original entries are not maintained for reconstituting the composite, and new entries may be inserted from time to time. As with a synthetic, the composite or germplasm pool may be maintained by open pollination in isolation, or by random mating from hand pollinations. The composite may serve as a source population for inbred line development.

BREEDING OBJECTIVES

Choice of proper objectives is necessary for the corn breeder to develop hybrids that will be adapted to the area in which they are to be grown and superior to those already in use. The sound choice of objectives must be based on a careful appraisal of the plant characteristics that need to be improved to provide a higher yielding or a more stable yielding hybrid for the farmer to grow, or to produce a novel hybrid with unique characteristics. Breeding objectives need to be reevaluated and updated as changes occur in production practices or in the production environment, such as the result of conservation compliance or no-till practices.

Grain Yield

Corn hybrids replaced open-pollinated cultivars because they produced higher grain yields. Over the next 50 years, development and use of genetically improved hybrids, combined with improved cultural practices, resulted in a 340% increase in corn yields in the United States (Fig. 1.2). The potential for high grain yield is a complex objective, affected by the expression of genes associated with nutrient uptake, photosynthesis, transpiration, translocation, and metabolism of the corn plant, and interaction of the genes in different environments. Corn is a C_4 plant and, along with sorghum, has a higher rate of photosynthesis than a C_3 plant like wheat or soybean. Grain yield is also affected by genes associated with characters that contribute to stability of production, such as optimum maturity, stalk quality, resistance to environmental stresses, or resistance to disease pathogens and insect pests. The potential for high grain yield cannot be evaluated accurately by visual observations; it is measured in yield trials, accurately conducted at several locations and in several seasons so that genotype × environment interactions can be assessed. In the pursuit of higher grain yields in hybrid corn, extensive research has been conducted in related disciplines, such as quantitative genetic theory and its application in development of breeding procedures, improved field plot techniques that enable the breeder to obtain a more accurate evaluation of field performance, and refined statistical techniques which permit a clearer interpretation of research results.

Adaptation

Adaptation, like yield, is a complex objective in hybrid breeding that is directly affected by cultivar maturity; response to soil fertility level and conservation tillage practices; seedling cold tolerance; and resistance to heat and drought. Indirectly, adaptation is affected by other plant characters such as husk covering, root and stalk quality, disease and insect resistance, and endosperm properties that affect seed storage.

MATURITY TO FIT THE AREA OF PRODUCTION. Corn is a short-day plant, with time of flowering influenced by photoperiod and temperature. In tropical and subtropical climates, corn may be grown throughout the year if soil moisture is available; in temperate climates the corn-growing season is limited to the frost-free period. Generally, corn hybrids that will most completely utilize the full growing season and still safely mature will be the most productive hybrids to grow in a region limited by length of the production season. Yet, early maturing hybrids have certain advantages that foster their use, such as early harvest before damage from rain at time of harvest, or to facilitate planting of the succeeding crop in a rotation system. Early maturing hybrids adapted to the shorter growing seasons in higher latitudes or at higher altitudes will be shorter and have fewer leaves than hybrids adapted to the lower latitudes and longer growing seasons. The shorter growing season is compensated for in part by days with longer photoperiods. Tropical races of corn tend to be taller and have more leaves than the races adapted to temperate climates (Fig. 17.10).

RESPONSE TO SOIL FERTILITY. That certain strains of corn are more productive on fertile soils and that other strains are more productive on poor soils was once a popular belief. Present practice is to correct soil deficiencies rather than to search for genotypes that respond more favorably to fertility differences. At higher fertility levels, planting rates of corn are increased, creating a need for hybrids with smaller plants and shorter and stronger stalks. Short-statured hybrids generally have smaller ears, which are compensated for by higher planting rates.

COLD TOLERANCE. Cold tolerance refers to the ability of a corn hybrid to germinate rapidly at temperatures around 10°C, while resisting invasion of soil-borne pathogens that incite seedling blights at these low temperatures. Hybrids with cold tolerance are desired for early planting in cold, wet soils, or for no-till corn production. Cold tests of corn inbreds and hybrids are conducted by germinating seeds in contact with pathogen-infested soil at a temperature of 9 to 10°C for a period of 7 to 10 days and then completing the germination in a higher temperature.

FIG. 17.10. Field of tropical corn growing in Peru. Note the extreme height of the tropical corn.

