CHAPTER NINE

Oat

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The cultivated oat (Avena sativa L. and Avena byzantina C. Koch) ranks fifth among cereals in world production. Oats are a cool-season crop, and while they are grown to some extent on every continent, their production is of far greater importance in the cool climates of the northern hemisphere. The Soviet Union, Europe, and the United States are the leading producers of oats, accounting for 80% of the total production (Table 9-1). They are followed in order by Australia and Canada. Specific areas of greatest production are in the north-central U.S., the prairie provinces in Canada, western Russia, countries of northwest Europe, and the British Isles.

In the United States, South Dakota, Minnesota, North Dakota, Wisconsin, and Iowa are the major oat-producing states, accounting for more than 60% of the total U.S. oat grain production. A large area (567,000 ha in 1983) of oats is planted in Texas, but most of it is grazed or harvested for silage. There has been a steady decline in oat production in the United States since about 1965. The average planted area from 1963 to 1967 was 9,853,245 ha, while 8,217,450 ha were planted in 1983.

Most oat grain is used for livestock feed on the farms where grown. Oat straw is a valuable source of bedding for livestock. Oats are often used as a grazing crop or harvested for hay or silage, and they are widely used as a companion crop for underseeded forage legumes in dairy states.

The per-capita human consumption of oats in the United States has remained constant, but because of a decrease in total production, the percentage of the total crop used for human foods increased from 7% in 1975.
Table 9-1 Harvested Area and Production of Oats in Major Oat-Producing Countries in 1983

<table>
<thead>
<tr>
<th>Country or Continent</th>
<th>Harvested Area</th>
<th>Production</th>
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</thead>
<tbody>
<tr>
<td>Soviet Union</td>
<td>12,516,000 ha</td>
<td>16,000,000 t</td>
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<tr>
<td>Europe</td>
<td>4,888,000</td>
<td>12,479,000</td>
</tr>
<tr>
<td>United States</td>
<td>3,682,000</td>
<td>6,928,000</td>
</tr>
<tr>
<td>Australia</td>
<td>1,995,000</td>
<td>2,360,000</td>
</tr>
<tr>
<td>Canada</td>
<td>1,400,000</td>
<td>2,773,000</td>
</tr>
<tr>
<td>South America</td>
<td>651,000</td>
<td>838,000</td>
</tr>
<tr>
<td>Africa</td>
<td>619,000</td>
<td>247,000</td>
</tr>
<tr>
<td>China</td>
<td>450,000</td>
<td>800,000</td>
</tr>
<tr>
<td>Mexico</td>
<td>70,000</td>
<td>70,000</td>
</tr>
<tr>
<td>World</td>
<td>26,588,000</td>
<td>43,101,000</td>
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to 12% in 1984. In 1984, the Soviet Union used 22.5% of its production for human food. On a world-wide basis, 18% was used for human foods. The remainder was used for livestock feed or as seed for planting.

*Avena* has both wild and cultivated species that occur in each of three ploidy levels, but most of the important cultivated oats belong to the hexaploid group. *Avena sativa* L. is by far the most important cultivated species in the United States and in the major oat growing countries of the world. Coffman (1961) estimated that more than 80% of the world production area was devoted to cultivars belonging to this hexaploid species. Cultivars of this species dominate the major oat-growing areas of North America, northern Europe, and Asia. Most *A. sativa* cultivars are spring sown and are grown in the cooler areas of the world.

Cultivars of the cultivated species *Avena byzantina* C. Koch (common red oats) occupy most of the remaining oat area. The differences between *A. sativa* and *A. byzantina* seem to be minor, and Baum (1977) classified both as *A. sativa*. Most *A. byzantina* cultivars are fall-seeded winter oats. Winter oats are grown to some extent in most major oat-producing countries, but probably more than half of the total winter oat production is in the United States. Winter oats are not as winter hardy as other winter cereals, so their production is restricted to areas where the winters are mild or where snow cover protects the plants when very low temperatures prevail. In the United States, the northern limits of successful winter oat production are roughly marked by the states of Maryland, Virginia, Kentucky, Arkansas, and Oklahoma. Fall-sown winter oats are an important source of pasture for grazing in the southwest United States.

Cultivars of the cultivated species *Avena nuda* L., commonly known
as hull-less or naked oats, have been grown in small amounts from time to time in the United States, and the species is reported to be grown extensively in some areas of China. *A. nuda* is very distinct and unlike any other cultivated species because the kernels are loose within the enclosing lemmas and paleas (hulls). When threshed, the kernels separate from the hulls, in the same manner as wheat kernels. Also, rachillas connecting the several florets within each spikelet of *A. nuda* are much longer than in other species, giving spikelets an extended, droopy appearance. Although workers in the United Kingdom and Canada have been devoting time and effort to the improvement of hull-less oats for several years, only recently has there been renewed interest in the United States. Canadian workers have recently released the hull-less cultivar 'Terra' (McKenzie et al., 1981).

All the important cultivated species of oats are hexaploids. Oat breeders commonly make crosses among the several species; therefore, the resulting cultivars often have characteristics of several species. Except for the hull-less types, cultivars may be difficult to classify as to species.

Temperature is the most important environmental factor determining the types of cultivars grown in specific production areas. Consequently, winter oats are the predominant type in areas with mild winters, early-maturity spring oats are grown in areas just north of the winter-oat area, and midseason to late-maturing cultivars predominate in the cooler, temperate zones.

The oat plant is basically a cool-season plant, and the areas of greatest oat production are in the cooler temperate zones. Oats are especially sensitive to warm temperatures at anthesis and during the grain-filling period. High temperatures during these periods will cause sterility, poor grain filling, and reduced yields. Early-maturing cultivars are grown in the warmer climates because they will often complete grain filling before the very hot summer temperatures occur.

The market classes and grade standards for oats are specified in *The Official United States Standards for Grain*, published by the U.S. Department of Agriculture (USDA). Based on these standards, oats are divided into five market classes according to the color of the hulls that surround the grain: white, gray, red, black, and mixed. While there are individual preferences for certain color classes for specific purposes, there seems to be no scientific evidence to suggest that hull color has any effect on nutritional quality of oats for human consumption or for livestock feed. It is interesting to note that white oats are favored for horse feed in the United States, while black oats are favored for the same purpose in some other parts of the world.

Each color class of oats is divided into five grades based on factors
such as test weight, sound oats, heat-damaged kernels, and foreign material. For example, U.S. No. 2 White Oats must have a minimum of 32 lb per bushel (411.8 kg/m³) test weight and 94% sound kernels, and a maximum of 0.3% heat-damaged kernels and 3% foreign material. Hull color and test weight are highly heritable characters that are relatively easy to select for by conventional oat breeding techniques.

TYPES OF CULTIVARS

Mode of Propagation

The cultivated and wild species of oats are annual, self-pollinating grasses. Outcrossing seldom exceeds 0.5%. Bonnet (1961) provided an excellent description of the development, morphology, and histology of the oat plant. According to him, the major morphological characteristics of oats are typical of grasses. The oat stem is composed of a series of nodes and internodes with alternate leaves. The stem usually contains four to seven elongated internodes and the uppermost internode (peduncle) is often as long as the combined length of all other internodes.

Each mature stem terminates in a loose, open panicle (Fig. 9-1). The main axis of the panicle terminates in a single spikelet. Alternate groups of branches arise from the main axis and each branch terminates in a single spikelet. The number of spikelets per panicle normally ranges from 25 to 45 depending on genotype and growing conditions.

