have generally better resistance to the rusts than durums do. That reflects the longer and more intensive breeding work that has gone into the bread wheats. And it underscores the opportunities that lie ahead in durum breeding.

The advent of screening nurseries such as the RDISN has enabled plant breeders to find varieties that have strong resistance to individual diseases—that is, varieties that are resistant in many locations. Usually these varieties have many other weaknesses which make them low yielding. Some of them are even in a different subspecies of *Triticum turgidum* than durum.

Combining diverse sources of resistance to different diseases and bringing them into a high yielding plant type is a task that CIMMYT's extensive breeding program is well equipped to do efficiently.

In the winter season at Giudad Obregon all durums are inoculated with stem and leaf rust to eliminate susceptible lines. In the summer season at the Toluca station severe natural infections of

BETTER FARMING METHODS

Yields of durum in the Mediterranean region are low for many reasons such as periodic droughts, poor varieties, diseases, high temperatures in the spring. These hazards are beyond the control of the farmer. But weeds and low soil fertility also depress yields and CIMMYT scientists in Tunisia and Algeria are helping local scientists find ways for the farmer to combat these two critical problems.

Through experiment station trials and demonstration plots in farmer's fields, the scientists are spreading knowledge of the benefits that come from low-cost herbicides and application of fertilizer.

In addition, however, CIMMYT has brought in specialists to introduce a cereal-forage legume rotation which has been highly successful in Southern Australia which is ecologically similar to the Mediterranean basin.

This rotation system attacks the weed problem at its heart—the weed fallow system which has been traditionally used to provide pasture for sheep in vast areas of the Mediterranean region. In these areas, farmers grow wheat in one year and then let the land lie fallow the next. But weeds are allowed to grow in the fallowed field and sheep owners pay the farmer for grazing privileges. Some economists speculate that the farmer's profit from the weed fallow almost equals his profit from the wheat crop. Unfortunately, the weed fallow leaves high populations of weed seeds in the soil which germinate in the wheat crop.

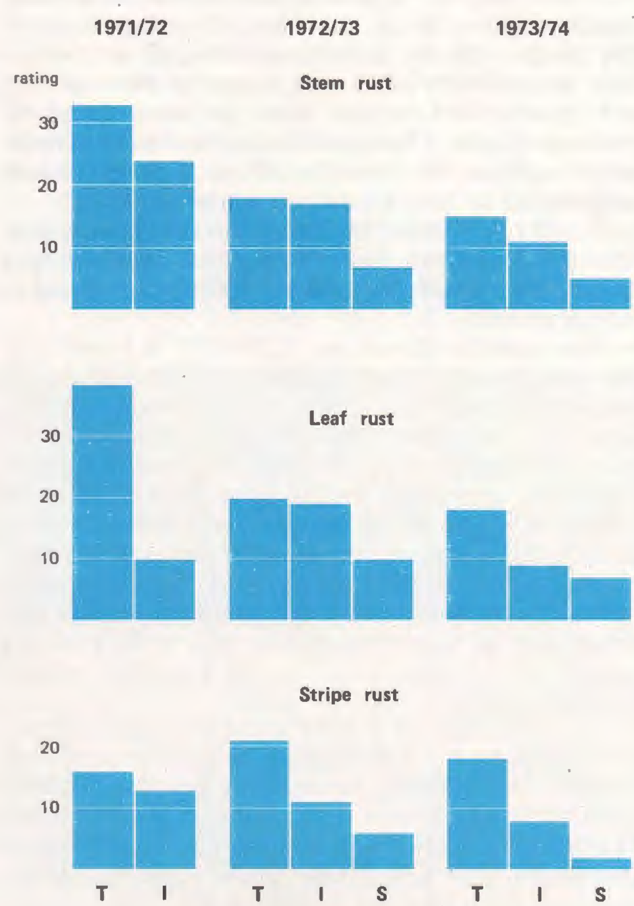
The wheat-forage legume rotation being introduced is based on the *Medicago* species of legumes commonly called "medics." Medics are native to the Mediterranean basin and with proper management (mainly shallow soil tillage and application of phosphorus) medics compete vigorously with weeds.