RESISTANCE TO HEAT AND DROUGHT. Heat and drought stress reduces yield and quality of corn through restriction of root development, or reduction in leaf area during plant vegetative development, or by associated effects such as poor seed set, ear droppage, higher smut incidence, greater insect damage, or fungal mycotoxin production on diseased ears. Damage from heat and drought stress is most severe if it occurs at flowering causing reduced seed set and barren ears. High-temperature stress, above 38°C, reduces pollen viability, whereas drought stress reduces the rate of silk elongation so that silk extrusion may not synchronize with pollen shedding. Breeding for resistance involves selection of inbred lines that tolerate to a greater extent the adverse effects of heat and drought stress.

BREEDING FOR CONSERVATION TILLAGE PRACTICES. New tillage practices involving variations of minimum tillage and no-till cultural procedures are aimed at conservation of soil, fuel, and labor in corn production. Changes in cultural practices change the environment in which the corn hybrid is grown, specifically reducing the soil temperature at planting time. These changes need to be assessed in the breeding program.

Stalk Quality

Stalk quality refers to the stalk structural development, maturity, disease resistance, and pest resistance that enable the hybrid plant to stand until mechanically harvested without lodging. Losses in yield due to lodging result from the corn plant leaning over, fostering development of light, chaffy, and immature ears; or the ear touches the ground and is damaged from kernel rots. An inbred line or hybrid is classified as root lodged when it leans more that 30 degrees from the vertical (see Fig. 12.2). Root lodging may be caused by inherently weak root systems, or from roots damaged by disease or insects. A strong root system will enable the corn plant to stand against the buffeting of wind and rain. Progress in resistance to root lodging is made by breeding for shorter plants, plants with low ear placement, increased resistance to root diseases, and resistance to insects that feed on corn roots. The force required to pull corn plants from the soil is used to measure the anchorage and strength of the corn root systems.

A corn plant is classified as stalk lodged if the stalk breaks below the ear (see Fig. 12.2). Stalk breakage may occur either before or after the plant matures. The diameter and thickness or toughness of the hard outer shell or rind affects the inherent stalk strength. Stalk breakage is reduced by breeding for stronger stalks and for resistance to stalk-boring insects, such as the European corn borer (*Ostrinia nubilalis*) and resistance to stalk-rotting diseases. Recurrent selection procedures are effective in developing populations with stronger roots and stalks.

Resistance to Ear Dropping

Resistance to ear dropping is important because ears broken off and dropped to the ground cannot be recovered by a mechanical harvester. Resistance to ear dropping is evaluated by the percentage of ears on the ground at the time of harvest. Hybrids differ in their susceptibility to ear dropping. The amount of ear dropping is affected by the length and strength of the shank, weight of the ear, and disease and insect injury to the shank. The shank supports the ear and is the structure through which photosynthates are conducted as the ear develops. Heavy ears require strong shanks that do not break. Ear droppage is increased with injury to the shank, such as European corn borer tunnels, or subsequent invasion of borer tunnels by corn disease pathogens. Long shanks are structurally weaker and increase the surface available for

European corn borer tunneling. Resistance to ear dropping is increased by selecting for short, strong shanks, and resistance to stalk borers and stalk and ear rots. In selection for short, strong shanks, the shank needs to be long enough for the ears to bend downward when mature to reduce ear rotting from moisture being collected and impounded in the base of the husks.

Husk Covering

The husk protects the ear of corn from weather damage and reduces the injury caused by insects and birds. In the United States Corn Belt, a loose-fitting husk just long enough to cover the end of the ear is desirable to facilitate rapid drying and harvesting. In tropical and subtropical regions, a long husk extending beyond the tip of the ear and remaining tightly closed after maturity is useful in preventing insect and bird injury to the ear.

Rapid Dry-Down

Dry-down refers to the drying of the husk and ear as the corn plant matures. Rapid drying of the husk and ear permits early harvest and grain storage and avoids damage and loss from prolonged standing in the field before harvest.

Disease Resistance

In the beginning of hybrid corn development, progress was made in breeding disease-resistant hybrids by selecting for improvement in plant characters affected by plant disease, such as greater cold resistance, lodging resistance, or higher yield. Inbreds and hybrids susceptible to infection by pathogens inciting root- or stalk-rot disease would be eliminated from the breeding nursery because they lodged or produced unsatisfactory yields due to damage caused by the disease pathogens. Host reactions to many corn disease pathogens, including the complex of *Pythium* spp. and *Fusarium* spp. that incite root, stalk, or ear rots, are polygenicly inherited. Host reaction to other disease pathogens, such as *Puccinia sorghi* Schw. causing common rust, or *Bipolaris maydis* (Nisik.) Shoem. (Syn. *Helminthosporium maydis* Nisik. & Miyake) that incites southern corn leaf blight is race-specific with single-gene resistance to specific races. Progress in disease resistance breeding is facilitated if techniques are available for inoculation of inbred lines and hybrids with disease-producing pathogens.