Bonnet (1961) divided the life cycle of the oat plant from germination to mature seed into four stages: vegetative, transition, reproductive, and seed. The initiation and duration of each stage is influenced by genotype and the environment. The reproductive stage is highly responsive to photoperiod, and oats are normally considered a long-day plant. The reproductive stage is significantly delayed when day length is less than 15 to 16 hours. Nicholls (1974) reported that 54 10-hour days were required from germination to floral initiation, while only 13.5 16-hour days were required. The duration of each stage is influenced by temperature, with higher temperatures causing a shorter duration of each stage.

Although oats are generally considered sensitive to photoperiod, Burrows (1985) has worked extensively with oat genotypes that are mostly insensitive to photoperiod. He used this characteristic to develop ‘Donald,’ a day-length-insensitive cultivar.

Each oat spikelet usually contains from one to three florets enclosed in two empty glumes, with the tip of one glume extending slightly above the other (Fig. 9-2). Usually only the two basal florets are fertile, but occasionally three or more are fertile.

Each oat flower is perfect and has three stamens, a pistil, and two
lodicules. The flower is enclosed by two bracts, the lemma and palea, which are referred to as hulls on the harvested oat grain. The lodicules swell, causing the flowers to open during anthesis. Under field conditions, natural anthesis usually occurs in the afternoon, but the exact time varies with geographic location and environmental conditions. Temperature variation seems to be a major factor determining the time of day of natural anthesis. On most days, anthesis occurs in the afternoon when the temperature has reached its maximum for the day and has begun to decline. Anthesis occurs in oat florets in the order that they emerge from the sheath. Completion of anthesis for a single large panicle may require up to 8 or 9 days. Anthers of an individual floret normally shed pollen just before and during flower opening, which helps ensure natural self-fertilization.
Figure 9-2  Side view of oat spikelet showing dorsal (shorter, overlapping) glume, primary floret, secondary floret, and ventral (longer, underlapping) glume. (From Hybridization of Crop Plants, p. 431, by permission of the Crop Science Society of America and American Society of Agronomy.)

Past and Present Cultivar Types

Oats are not native to North America. Therefore, all cultivars grown on this continent during the early years were introduced from other countries. Some important cultivars introduced and extensively grown in the United States were 'Red Rustproof' in 1797, 'White Russian' in 1850, 'Silvermine' in 1895, and 'Kherson' in 1896. Many of these introductions were heterogeneous mixtures of homozygous genotypes. The early breeders practiced mass selection with self-pollination and, later, pedigree selection in these mixed populations to isolate the highest-yielding and best-adapted individual genotypes. 'Burt,' 'Fulghum,' and 'Albion' are examples of important cultivars selected by this procedure.

The cultivar 'Red Rustproof' provides an excellent example of the tremendous variability that existed in some of the early introductions. F. A. Coffman (1961) observed many fields of unselected 'Red Rustproof' throughout the southern United States in 1926 and noted extensive diversity in plant characters, kernels, colors, and types. He observed
that "plants in the fields looked more like bulked hybrid populations than like plants of any specific variety." Stanton (1955) estimated that more than 100 cultivars had been derived from 'Red Rustproof' and grown commercially in North America and other parts of the world.

Most traditional oat-breeding procedures have developed around the concept of pure-line breeding. Most modern oat cultivars are highly homozygous and very uniform in appearance. Current seed-certification and plant variety protection regulations also demand a high level of uniformity within each cultivar.

A notable exception to traditional cultivar homogeneity has been the development of multiline cultivars to combat crown rust in oats. This procedure involves the backcross development of isolines that are genetically similar, except for genes controlling crown rust resistance. The isolines, each with a different gene for resistance, are composited to form the multiline cultivar.

EXTENT AND NATURE OF BREEDING PROGRAMS

Most cultivar development of oats is centered in public breeding programs. Based on economics, use, and market patterns, it seems unlikely that private companies will become heavily involved in oat breeding. Therefore, continued availability of improved oat cultivars will depend almost entirely on the amount of resources that public agencies devote to oat breeding. Only a few moderately large and complete public programs exist at present, and any significant decline in number or scope of existing programs is sure to have a major detrimental impact on the future development of improved oat cultivars.

The only active private oat breeding program in the United States is conducted by CR Seeds, formerly Coker's Pedigree Seed Co., at Harts-ville, South Carolina. Since about 1910, Coker's has had a long and distinguished record of producing excellent winter oat cultivars for production in the southern part of the United States. There are also a few private oat breeding programs in Canada and Europe, but their total impact is small compared with that of the public sector.

While only a few private companies breed oats, several companies and private organizations provide significant financial support to public oat-breeding programs. Included among these are the various state crop improvement associations, foundation seed associations, and the Quaker Oats Company. Quaker Oats provides significant funding for 14 public oat-breeding programs in the United States and Canada.

In the United States, approximately 20 state agencies conduct oat breeding programs, many of which are joint efforts with U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS). Some of
the programs are rather small with only a part-time oat breeder who also breeds other crops or who has other responsibilities. Fortunately, several of the major oat-producing states, including Iowa, Minnesota, North Dakota, South Dakota, Wisconsin, and Texas have large and productive oat breeding programs.

Most oat breeding in other major oat producing countries, including Australia, Canada, Europe, and the Soviet Union, is conducted by public agencies. In Canada, provincial, federal, and university scientists breed oats. The program at Ottawa, Ontario and Winnipeg, Manitoba are examples of excellent Canadian public oat breeding programs.

**BREEDING OBJECTIVES FOR CULTIVAR DEVELOPMENT**

Improvements in agronomic traits, disease resistance, and grain quality command major attention in oat breeding programs. Grain yield, straw strength, and resistance to leaf (crown) rust (Puccinia coronata Cda. var. avenae Fraser and Led.), stem rust (P. graminis Pers. f. sp. avenae Eriks. and E. Henn), loose smut [Ustilago avenae (Pers.) Rostr.], leaf and stem Septoria (Septoria avenae Frank), and to the barley yellow dwarf virus (red leaf virus) remain as top-priority concerns in most programs, as they have for many decades. Traditionally, oat grain quality has been reflected by two physical parameters, test weight (weight per unit volume) and groat percentage. Oat breeders continue to strive for high test weight (heavy) oats with high groat (low hull) percentage. In the mid-1960s, the report of unusually high groat protein concentrations in Avena sterilis L. (USDA, 1967; Murphy et al., 1968), of 23 to 30% compared with 14 to 18% in common cultivars sparked efforts to improve the nutritive and energy levels of oats. For convenience, this broad array of important traits are partitioned into morphological, physiological, and biochemical categories for more detailed consideration.

**Morphological Traits**

*Grain Yield.* The primary yield components of oats are number of panicle-producing tillers per unit area, number of florets (seeds) per panicle, and seed size (weight). Oats, like other cereals and grasses, have the desirable capability of compensation among the three yield components. For example, smaller seeds often are produced on panicles that have a large number of florets. Thus, breeders must pay attention to all three traits as they select genotypes for use as parents in hybridization schemes. Most modern oat cultivars have the genetic capability of
producing more than 3600 kg/ha of grain. High-yield levels require quality seed, proper production practices, adequate soil moisture, and the absence of severe disease infection.

Straw Strength. Straw strength is a very important morphological trait. The ability to resist lodging helps to ensure good grain filling, high test weight, minimal harvest loss, and minimal damage to underseeded legumes. In most cases, straw strength must be dealt with as a quantitative trait, although stiffness associated with the dwarf genes in ‘Scotland Club’ and ‘Milford’ (Patterson et al., 1963, 1964), gene Dw-6 in Canadian dwarf OT207 (Brown et al., 1980), and gene Dw-7 in North Carolina dwarf NC 2469-3 (Marshall and Murphy, 1981) follows a more discrete inheritance pattern.