In the fallow year, medic provides much better forage for sheep than the weed-fallow would. Since the medic surpresses weeds in the fallow, the following wheat crop has fewer weeds (some medic may sprout in the wheat but since it is a low-growing crop it doesn't compete greatly with the wheat). Moreover, since it is a legume, medic fixes nitrogen in the soil which then is available to the wheat.

As more and more farmers adopt varieties that can take advantage of high soil fertility, the payoff from the legume-wheat rotation should be explosive.

stripe rust, septoria, and scab occur. But the real torture test comes when lines are placed in international trials, notably the International Durum Screening Nursery. Glenn Anderson, associate director of CIMMYT's wheat program calls the IDSN the most valuable international durum trial CIMMYT conducts. In the IDSN, seed of about 200 CIMMYT advanced lines is sent to 30 durum growing areas each year. Results from the IDSN trials show which lines have resistance to a disease at location after location and thus which lines have broad resistance to many diseases.

When a line is tested at numerous locations it is exposed to many different forms and intensities of a disease. A line that is resistant to a disease at most locations probably will remain resistant to the disease for many years. New forms of the disease may arise in a locality, but there is a reasonable chance that the new form will be one which already existed elsewhere in the world. Hence the variety that has shown broad resistance in international tests is likely to have resistance to new forms.



Uniform trials coordinated by CIMMYT and conducted from North Africa to India show that traditional durum (T) are much more vulnerable to rust epidemics than improved (I) or new semi-dwarf (S) durums. A rating below 5 suggests a satisfactory level of resistance; 5 to 10 suggests adequate resistance but that new sources of resistance may be needed soon; 11 and above suggests that varieties could be heavily damaged whenever the conditions for an epidemic are right, and such varieties should be replaced.

The IDSN also helps breeders avoid wasting time, energy, and scarce experimental land on lines that have narrow resistance. A line may have good resistance in Mexico but at other locations around the world it may be vulnerable. Such lines have little prospect for stable long-term resistance and they are eliminated.

CIMMYT breeders reach outside durums to find sources of resistance to disease. Since experimental plots of durum are grown side by side with CIMMYT's bread wheats and triticales (a new crop created by crossing wheat and rye), CIMMYT durum breeders have easy access to thousands of bread wheats and triticales that have been rated internationally for disease resistance. Bread wheats are good sources of resistance to scab and both bread wheats and triticales are being used as parents to transfer their sources of septoria resistance to durums.

- *Multilines.* As an additional weapon against rusts, CIMMYT has begun work on a durum multiline variety. A multiline variety is created by making crosses between a widely adapted, high yielding variety—CIMMYT is using Cocorit—and numerous other varieties which have many different genes for rust resistance. The progeny are selected until the lines are essentially identical to the recurrent parent (Cocorit) except that they have different genes for resistance to rusts.

Mixing the seed of 15 to 20 lines creates a multiline variety. If a new race of rust occurs in a locality, only one of the lines—5 or 6 percent of the plants—is likely to be susceptible. Even susceptible plants in the field may escape or develop only a mild infection because they are surrounded by resistant plants. Thus multiline varieties are intended to combat the brushfire effect that severe rust outbreaks can have in uniform varieties.

CIMMYT is only in the early stages of multiline development. Several years of breeding and testing lie ahead before durum multilines will be in farmers fields.

- *New plant architecture.* CIMMYT is looking at the possible merits of creating durums with fewer leaves than normal. Gerry Kingma explains that fewer leaves might help the plant use moisture more efficiently by reducing evapotranspiration. Moreover, the plant would have fewer places to collect dew and fewer leaves to rub together. Diseases such as septoria need moisture on the surface of the plant to flourish; contact between leaves helps the disease move from plant to plant. The advantages of fewer leaves will have to be weighed against the drawback of having a smaller photosynthetic area.

The fight against disease suggests another possible change in the architecture of the durum plant. Breeders are looking for durums that have a long peduncle—the "neck" that bears the grain head. The idea is that if the grain head stands well above the leaves, less water will splash onto the head, reducing the frequency of damaged by scab.

CIMMYT scientists are also interested in producing durums with upright leaves instead of the droopy leaves common to most wheat varieties. Upright leaves should allow more light to reach the lower leaves. Two benefits might result: more tillers (auxiliary stems) might survive and bear grain, and the rate of photosynthesis in lower leaves might increase because they would be less shaded by the upper leaves.