The resistant reaction of a hybrid is dependent upon the genes for resistance in the inbreds. If resistance is a qualitative character controlled by one or a few genes, having the gene or genes for resistance in one inbred of a single-cross hybrid may be sufficient, although the level of resistance could be affected by presence of modifier genes in the other inbred. If resistance is a quantitative character, the hybrid will generally have greater resistance if both inbreds contain genes for resistance.

A large number of pathogens incite disease in corn. These include: (a) seed rots and seedling blights (*Diplodia maydis*, *Fusarium moniliforme*, *Pythium* spp); (b) root rots (*Fusarium* spp., *Pythium* spp.); (c) stalk rots (anthracnose, bacterial stalk rot, charcoal rot, *Diplodia* stalk rot, *Fusarium* stalk rot, *Gibberella* stalk rot); (d) ear rots (*Aspergillus* ear and kernel rot, *Diplodia* ear rot, *Fusarium* kernel and ear rot); (e) foliar disease (anthracnose, *Helminthosporium* leaf spot, northern corn leaf blight, rust, southern corn leaf blight); (f) virus disease (maize dwarf mosaic virus, MDMV, and maize chloric dwarf virus, MCDV); (g) systemic disease (head smut, sorghum downy mildew); and parasitic seed plants (witch weeds). The breeder needs to identify the diseases causing extensive damage in his production region, find genes for resistance to the pathogen, and incorporate the resistance genes into the inbred lines and hybrids being developed.

Insect Resistance

The principal insect predators in corn are: (a) rootworms (western corn rootworm, northern corn rootworm, and southern corn rootworm); (b) corn earworm (*Heliothis zea*); (c) corn borers (European corn borer, southwestern corn borer, and the southern cornstalk borer); and (d) stored-grain insects (rice weevil, maize weevil, Angoumois grain moth, Indian meal moth). As with corn diseases, the breeder must assess the insect damage in his production region, search out sources of resistance genes to insect species that cause the greatest economic loss, and incorporate the genes for resistance into the inbred lines and hybrids being developed. Resistance to many insect pests is quantitatively inherited, thus eliminating the backcross procedure as a breeding method for transferring resistance genes to a susceptible genotype. For the European corn borer, different genes are involved in resistance to leaf feeding by first generation borers and resistance to sheath-collar feeding by second and later generation borers. Resistance to tunnel boring is evaluated by comparing the length of the borer tunnels in different inbred lines (Fig. 17.11). Recurrent selection may be used to increase the level of resistance for quantitatively inherited characters in a breeding population. Methods for rearing the insect species and their dissemination in breeding populations are requisites for evaluation of resistance.