Breeders may encounter two problems associated with straw strength improvement. First, the partitioning of photosynthate into the structural plant versus the grain often leads to stiff-strawed genotypes which are low yielding, or high-yielding genotypes which are weak-strawed. Secondly, stiff-strawed genotypes may not be sufficiently resilient to withstand winds when the soil becomes saturated during heavy rain storms. These climatic stresses cause stiff plants to tip over because the upper root mass and surrounding soil lose anchorage.

Straw Yield. High straw yields are desirable in those regions where an animal or dairy economy results in high market value for straw. Oat straw yields commonly range between 3300 and 5000 kg/ha, and are influenced by genotype, location, vegetative vigor, and cutting height. Although semidwarf oats generally produce lower straw yields, they still are worthy of consideration, if additional nitrogen fertilization results in economical increases in grain and straw production.

Test Weight and Groat Percentage. These two physical traits usually are highly correlated, and selection for high levels results in selection against large, hully kernels. Test weights of cleaned samples of modern oat cultivars usually range from 36 to 40 lb per bushel (463 to 515 kg/m³). Groat percentages of 68 to 72% are common. Although F₂ populations show a continuous or quantitative distribution for test weight, heritability is high (0.62 to 0.97) (Pawlisch and Shands, 1962; Wesenberg and Shands, 1973). Heritability values for groat (caryopsis) percentage range from intermediate to high (0.34 to 0.93) (Wesenberg and Shands, 1971 and 1973; Stuthman and Granger, 1977). Lower heritability estimates are obtained from crosses between parents with similar groat percentages. In some cases, hull percentage may be controlled by relatively few genes which become fixed as early as F₂, resulting in high heritability estimates.
Physiological Traits

*Physiological Processes.* Much effort has been expended in studies of physiological processes in the oat plant that may contribute to biological yield. Photosynthetic rate, photosynthetic capacity, growth rate, photosynthetic source-sink relationships, nitrogen assimilation, leaf area, leaf area duration, leaf senescence, and mineral uptake, transport, and deposition are examples of processes that have received attention in recent years (Youngs et al., 1982). Several workers have suggested that a greater vegetative growth rate may be a more realistic means of increasing biomass production than lengthening growth duration (Takeda and Frey, 1976, 1977; Takeda et al., 1979; Helsel and Frey, 1983; Helsel and Skrdla, 1983; Johnson et al., 1983). McKee et al. (1979) concluded that it may be easier to increase rate of grain fill by altering cultural factors and selecting appropriate genotypes to increase leaf area index and leaf area duration than to drastically lengthen the mean fill period. To date, physiological research of this type has been exploratory, and useful screening techniques remain to be discovered. New knowledge about physiological processes within the oat plant ultimately should have practical value if the breeder is to utilize this new information to select parents for crossing.

*Disease Resistance.* Breeding for disease resistance commands major attention in nearly all oat improvement programs. Leaf and stem rust, smut, and Septoria are caused by fungi; while barley yellow dwarf and soilborne mosaic are caused by viruses. Breeding for resistance often is complicated by the continual development and spread of physiological races and biotypes of the casual organisms. Leaf and stem rust are heterocyclic fungi, and recombination leading to new races occurs on an alternate host, *Rhamnus cathartica* (buckthorn) for leaf rust and *Berberis* spp. (barberry) for stem rust. In the major oat-growing regions in north-central United States and in central Canada, the source of infectious spores may be either aeciospores from the alternate host oruredospores windblown from earlier-planted, more southerly oat crops. While single-gene resistance to specific races has nearly always been found, the value and use of multigenic sources of generalized or specific resistance is universally recognized.

The barley yellow dwarf virus, spread by aphids, has increased in prevalence and severity during the past 30 years to the point that it is now the most destructive disease affecting oats in the United States. Breeding for this quantitatively inherited trait is an arduous task involving infestation of breeding lines with artificially raised aphids that contain the virus.
Protein

Protein concentration in mature oat groats is inextricably linked with soil nitrogen (N) availability and uptake, N transport and assimilation in the vegetative structures, direct N transport and remobilization from plant structures into developing seeds, carbohydrate deposition in developing endosperms, and the number and size of seeds per unit area. These complex relationships may cause a wide range in protein percentages for the same genotype grown in different parts of the same field, in different fields, in different regions of the same state, in different states or countries, or in different years. Thus, it is important that cause-effect relationships be considered when genotypes are being evaluated. For example, the deposition of available N into the relatively fewer available kernels of a lower-yielding genotype usually results in a higher groat protein percentage. This was confirmed experimentally by Peterson (1983) who found that kernel and straw N concentrations were increased by artificially removing different percentages of the spikelets shortly after heading. Also, oat kernels from a long, thin-kerneled genotype typical of wild oat species may have high groat protein percentages, but the high protein percentage actually results from low carbohydrate deposition in the kernels (Rines et al., 1980). It is not surprising that increased grain yield often is associated with lower protein concentration because of the distribution of available N into more kernels.

The initial breeding and selection efforts begun in 1965 and 1966 have resulted in the development and release of several agronomically competitive, high-protein oat cultivars, including 'Dal' (Wisconsin, 1972), 'Otee' (Illinois, 1973), 'Goodland' (Wisconsin, 1974), 'Spear' (South Dakota, 1974), 'Preston' (Minnesota, 1982), and 'Proat' (Minnesota, 1985). Depending upon N fertility level and other environmental factors, these cultivars generally have a groat protein concentration range of 17 to 21% compared with 14 to 18% for most other cultivars. At this time, the economic benefits to the producer of high protein oats are less than value gained due to high yields of high test-weight grain. Thus, in most breeding programs, protein ranks lower in priority than key agronomic and disease traits.

Takeda and Frey (1979) summarized estimates of heritability for oat protein percentages obtained by other workers using different populations and different methods of calculation. Heritability values ranged from 15 to 89% with a mean of 46%. Takeda and Frey (1979) obtained estimates of 39% for protein percentage and 45% for protein yield. They pointed
out that these intermediate heritability values suggest that genetic gain from selection for increased protein should be easy to accomplish. It is our experience that these expectations tend to hold only when one selects for protein percentage and ignores grain yield. Takeda and Frey (1979) found that protein percentage was negatively associated with grain yield and that protein percentage had little effect on protein yield per unit area. Grain yield was the primary determinant of variation in protein yield, a result identical to that reported by Clamot (1978). Takeda and Frey (1979) suggested using a selection index that would provide simultaneous selection in appropriate proportion for both grain yield and protein percentage in order to improve protein yield, and this is now done either rigorously or informally by many oat breeders.

Lipids and Fatty Acids. Levels of oil concentration in current oat cultivars range from 4 to 9%, with an upper level of 11.6% identified in certain breeding stocks (Brown and Craddock, 1972; Luby and Stuthman, 1983). If oil concentration could be increased while high protein concentration and high grain yields were maintained, the nutritive value of oat grain would increase and oats would become a more useful human food and animal feed.

In contrast to the extreme variation among environments for protein concentration, Youngs and Forsberg (1979) found genotypic stability for oil percentages over a wide range of environments. Closely related is the conclusion reached by Lindberg et al. (1964) and de la Roche et al. (1971) that environment does not affect fatty acid composition in oats. The minimal environmental influence and high heritability of oil concentration indicate that selection for either high or low oil can be accomplished without excessive nongenetic influences (Baker and McKenzie, 1972; Brown and Craddock, 1972; Brown et al., 1974; Frey et al., 1975).

Changes in oil concentration are likely to be accompanied by changes in fatty acid composition. Fatty acid composition influences the storage qualities and the culinary commercial utility of an oil (Downey and McGregor, 1975). Therefore, changes in oat oil composition have to be monitored if oil levels are raised. Broad-sense heritability estimates have been high for palmitic (0.63 to 0.91), oleic (0.66 to 0.99), and linoleic (0.64 to 0.96) acids (Youngs and Puskulcu, 1976; Thro, 1982; Thro et al., 1983; Karow and Forsberg, 1984, 1985). At present, most oat breeders screen their advanced breeding selections for oil percentage, but not for fatty acid composition. Only a few breeders are consciously trying to raise oil percentage.