Although durums tend to produce fewer grains per hectare than bread wheats, semi-dwarf durums yield as well as semi-dwarf bread wheats because the durums have larger and heavier grains. To increase the number of grains per hectare, CIMMYT breeders are planning crosses between durums and triticales. Many triticales have unusually large

SENSITIVITY TO DAYLENGTH

In many plants the time of flowering is determined by the length of day. This mechanism has advantages, but it is also a barrier to wide adaptation. Daylength sensitivity can help a species survive by reducing the chances that flowering will occur during a frost. Frost would destroy the flowers, preventing the production of seeds.

Daylength sensitivity in cereals means that plants flower only when "long" days occur. Near the arctic circle, a species might require days with 20 hours of light to induce flowering. Another species nearer to the equator might require only 14 hours of daylight. Since "long" days at any latitude occur at a warmer time of year than "short" days, daylength-sensitive plants flower when the chances for successfully completing the reproductive cycle are best.

But daylength sensitivity also prevents such plants from performing well when they are planted in latitudes north or south of their native location. When a daylength-sensitive plant is moved south in the Northern Hemisphere, flowering may be delayed by as much as 6 weeks. If a plant flowers too late, grain development in some locations will take place during excessively hot or dry weather and in other locations when the weather is turning cold.

An important facet of the wide adaptability of CIMMYT-developed cereals is the elimination of daylength sensitivity. Thus an "early" variety that flowers in 75 days in one location will flower in 75 days in other locations (provided that the temperature pattern is about the same). Similarly, a daylength insensitive "late" variety that flowers in 120 days will flower in the same time at other locations.

spikes (grain heads) with many florets. If these characters can be transferred to durums while maintaining large kernel size, the yield potential of durums could substantially exceed the yield potential of bread wheats.

• *Drought resistance.* For plant scientists, drought resistance is still little explored terrain. The subject is exceedingly complex. Moisture stress can occur in a variety of ways during the growing season and numerous mechanisms may make it possible for a plant to survive or escape drought.

Experiments by Tony Fischer, CIMMYT's wheat physiologist, have given indications that the durums as a class may be somewhat more drought resistant than the bread wheats, but identification of specific characters that breeders could introduce into improved lines still lies in the future.

Evidence exists, however, that good drought resistance already occurs in some semi-dwarf durums. In the 1973/74 Rainfed Wheat Yield Trial, coordinated by the Arid Lands Agricultural Development Program, a sister line of Cocorit was the highest yielding durum. The trial was conducted at 18 locations in the Middle East, South Asia, Africa, and Europe. Twenty-four durums and bread wheats were tested at each location. A local variety was added as a check at each site.

Over the wide range of moisture and disease conditions at the 18 locations, Cocorit "S" yielded 2.9 tons per hectare. Only Pitic 62, a semi-dwarf bread wheat, was higher yielding—by merely 40 kilograms. At 12 of the 18 locations, Cocorit "S" was either the highest yielding entry or not significantly different from the highest yielding entry. The next best durum was in the highest yielding group at only seven locations. Only at four locations was the local check (which presumably was adapted to local conditions) in the highest group.

Germ plasm development and distribution

Plant breeding is a numbers game and CIMMYT runs the biggest game in town. CIMMYT draws on 10,000 durum varieties for basic germ plasm. About half the varieties are in CIMMYT's working germ plasm bank and half are requested from the germ plasm bank of the U.S. Department of Agriculture.

CIMMYT's massive breeding program stands on two legs. One is the ability to make thousands of crosses a year, using traditional varieties that may have one or two highly desirable characteristics and modern varieties that need to be strengthened in some aspect or other. The other is worldwide testing to sort out lines that are widely adapted.

George Varughese says:

> High yield and adaptation result largely from the operation of additively operating gene complexes. The plant breeder depends largely on the hybridization of diverse germ plasm to bring together these additive genes which can normally be identified from materials of diverse origin. Multiple crossing [brings] together co-adapted gene complexes from diverse sources. However, the hybridization of materials possessing desirable attributes has little value unless the proper types of selection pressures are used to identify those genotypes combining the desirable characters in their optimum intensities.