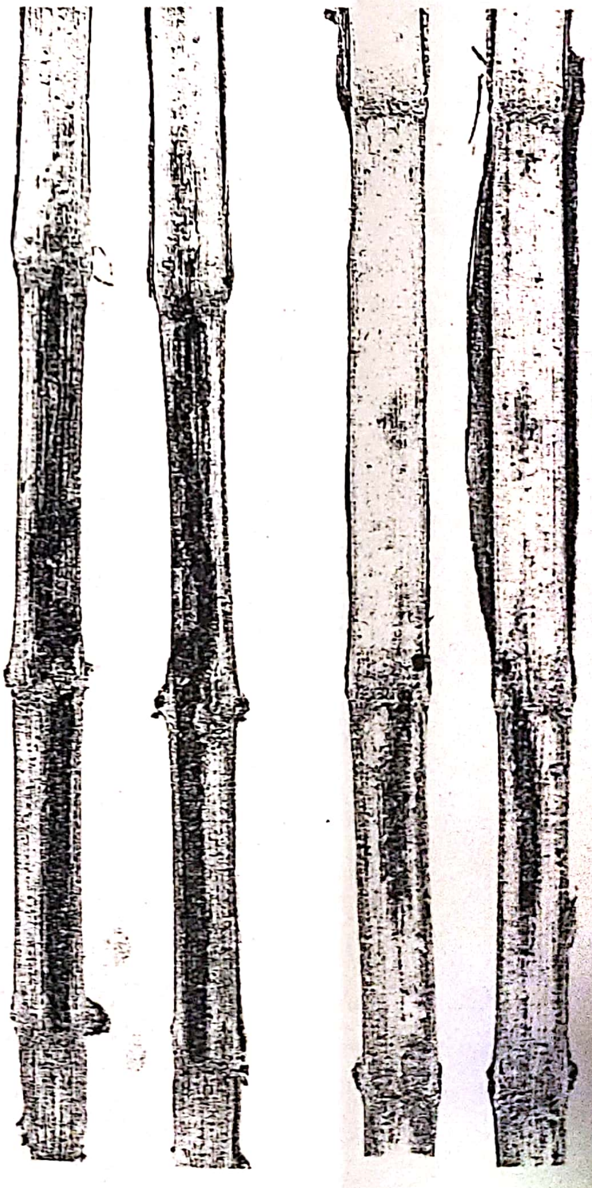

FIG. 17.11. Comparison of damage from European corn borer in stalks of a susceptible (left), and a resistant (right) corn hybrid. Resistance of inbred lines and hybrids is compared by measuring the length of the borer tunnels.

Quality

Improvement in quality of corn by breeding must take into consideration the use that will be made of the corn. About 90% of the corn utilized in the United States is used as animal feed; the remaining 10% is used in milling and other industrial uses, or for seed. Corn is a high-energy food. It is low in protein and requires supplementation with high-protein feeds to improve its nutritive value for animal or human food. Corn oil is a valuable by-product of milling. Breeding for higher protein or higher oil content has not been given a high priority in the United States because corn marketing practices do not reward growers for producing corn with higher protein or oil.

BREEDING HIGH-PROTEIN CORN. In a selection experiment at the Illinois Agricultural Experiment Station, the protein content of the 'Burr White' cultivar of open-pollinated corn was increased from 10.9 to 26.6% protein after 70 generations of ear-to-row selection (Fig. 17.12A). Increasing the total protein of corn by breeding does not increase the feeding value of the high-protein corn to nonruminant animals in proportion to the increase in the percentage of protein because the increase is in the *zein* fraction of the protein present in the endosperm. The zein fraction composes about 80% of the total kernel protein and is nutritionally deficient in the essential amino acids, lysine and tryptophan. Corn yields are generally reduced as protein content is increased.

IMPROVING PROTEIN QUALITY. The poor quality of corn protein caused by deficiency of lysine in the zein fraction may be improved significantly by addition of the mutant genes opaque-2 or floury-2. Generally, grain yield and kernel weight are reduced by introduction of the opaque-2 or the floury-2 gene, and the corn kernel has a soft, starchy endosperm. A few corn hybrids containing the opaque-2 gene have been developed and have a limited market for feeding nonruminant animals such as swine.

HIGH OIL CONTENT. In an experiment, parallel to the protein selection experiment at the Illinois Agricultural Experiment Station, and conducted with the same Burr White open-pollinated corn, the oil content of corn was increased from 4.7 to 16.6% after 70 generations