Amino Acids and Other Nutritionally Related Traits. Among the cereal grains, oat protein has the highest biological value (Frey, 1973). Breeders can raise oat protein percentage without fear of altering the highly desir-
able amino acid balance that exists in oats (Peterson, 1976). This is possible because the globulin fraction, whose amino acid composition is similar to that of the total protein, increases more than the prolamin and albumin fractions with increases in total protein. Raising the level of lysine, threonine, and/or methionine would enhance the nutritive value of oats, but the potential for such increases is limited by the fact that there is only minimal variability for amino acid composition among species, genotypes, or environments (Robbins et al., 1971; Briggle et al., 1975; Peterson, 1976; Rines et al., 1980). Quantitative investigations of genetic variability and associated nutritional value for starch quality, fiber level, mineral and vitamin content, and enzyme level and activity are now being considered, but breeding programs to improve these traits have not been initiated.

STEPS IN CULTIVAR DEVELOPMENT

Modern oat breeding programs rely almost entirely on hybridization to create populations of genotypes for the development of new cultivars. Therefore, the basic steps in oat cultivar development are:

1. Selection of parents
2. Hybridizations among selected parents
3. Inbreeding and selection among progenies
4. Replicated testing
5. Multiplication and maintenance of seed of new cultivars

Selection of Parents

Selection of parents is the first and one of the most important steps in a successful oat breeding program. The parents selected will depend on the objectives of the program and the availability of genotypes to meet the specific objectives. Crossing two breeding stocks with complementary traits is a common practice.

Hybridization Among Selected Parents

This is an important and necessary step in any oat breeding program. Induced or chance mutations rarely produce a population of genotypes that leads directly to a new cultivar. In most cases, mutant genotypes need to be hybridized with other parents before a successful cultivar is developed. The purpose of hybridization is to create a population of genotypes from which improved cultivars can be selected. This is usually done by making hybrids between selected homozygous parents.
Inbreeding and Selection Among Progenies

The breeder has available a large number of genotypes from which to select in a segregating population. Selection may begin as early as the F₁ generation, or may be delayed until later generations when homozygous genotypes are available. Selection in early generations is usually limited to easily identified traits, such as disease resistance and certain morphological traits. In each segregating generation, naturally self-pollinated seed from selected panicles or plants is used to plant the next generation. Artificially induced disease epiphytotics or insect infestations in field nurseries or in the greenhouse are essential screening techniques. This procedure is continued for several generations after which seed from individual homozygous panicles, plants, or progeny rows is increased for evaluation in replicated performance trials.

Oat breeders in the northern United States and in Canada have used winter nurseries in Australia, Mexico, Puerto Rico, or Arizona (U.S.) to advantage. These nurseries are used to gain an extra generation between field seasons for breeding materials of or for preliminary seed increase of a genotype scheduled for future release. The breeding materials can be handled either as bulk populations or as individual pure lines.

Replicated Performance Testing

In preliminary and advanced performance trials, careful attention is directed to evaluation of quantitative characters that often have low heritability and high environmental effects, such as yielding ability and lodging resistance. Such performance trial evaluations must be conducted for several years in several different environments before an informed decision can be made. Any test selection that performs well in these trials and that is superior to existing cultivars is a candidate for release as a new cultivar.

Multiplication and Maintenance of Seed of New Cultivars

Any successful oat breeding program must include a procedure to provide an adequate supply of high quality, genetically pure seed to farmers. The oat breeder usually supervises the initial multiplication of seed of the new cultivar. Multiplication often begins while the potential cultivar is still in the advanced stages of performance evaluations. This initial volume of seed provided by the breeder (breeder seed) is further increased, usually by a foundation seed organization or some other public or
private agency. The initial supply of seed is sold to seed dealers who
make a further increase for sale to farmers for on-farm planting.

During all stages of multiplication, careful attention must be given to
maintenance of genetic and mechanical purity. Proper field isolation
must be provided so that outcrossing with other cultivars is held to a
minimum. Mechanical mixtures that can occur during harvesting and
processing of seed must be avoided.

**SOURCES OF GENETIC VARIABILITY**

**Sources of Germplasm**

A great diversity of oat germplasm is available for use by oat breeders.
Seeds of released germplasm lines or cultivars generally are maintained
by the originating station, and stocks are furnished on request. Much in-
formal exchange of experimental germplasm also takes place among oat
breeders (Forsberg and Smith, 1980). National and international perform-
ance and disease nurseries are important vehicles for mutual examina-
and exchange of germplasm. The USDA Uniform Early and Midseason
Oat Performance Nurseries, the Eastern and Western Co-operative Oat
Tests of Canada, and the USDA International Oat Rust Nursery are ex-
amples. National collections, such as the USDA oat collection in the
Germlasm Resources Laboratory, USDA-ARS, Beltsville, Maryland,
and the Canadian oat collection maintained by Plant Gene Resources of
Canada, Ottawa, Ontario, are extremely valuable sources of germplasm.

In the United States, seed or plant materials from another country
must be introduced through the Plant Germplasm Quarantine Station,
Beltsville, Maryland, before they can be included in the National Plant
Germplasm System. Oats are evaluated in a nursery at Mesa, Arizona,
where the plants are observed for seedborne diseases. Individual states or
provinces sometimes have rules and regulations governing the shipment
or introduction of seeds or plant material. Scientists should take special
precautions as they exchange plant and seed materials directly with their
colleagues in other countries to avoid the spread of seedborne diseases.

**Types of Parents and Populations**

Types of parents and populations used in hybridization are inextricably
linked to the specific breeding procedure being followed. Conventional
crosses are made most often between two homozygous and homogeneous
pure-line parents. It must be realized that modern-day oat cultivars
represent elite combinations of genes, and progenies from crosses between cultivars or other adapted breeding stocks and a line lacking in even one trait may not measure up to commercial standards. Backcrossing is usually accomplished by crossing the recurrent parent onto heterozygous, homogeneous F₁ plants or onto heterogeneous F₂ populations. Populations perpetuated generation after generation by bulk harvest procedures can be used as sources of parental material and breeding stocks.

Intercrossing among F₁ or F₂ plants may help to break linkage blocks and foster more desirable combinations of genes (Jensen, 1970; 1978). This method of developing populations is best suited to traits such as straw strength or disease resistance where the performance of potential parent plants can be determined before anthesis. For traits such as grain yield or groat protein, crosses would have to be made at random.

Gene transfer between species in different ploidy levels requires special techniques and extra effort. The use of bridging types, such as derived tetraploids or 6x amphiploids, has facilitated transfer of genes from diploids and tetraploids to hexaploids (Sharma and Forsberg, 1977; Brown, 1984).

Attempts to use chemical mutagens to create useful mutations have not been successful in oats. Irradiation with thermal neutrons or gamma rays has played a role in gene transfer (Sharma and Forsberg, 1977; Brown, 1984) and in the occurrence of dwarf gene Dw-6.

Population Development by Hybridization

Procedures for Artificial Hybridization. The detailed procedures for artificial hybridization of oats have been described by Brown (1980), and only a brief account is presented here. Oat crosses can be made in the field, greenhouse, or growth chamber. Environmental conditions that provide optimum conditions for plant growth and development provide optimum plants for crossing. Conditions that are ideal for growth and development are also favorable for disease and insect development, so it is sometimes necessary to use fungicides and insecticides to protect susceptible parents that are to be used for crossing. Field-grown plants may need to be protected from birds and animals.