For making thousands of crosses a year, the conventional method is too slow. CIMMYT had to invent a new way to pollinate wheat—what the breeders like to call the "go-go" method of pollination. The go-go method allows a cross to be made in 60 seconds while the usual crossing method takes 5 or 10 minutes per head.

In the go-go method each floret on a head is cut in half to expose the stigma (female organ) and the stamens (male organs). The stamens are then removed, creating, in effect, a female plant. The head is covered with a glassine bag to prevent accidental pollination by nearby plants. The florets of the plant selected to be the pollinator are also cut in half. The entire pollinator head is then removed and exposed to full sunlight. Sunlight induces the exposed anthers to extrude and shed

Marco Quiñones, former CIMMYT durum breeder and currently leader of cereal programs in Northwest Mexico—the nation's wheat bowl—inspects durums being multiplied for possible release to farmers. CIMMYT and the Mexican cereal program work side-by-side in developing new wheats.

pollen. When pollen is being shed freely, the pollinator head is inserted through a slit in the bag covering the female head and twirled a few times to shake off pollen. One pollinator head can be used to make crosses with two to four female heads.

The usual system of crossing involves a female parent created in the same way. But pollen must be collected from the pollinator plant, placed in a small bottle, and then brushed onto the female head with a camel's hair brush. Removing the pollen from the anthers and transfering it to a small bottle is a tedious and time-consuming procedure.

Using the go-go method of pollination, CIMMYT is able to assemble many combinations of additive genes each year. Then to get the combinations tested quickly, CIMMYT's durum program distributes early generations of double crosses and top crosses to breeders in other countries. For example, double crosses are created by pollinating variety A with variety B which gives about 40 grains of F_1 seed, A x B. At the same time variety C is pollinated by variety D, giving another 40 grains of F_1 seed, C x D. Then both batches of F_1 seed are sown and, when the plants are flowering, 10 heads of (A x B) are crossed with 10 heads of (C x D). Ten heads of (A x B) x (C x D) result.

Half of the precious seed is divided among national durum programs in Algeria, Tunisia, Turkey and India. The other half is grown in Mexico. When this seed is planted it segregates furiously—tall and short plants, disease-resistant plants and susceptible plants, plants with good grain and plants with poor grain, and so forth. But with luck a small fraction of the plants have few of the undesirable characters of the original four parents and most of the good characters.

In 1974 CIMMYT sent out seeds of 3300 F_1 multiple-cross durums. From the known characteristics of the parents such as drought resistance and disease resistance, the crosses were classified so that each area received only crosses likely to be appropriate for it. The cooperating national programs planted and evaluated the crosses. Information exchanged among the programs and CIMMYT help each decide which crosses have promise and which are hopeless. The crosses that are retained can be put into selection procedures leading to a commercial variety or they can be crossed again with the national programs' own F_1 crosses.

To spread the benefits, some of the national programs that receive F_1 materials from CIMMYT then share the F_2 (next generation) seed with other national programs. They also send certain superior lines back to CIMMYT for use as new parents.

Sending out heterozygous early generations saves research time, although it demands a mammoth-sized crossing program. The alternative would be to make crosses and then select the best progeny for several generations in Mexico before sending them out for international testing. Only at that time can the breeder be sure that his experimental line is widely adapted. If it is not, the breeder has lost several years of work.

A particular advantage of making and testing many F_1 crosses is that crosses between early maturing, semi-dwarf varieties and late-maturing, tall varieties that have desired characteristics such as good grain quality or certain sources of disease resistance usually produce some progeny that combine early maturity, short height, and the desired characteristics. Simply crossing a modern variety and a tall variety and then backcrossing would take several generations to create a plant with the good background of the modern variety and the desired characteristics of the tall variety.

Through distribution of early generations of crosses and other mechanisms such as the International Durum Screening Nursery, the International Durum Yield Nursery, and the Regional Insect and Disease Screening Nursery, CIMMYT gives national durum breeding programs access to a cornucopia of improved germ plasm. The international nurseries also help nations test their durum crosses and selections across a wide spectrum of ecological conditions. An invaluable adjunct of the nurseries is the network of wheat scientists who correspond with each other, exchange breeding lines, and hold meetings from time to time. Through the joint efforts of these scientists, a new age is beginning for one of man's oldest crops.

Steven A. Breth

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