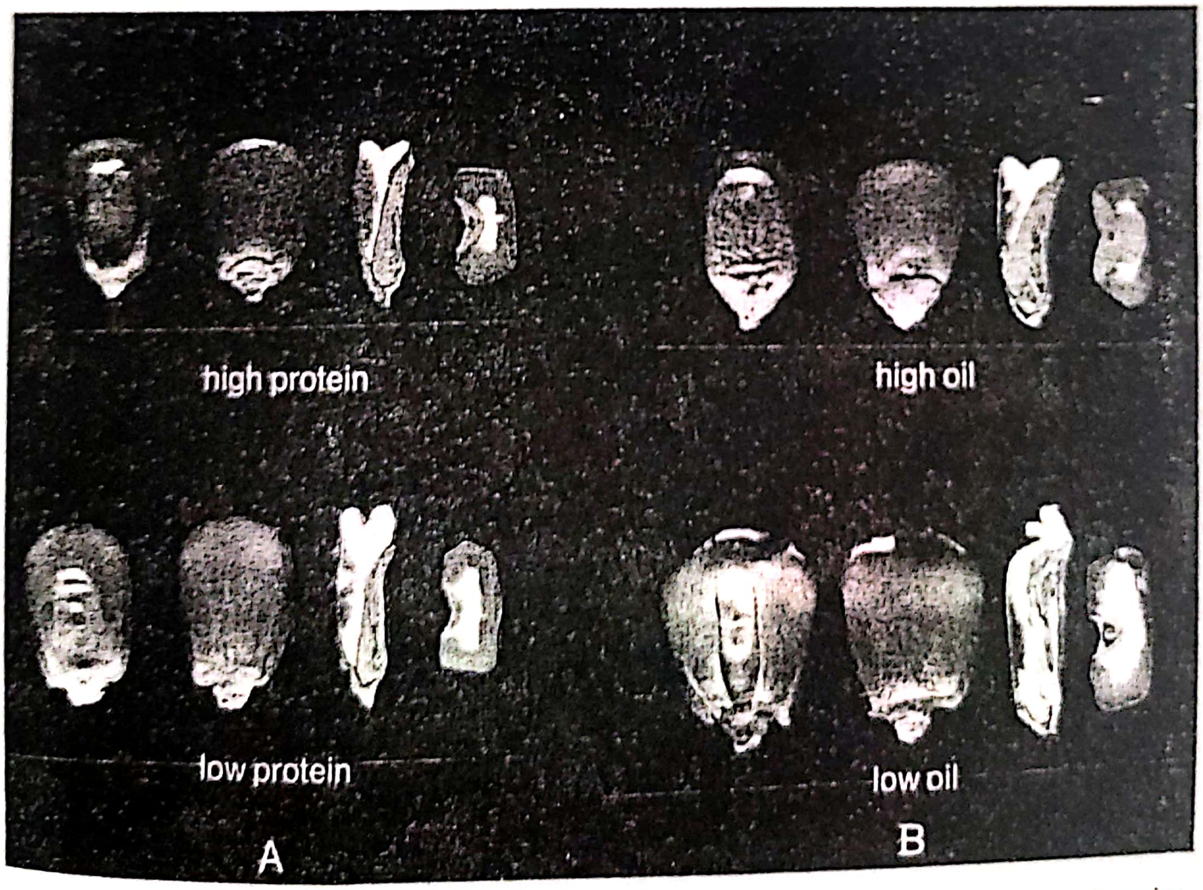

FIG. 17.12. Kernel characteristics of strains selected for chemical composition. (A) High- and low-protein strains. High-protein strains have smaller kernels with a larger proportion of horny endosperm than low-protein strains. (B) High- and low-oil strains. High-oil strains have kernels with a larger proportion of germ than low-oil strains.

of ear-to-row selection (Fig. 17.12B). Because most of the oil in corn is in the germ, selection for strains with large germs will increase the percentage of oil. High oil content is valuable to the industrial user of corn who extracts germ oil as a by-product in milling, or for feeding poultry, swine, or dairy cows. Increasing oil content in corn by breeding normally leads to a decrease in grain yield and a decrease in the unsaturated fatty acid, linoleic acid, desirable for low-cholesterol diets.

CORN FOR MILLING. Corn used for milling is processed either by dry milling or wet milling.

Corn used in the dry milling process goes into the manufacture of brewers' grits and flakes, hominy grits, corn meal, and other products. The dry miller prefers white endosperm corn with a semihard kernel, moderate indentation, and a white cob. Breeders have developed white corn hybrids with kernel characteristics desired for dry milling. The wet milling process is used to extract starch from the corn kernel for industrial uses, but oil and proteins are recovered as valuable by-products. High kernel weight and resistance to seed molds are important grain quality considerations.

SPECIAL-PURPOSE HYBRIDS

In addition to the development of corn hybrids for the larger use of the livestock feeder and the corn-milling industry, hybrids have been developed for special purposes, such as *sweet corn, popcorn, waxy corn*, or *cob pipe corn*. Sweetcorn hybrids are generally recessive for the endosperm gene sugary (*su*). Sugar content may be increased and period of peak quality extended by presence of the mutant gene, shrunken-2 (sh_2). Sweet corn hybrids with these genes are often referred to as "supersweet" or "extrasweet." Waxy corn contains a special type of endosperm starch, amylopectin, which permits it to be used in the manufacture of adhesives, gums, paper sizing, and puddings. Cob pipe hybrids have large cobs used in the manufacture of corncob pipes.

INTERNATIONAL MAIZE AND WHEAT IMPROVEMENT CENTER

The International Maize and Wheat Improvement Center (CIMMYT) is an international research center dedicated to worldwide improvement of corn and wheat. The objective of CIMMYT's corn program is to assist in the development of national and regional corn improvement programs in tropical and subtropical corn-producing countries where corn is utilized as human food. CIMMYT's activities include the maintenance of a germplasm bank; coordination of international corn testing trials; a research program to develop improved corn populations, inbred lines, and hybrids for distribution to corn research workers in cooperating countries; and sponsorship of workshops and training programs for corn research workers.

STUDY QUESTIONS

1. Why has plant breeding been so successful in the development of improved corn cultivars?
2. What plant breeding methods are used to develop improved cultivars of corn? Can these same breeding methods be used to develop new cultivars of other crop plants? If so, which crop plants?