Optimum conditions for greenhouse and growth chamber crossing are similar to those for field crossing. Most oat crosses in the greenhouse are made in the winter when it is easier to maintain the cooler temperatures, that are needed for best results. Fertility, moisture, light, and temperature, should be controlled to provide vigorous, healthy plants. Supplemental lighting is essential to extend the photoperiod and increase light intensity. For example, in the greenhouse at Urbana, Illinois, during the winter, excellent crossing results have been obtained using metal halide lights with a 12- to 13-hour photoperiod. The lights are often left on dur-
ing the entire day, especially on cloudy days. Temperature is maintained at 25 to 30°C during the day and 20 to 25°C during the night.

Plants for greenhouse crossing can be grown in pots, in soil beds, or by using any method that provides healthy plants. Some oat breeders prefer growing plants in pots so that they can be moved about for convenience when crossing.

The equipment needed for oat crosses consists of small sharp-pointed scissors, forceps, glassine bags, paper clips or staples, and small tags (Fig. 9-3). Suitable forceps are the most important and necessary item of equipment. Some breeders use sharp-pointed forceps with curved ends, but others prefer straight ends. The tips of the forceps are sometimes rounded and filed to a more or less flat edge to minimize damage to the florets.

Glassine bags, used to protect the emasculated florets from outcrossing, can be of various sizes depending to a great extent on the preference of the breeder. Some breeders use a bag that is just wide enough to cover the emasculated florets and long enough to be secured to the culm just below the emasculated florets.

The optimum time to emasculate oat florets is when the anthers have obtained full size, but are not yet ready to dehisce. Natural anthesis of in-

**Figure 9-3** Equipment for making oat hybridizations: tag and paper clip, various sizes of glassine bags, forceps, and scissors. (From Hybridization of Crop Plants, p. 432, by permission of the Crop Science Society of America and American Society of Agronomy.)
individual florets begins in the uppermost florets of the panicle and proceeds in the order of their emergence from the boot. Anthesis will usually occur in individual florets within 1 to 3 days after emergence from the boot. Knowing the order of emergence and being able to predict the relative maturity of the anthers will help the breeder select the proper florets for emasculation.

Emasculation can begin at any place on the panicle, but most often the florets near the top are emasculated. Five to eight primary florets usually are emasculated on each panicle, although more can be emasculated on large panicles, when florets near the center of the panicle are used, or when both primary and secondary florets are used. Although the more mature florets are easier to emasculate, their anthers are more likely to shed pollen and cause accidental selfing during the emasculation process. Florets can be emasculated at any time of day, except during natural anthesis. Most breeders emasculate in the morning to avoid the period of natural anthesis which normally occurs in the afternoon.

The incidence of accidental selfings during emasculation increases as the time for natural anthesis approaches; however, some breeders successfully emasculate and pollinate florets simultaneously. When this is done, emasculations must be made very near the period of natural anthesis to have receptive stigmas and usable pollen, and only three to five florets can be used on each panicle. While this method works well for experienced breeders, it should not be used by inexperienced workers or for purposes where an occasional self cannot be tolerated or detected.

Through practice and experience, each breeder develops an individual technique for manipulation of floral parts during emasculation. The outer glumes are separated with forceps and the secondary floret is removed by snipping or breaking the rachilla with the forceps. The palea is separated from the lemma by inserting the tip of one prong of the forceps between the lemma and palea and pulling forward on the palea. This exposes the three anthers (Fig. 9-4) which are extracted with the forceps, using care to avoid breaking any near-ripe anthers and to avoid damage to the two stigma branches.

Emasculated florets are covered with a glassine bag to exclude unwanted pollen. The bag should be just wide enough to cover the emasculated florets and long enough to be folded and secured with a paper clip or staple (Fig. 9-5). When making field crosses, panicles are sometimes supported by a stake, but this is usually not necessary when a small bag is used.

Clear days with moderate to low temperatures are ideal for gathering functional pollen and making successful pollinations. Most breeders consider the optimum time between emasculation and pollination to be 1 to 3 days; however, some breeders report excellent results from pollinations made in the afternoon following morning emasculation on the same day. When pollinations are made on the same day as emasculation, extreme
Figure 9-4  Floret opened for emasculation. Note position of fingers on one hand holding spikelet and the other holding forceps. The lemma and palea have been separated and the palea is held between the forefinger and thumb. (From Hybridization of Crop Plants, p. 435, by permission of the Crop Science Society of America and American Society of Agronomy.)

care must be used to prevent natural selfs. Selfing can be reduced to a minimum by emasculating 1 or more days before natural anthesis and permitting 2 to 3 days between emasculation and pollination. The seed set percentage following crossing usually will be reduced if more than 3 days elapse between emasculation and pollination. When many florets are emasculated on one panicle, it is sometimes desirable to pollinate them over a period of 2 or 3 days due to differences in maturity of the individual florets and receptivity of the females.

Oat pollinations are usually made in the afternoon, but the best time will vary from day to day. The optimum period for pollination will usually begin 1 to 2 hours before natural anthesis and will extend until natural anthesis occurs. Even the most experienced breeder must determine the best period each day through trial and error by examining anthers in the most mature florets in which anthesis has not yet occurred. Anthers suitable for making pollinations will be yellow and plump, and should split and dehisce pollen within 1 minute when removed from the floret and placed on the hand.

When making pollinations, the lemma and palea of each emasculated floret are separated as for emasculation. A mature anther held between
the prongs of the forceps is gently tapped against the inside wall of the lemma to make sure that pollen is released from the anther and deposited on the stigma hairs. When all emasculated florets have been pollinated, the glassine bag is replaced to prevent outcrossing. An experienced hybridist working under near-optimum conditions should expect at least 25% seed set in the field and 50% in the greenhouse.

The approach method is an alternative method for making pollinations in oats. The method was first described by Rosenquist (1927) and later refined for oats by Curtis and Croy (1958) and MacDaniel et al. (1967). These workers found that approach crossing had several important advantages over the more conventional method: (a) crosses can be prepared any time of day; (b) more florets can be pollinated on each individual panicle; (c) even very young florets can be emasculated because the male parent sheds pollen over several days, providing pollen when stigmas become receptive; (d) more than one cross can be made under the same

Figure 9-5  Emasculated florets bagged to exclude outside pollen. (From Hybridization of Crop Plants, p. 436, by permission of the Crop Science Society of America and American Society of Agronomy.)
bag by bagging panicles of the same male with several different emasculated females; (e) labor is reduced because it is not necessary to return to florets to apply pollen; and (f) seed set percentage is higher.

With the approach method, the primary floret is emasculated and the secondary floret is removed, after which the upper portion of each spikelet is removed by clipping straight across the outer glumes, lemma, and palea, just above the stigma (Fig. 9-6). Panicles of the male and female parents are enclosed under the same bag so that the lowest spikelet on the male parent is just above the upper spikelet on the female parent (Fig. 9-7). In the greenhouse, pots containing the male and female parents are placed next to each other, and blocks, or other devices can be placed under pots to adjust the height of panicles to the desired level.

Approach crossing also can be used for field crosses or to cross greenhouse-grown plants with field-grown plants. Culms in the appropri-

Figure 9-6 Spikelets clipped in preparation for approach crossing. (From Hybridization of Crop Plants, p. 439, by permission of the Crop Science Society of America and American Society of Agronomy.)
Figure 9-7 Female and male parents bagged together for approach crossing. Note the position of the florets of the male parent above those of the clipped female parent. ( Courtesy of M. D. McDaniel, Texas A&M Univ., College Station).

ate stage for use as male parents are cut from a plant and placed in test tubes of water attached to stakes. The male panicles are positioned just above the female, and a bag is placed over both the male and female panicles. (Fig. 9-7).

Procedures for Natural Hybridization. To date, there has not been a published report of a reliable and efficient way of producing natural hybrids in oats. A cytoplasmic male-sterile restorer system has not been
found. Although several cases of varying degrees of male sterility have been attributed to genetic causes, no allele has been found that provides suitable genetic male sterility for making natural hybrids in a breeding program. Lafever and Patterson (1964) used a male-sterile nullisomic as the female parent to produce a fertile F₁ monosomic, but they obtained only 11.7% seed set following natural cross-pollination by this method.

Several attempts have been made to use pollen control chemicals for making natural hybrids, but so far the results have not been encouraging. McDaniel (1985) has experimented with two chemical gametocides developed primarily for wheat. Both chemicals seemed to prevent natural selfing in oats, but when pollen was supplied by adjacent untreated males, hybrid seed set was very low. McDaniel suggested that the oat flowers of the chemically treated female plants may not open adequately to receive pollen from the male parent.

**BREEDING PROCEDURES**

Oat-breeding procedures used world-wide can be grouped into three general categories: introduction, selection, and hybridization followed by selection. In the United States before about 1930, all oat cultivars originated from direct introductions or by selections from those introductions. In early oat-breeding programs, the first step was to introduce and evaluate available cultivars from other countries, identify the highest yielding and best adapted, and increase and make them available to farmers. Many of the early introductions were mixtures of numerous genotypes, so breeders first used mass selection and later pedigree selection to isolate the highest-yielding and best-adapted genotypes from among the mixtures.

Although a number of different breeding procedures currently are used by individual breeders, a feature common to almost all of them is hybridization. Although successful hybridization of oats was reported as early as 1870, it was not until the 1930s that hybridization was widely used by oat breeders to develop segregating populations, followed by some type of selection to produce improved cultivars (Poehlman, 1979). Therefore, one of the oat breeder’s most important activities is the selection of superior parents to be used in the hybridization program. Parental selection will depend on the objectives of the program and on the availability of germplasm for meeting the objectives. Because of limitations of time and other resources, the oat breeder can use only a very small part of the total available parental material. The ultimate success of the breeding program will depend in large part on the ability of the breeder to select those parents that complement each other and whose progenies likely will be superior. Following hybridization, the most commonly used breeding procedures include backcrossing, pedigree selec-
Backcrossing

Backcrossing is a form of hybridization that is used to transfer a few genes controlling a simply inherited character to an otherwise desirable cultivar or genotype. The desirable cultivar, which should contain a preponderance of genes for desirable traits, is used as the recurrent parent, and the parent that contributes the simply inherited characteristic is the nonrecurrent or donor parent.

In backcrossing, the F₁ of the hybrid between the two parents is crossed back to the recurrent parent. After each backcross, only those plants containing the desired characteristic from the nonrecurrent parent are crossed back to the recurrent parent. The genes from the nonrecurrent parent are reduced by one-half with each successive backcross; thus most of the genetic contribution of the recurrent parent is rapidly recovered. Usually four to six backcrosses are considered sufficient to recover the prototype of the recurrent parent.

The backcross method has been used to transfer single genes for disease resistance from unadapted to adapted cultivars. For example, at the Purdue Agricultural Experiment Station, backcrossing was used to transfer specific genes for crown rust resistance that led to the development of several important cultivars including 'Clintland,' 'Clintland 60,' and 'Clintland 64.'

While backcrossing is an efficient, predictable, and rapid method of dealing with simply inherited characters, it does not provide an efficient means of improving characteristics that are under polygenic control. Unfortunately, many of the most important oat traits, including yield, lodging resistance, and grain quality are controlled polygenically and, therefore, are not very well adapted to the backcross procedure of breeding. Another drawback is that the upper limits of progeny performance are, for the most part, restricted to those of the recurrent parent. Advances due to genetic recombination are minimal or absent.

Pedigree Selection

Pedigree selection is the most commonly used oat breeding procedure. In this method, selection begins in the F₂ generation. Progenies from selected F₂ plants and later selfing generations are grown and selected until homozygosity is reached. This usually requires five to seven generations before individual lines are increased for yield testing. In the pedigree method, the breeder makes the appropriate cross and grows and harvests
seed from the F₁ population, which in turn is used to plant the F₂ population. Usually the individual seeds from F₁ plants are planted 5 to 7.5 cm apart in rows 30 cm wide to facilitate selection. The size of the F₂ population will vary depending upon the availability of seed, genetic differences between parents, objectives of the program, and the resources available for evaluating and making selections of individual plants. Usually several hundred individual plants or individual panicles are selected from each cross. The seeds from each of the plants are visually examined and usually 25 to 50 are selected. F₃ progeny of each selected F₂ plant are grown in a single row approximately 90 cm long, commonly referred to as a panicle or head row. A few breeders prefer larger F₃ plots such as a single 3-m row or two 90 cm rows, to aid visual selection. Some breeders use hills instead of rows. Individual hills are usually planted at the rate of 25 to 30 seeds per hill with hills spaced 30 to 60 cm apart. In the F₃, several panicles are selected from the progeny rows or hills with the best appearance. In the F₄ and later generations, the same procedure is followed until the desired level of uniformity (homozygosity) is reached. At this point, all plants from a selected progeny row are harvested in bulk and used for seed increase and yield testing.

The pedigree method of breeding is most effective when the characters of interest to be combined through hybridization are easy to identify and can be readily selected in the early generations. A detailed account of the development of the cultivar ‘Dal’ using the pedigree method is presented in Table 9-2.

Modifications of the pedigree procedure sometimes are used. The oat breeder may begin yield testing in early generations to determine the overall potential of the cross, and concentrate selection within the better performing crosses in later generations. Several breeders have successfully used replicated hill plots for early-generation yield evaluations. Hill plot evaluations can be made with a minimal amount of seed and land area.

Although the pedigree method is labor intensive and requires considerable effort, it can be systematized so that large numbers of crosses and progeny lines can be efficiently planted, evaluated, and harvested each year. The method also requires the recording of detailed records in each generation. One major advantage of the method is that only superior progenies for one or more of the desired traits need to be carried forward to the next generation.

**Single-Seed Descent**

The single-seed descent method is especially well suited for oat breeding, and this method, or modifications of it, has been popular with oat breeders. With the single-seed descent method, the F₁ population is
Table 9-2  Schedule for Development of the Oat Cultivar ‘Dal’

‘Dal,’ developed by H. L. Shands at the Wisconsin Agricultural Experiment Station, was released in 1972. It was derived using the pedigree method from the cross ‘Wis. Sel. X660’ × ‘Beedee.’ The purpose of the cross was to combine the leaf rust resistance of ‘Wis. Sel. X660’ with the superior yield and plump kernels of Beedee. ‘Wis. Sel. X660’ was derived from the cross ‘Trispernia’ × ‘Belar’ made in 1952 after the excellent rust resistance of ‘Trispernia’ was discovered by screening the USDA World Oat Collection in 1951.

<table>
<thead>
<tr>
<th>Year</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961</td>
<td>The ‘Wis. Sel. X660’ × ‘Beedee’ cross was made in the greenhouse in the spring of 1961, and five F₁ seeds were obtained. The five F₁ plants, assigned cross number X1289, were grown in the 1961 field nursery where they demonstrated the ‘Trispernia’ resistance to crown rust. Harvest was done on an individual-plant basis.</td>
</tr>
<tr>
<td>1962</td>
<td>The F₂ seeds from one F₁ plant were space-planted by hand at 7.5-cm intervals in two 5.4-m rows which were 30 cm apart. This population of 144 F₂ plants was visually evaluated for reaction to crown and stem rust during the growing season, and the most susceptible plants were pulled and discarded. Ten individual panicles were selected at harvest time, five of which were discarded during the winter based on seed quality.</td>
</tr>
<tr>
<td>1963</td>
<td>From each of the five selected F₂ panicles, a 1.5-m F₃ progeny row was grown in the 1963 field nursery. Four lines were discarded due to stem rust susceptibility. Seven panicles were selected from the fifth row which had good stem rust resistance. Four panicles were discarded, based on seed quality, during the winter inspection.</td>
</tr>
<tr>
<td>1964</td>
<td>An F₄ progeny row was grown in the 1964 field nursery from each of the three selected panicles. These three lines were resistant to crown and stem rust. Five panicles with the most desirable agronomic traits were selected from the row. The three panicles with the best seed quality were retained.</td>
</tr>
<tr>
<td>1965</td>
<td>An F₅ progeny row was grown in the 1965 field nursery from each of the three selected F₄ panicles. One of the rows was cut and threshed in bulk, and this F₅-derived line was assigned selection number X1289-3.</td>
</tr>
<tr>
<td>1966</td>
<td>X1289-3 was entered as an F₄ line in a preliminary yield trial at Madison, Wisconsin, with three replicates of two-row plots 3.0 m long with 30 cm between rows. Entries were arranged systematically in each replicate.</td>
</tr>
<tr>
<td>1967</td>
<td>X1289-3 was advanced to the preliminary yield test of 100 entries at Madison. The entries were grown in four-row plots 3.0 m long with 30 cm between rows. A partially balanced lattice design with four replicates was used. All entries in the test were evaluated for groat protein percentage.</td>
</tr>
<tr>
<td>1968</td>
<td>X1289-3 was evaluated at Madison as in 1967. High groat protein concentrations of 19.5 and 20.0%, in combination with superior agronomic performance, made this line a candidate for future release. Seed of X1289-3 was increased in a single drill plot 3.6 x 22.0 m with 15 cm between rows.</td>
</tr>
<tr>
<td>1969</td>
<td>X1289-3 was evaluated at Madison, as in 1967 and 1968, and in a four-replicate drill plot trial at Arlington, Wisconsin. The drill plots were 3.6...</td>
</tr>
</tbody>
</table>
by 22.0 m with 15.0 cm between rows. The plots were carefully rogued and the 87 kg of harvested seed became the initial breeder seed. Groat protein at Madison was 20.7%.

1970 X1289-3 was tested at Madison, Arlington, and five additional experimental farms in Wisconsin, and was entered in the USDA Uniform Midseason Oat Performance Nursery. A major increase of 3839 kg on 1.73 ha was produced by the Foundation Seed Program of the Agronomy Department at the University of Wisconsin in preparation for the production of foundation seed in 1971.

1971 Statewide and Uniform testing of X1289-3 was continued. Other states were informed of tentative release plans in March 1971. Foundation seed (80,982 kg) was produced by the Wisconsin Foundation Seed Program and by sister agencies in other interested states.

1972 X1289-3 was entered as an F_{4:6} line in a preliminary yield trial at growers of certified seed in January 1972. Data summaries indicated that 'Dal' had high grain yields, good crown rust resistance, high test weight, stiff straw, and high groat protein (19 to 22%). Certified seed was produced, a Plant Variety Protection certificate was applied for, and the certificate was awarded October 1976.

1973 Certified seed was available for purchase and planting on farms.

grown in the same manner as for the pedigree or bulk method. The F_2 and their progenies are advanced through succeeding generations by harvesting one seed from each plant in each generation to provide the population for the next generation. This procedure is repeated for several generations until a population of homozygous plants is available for selection. Seed from the homozygous plants is harvested and planted in panicle rows or hills, and the lines with desired traits are harvested for replicated testing.

The single-seed descent procedure is especially well suited when generations are advanced in the greenhouse. Optimum plant growth and development are not necessary because only one seed is needed from each plant. Thus, the segregating populations can be planted in thick stands which permits maximum use of limited greenhouse space and which results in cycle periods as short as 60 days from planting to harvesting.

The spring oat breeding program at the University of Illinois employs a modification of the single-seed descent technique. Plants are grown at very high density under limited soil fertility and moisture. These cultural stresses result in plants that produce one or a few seeds (Cisar et al., 1982). Beginning with the F_2 generation, 13-cm clay pots are partially filled with sand. Up to 125 seeds are spread on the surface of the sand and covered with 2 to 3 cm of soil. Fertilizer usually is not added during the growing season, unless plants show extreme nutrient deficiencies. Supplemental light is used to extend the photoperiod to 13 hours and to increase
Figure 9-8  Single-seed descent method of generation advance with approximately 125 oat plants growing in a 15-cm clay plot. (Courtesy of W. O. Scott, Emeritus Professor of Agronomy, Univ. of Illinois, Urbana.)

light intensity. Despite the thick planting, most of the plants produce at least one seed (Fig. 9-8), and the onset and completion of the reproductive process is accelerated so that seed can be harvested 60 to 75 days after planting. All plants from a cross are bulk harvested and threshed to provide seed for the next generation. Thus, the population can be advanced through two or three generations during the winter. With this
procedure, some of the plants in each generation are lost; therefore, the breeder needs to maintain rather large populations throughout the segregating generations to help ensure the continuation of an adequate number of different genotypes. A detailed account of the development of the cultivar ‘Ogle’ using this modified single-seed descent method is presented in Table 9-3.

A disadvantage of the single-seed descent method is that plants grown in the greenhouse are not subjected to adaptive stresses which must ultimately be faced in the field. This disadvantage will be less important if both parents are elite lines with minimal agronomic deficiencies. However, if one parent is lacking in one or more critical traits, the use of single-seed descent delays selection for response to an adequate sample of environmental conditions until advanced generation lines are evaluated in yield trials.

**Bulk Breeding**

In the bulk breeding method, the F$_2$ population is planted in rows 30 cm apart at the rate of approximately 100 seeds per meter of row, the plants are bulk harvested, and a random sample of the bulked seed is used to plant the F$_3$ generation. This cycle is repeated several times, usually until the F$_5$ to F$_7$ generation, at which time the bulk population is a mixture of homozygous plants. At this time, individual panicles or plants are selected from the bulk population and each is grown in an individual panicle row or hill. Individual lines with the desired traits are harvested for replicated testing.

The bulk population method is simple, inexpensive, and requires less labor and individual attention from the oat breeder, especially during the early segregating generations. It provides an excellent opportunity for artificial or natural selection to eliminate undesirable genotypes, particularly when the bulk populations are subjected to disease epidemics and other adversities during the segregating generations. Seed of the selected plants or panicles can be bulked and used to plant the population for subsequent generations. It should be recognized that certain desirable genotypes which do not compete well in a bulk population may be eliminated through natural selection. Some genotypes that do not survive in the bulk may be superior when grown in a uniform homozygous stand. For example, short, early, lodging-resistant genotypes may be gradually eliminated while tall, late, lodging-susceptible plants may be favored.

Some oat breeders use a modification of the bulk breeding method or combine the bulk method with the pedigree or other methods. One modification involves growing the F$_2$ and F$_3$ generations by the bulk method, then utilizing the pedigree method for the remainder of the generations.
Table 9-3  Schedule for the Development of the Oat Cultivar ‘Ogle’

‘Ogle’ was developed at the Illinois Agricultural Experiment Station, in cooperation with USDA-ARS, and released in 1980. ‘Ogle’ was derived by a modified single-seed descent method from a cross of ‘Brave’ with a homozygous selection from a cross of ‘Tyler × ‘Egdolon 23.’ The cultivar ‘Brave’ is high yielding and widely adapted, but is tall and lodging susceptible. It was developed by the Illinois Agricultural Experiment Station. ‘Tyler’ is a lodging resistant cultivar developed by the Indiana Agricultural Experiment Station, and ‘Egdolon 23’ is a very stiff-strawed, dwarf-germplasm line developed by the New York Agricultural Experiment Station. The major objective of the cross that led to ‘Ogle’ was to combine the high yield and wide adaptation of ‘Brave’ with the excellent lodging resistance and short stiff straw of the homozygous selection that was derived from the ‘Tyler’ × ‘Egdolon 23’ cross.

<table>
<thead>
<tr>
<th>Year</th>
<th>Procedure</th>
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<tbody>
<tr>
<td>1970</td>
<td>Cross was made in the greenhouse in the fall of 1970.</td>
</tr>
<tr>
<td>1971</td>
<td>Three F₁ seeds were harvested from the greenhouse in early spring. The three seeds were planted in a single hill in the field at Urbana, IL, in early April. All F₂ seed from the hill was bulk harvested. Approximately 300 F₂ seeds from the population were subdivided in three lots of 100 seeds, and each lot was planted in a 15 cm clay pot in the greenhouse in late August. All the F₂ seeds from the three pots were harvested in bulk, chill treated at 4°C between wet paper towels to break seed dormancy; 300 seeds were replanted in the greenhouse in early November using the same procedure as outlined for the first greenhouse cycle. About 300 F₃ seeds from the second greenhouse cycle were replanted using the same procedure as previously outlined, and F₃ seed from the third greenhouse cycle was harvested in late March 1972.</td>
</tr>
<tr>
<td>1972</td>
<td>About 300 F₃ seeds from the third greenhouse cycle were planted in the field at Urbana in a single-row plot 4 m long with a row spacing of 30 cm. Two hundred individual panicles were selected from the population. Each panicle was threshed separately, and following visual examination for kernel type, 110 were saved for further evaluation.</td>
</tr>
<tr>
<td>1973</td>
<td>F₄ progenies from each of the 110 individual F₃ plants selected were grown in the field at Urbana in a single row 1 m long with 30 cm between rows. Individual rows were evaluated for maturity, plant height, general appearance, and reaction to crown rust. Thirty-two rows were bulk harvested individually and evaluated for kernel type; 22 were saved and given a permanent selection identification composed by combining the year and row number in the nursery. Row number 2666 in the 1973 nursery, which was the direct progenitor of ‘Ogle,’ was designated 73-2664.</td>
</tr>
<tr>
<td>1974</td>
<td>73-2664 was entered in a preliminary performance trial with a single replication in an augmented design at each of two locations in Illinois. Individual plot size was four rows 30 cm apart and 3 m long.</td>
</tr>
<tr>
<td>1975</td>
<td>Because of excellent performance for yield and disease resistance in 1974, 73-2664 was advanced directly to advanced nursery trials for the 1975 growing season. A small seed increase also was grown to provide seed for additional testing.</td>
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</tbody>
</table>
1976 73-2664 was continued in advanced nursery trials at two locations in Illinois. It was entered in the larger advanced drill plot trials with three replications at three locations with each plot consisting of six rows 20 cm apart and 23 m long. It also was entered in the Uniform Midseason Performance Nursery. Seven hundred individual panicles were selected from 73-2664.

1977 73-2664 was continued in all Illinois trials and in the Uniform Nursery. Seeds of each of the 700 panicles were planted in single-hill plots. Atypical hills were removed before harvest, and 600 hills that were of uniform appearance were bulk harvested to provide approximately 15 kg of breeder seed.

1978 73-2664 was continued in all Illinois trials and in the Uniform Nursery. An increase plot of 10 kg of breeder seed was grown on 0.1 ha on the Agronomy Farm at Urbana and produced approximately 200 kg of seed.

1979 In February, the performance data for 73-2664 were reviewed by the Plant Variety Review Committee of the Illinois Agricultural Experiment Station. The committee recommended that a major increase be initiated and that a final decision on release be delayed until the 1979 performance data were available. 73-2664 was continued in all Illinois trials and in the Uniform Nursery. Illinois Foundation Seeds, Inc., was provided with 125 kg of breeder seed, which they planted on 3.5 ha. The seed field produced 2800 kg of conditioned seed.

1980 In January 1980, the Illinois Plant Variety Review Committee recommended that 73-2664 be released and named 'Ogle.' Plant Variety Protection was not applied for. A formal notice of release was prepared and approved by the USDA-ARS and by the Illinois Agricultural Experiment Station. Breeder seed was shared with Iowa, Indiana, Nebraska, New York, Pennsylvania, and South Dakota for simultaneous increase and distribution.

1981 Foundation seed of 'Ogle' was produced in participating states and distributed to seed growers for 1982 certified seed production.

1982 Seed growers produced the registered class of certified seed to be sold to farmers for planting in 1983.

1983 'Ogle' was grown by farmers for commercial production.

Multiline Breeding

Oat researchers at the Iowa Agricultural Experiment Station have pioneered the use of multiline breeding to combat crown rust in oats (Browning and Frey, 1969). Different, individual genes for rust resistance are transferred by backcrossing into the same adapted, recurrent parent to form isolines, each with a different gene for resistance. Seed of the isolines is composited to form the multiline cultivar. The isolines making up the cultivar may be changed from year to year, depending upon the prevalence of specific races of the rust pathogen. The Iowa Experiment Station has released several multiline cultivars, including multiline 'M68,'
'M69,' and 'M70,' and multilines 'E68,' 'E69,' and 'E70' (Frey et al., 1971a, 1971b). These cultivars have performed quite well and have provided excellent protection from crown rust damage.

While the multiline breeding approach has provided an effective method for dealing with crown rust of oats, it has several disadvantages that are similar to those of the backcross method. Generally, the system provides for no genetic improvement in yield or other important characteristics, except that provided by the disease resistance. The system is labor intensive because considerable effort is required to develop and maintain the isolines which are composited each year to form the multiline cultivar. The nature of multiline breeding dictates that releases of new and improved recurrent parents will be delayed while isolines are produced and increased. This delay often makes it difficult for the multiline cultivars to compete with other pure-line cultivars, especially when major yield improvements continue to occur with the more conventional procedures.

Recurrent Selection

Oat breeders generally have not used rigorously designed recurrent selection schemes to improve germplasm populations of oats. Their failure to use such schemes is partly due to the difficulties associated with making a sufficient number of intermatings which, in oats, must be made by hand crossing. Oat breeders seem to have concluded that the expected results from a carefully designed and executed recurrent selection program would not justify the time and effort required.

Oat researchers at the University of Minnesota have conducted a recurrent selection program for grain yield in oats (Stuthman and Stucker, 1976; Radtke, 1982; Payne et al., 1983). Their program was initiated in 1968 when they intermated 12 oat genotypes. In each cycle, progeny were advanced from F₂ to F₄ by single-seed descent, after which lines from each cross were evaluated in hill plots. Following three cycles of recurrent selection, they found a total yield improvement of 10%, or 3.3% per cycle. Each cycle required 3 years; therefore, gain per year was 1.1%.

Additional Considerations

Correlated Responses. Regardless of breeding method, selection for only one specific trait at a time may result in correlated responses in other important traits. For example, Marshall (1976) found that selection only for winter hardness in winter oats resulted in a shift from erect to decumbent
juvenile growth and in taller, later plants. In the Minnesota recurrent selection program, increases in grain yield were accompanied by increases in grain and groat weight and number of seeds per panicle, a slight increase in plant height, and a slight delay in maturity. Johnson et al. (1983) and Helsel and Skrdla (1983) found that selection for vegetative growth rate or for higher grain yield resulted in taller, later plants.

In advanced breeding nurseries, it is common for many of the top-yielding entries to have average-or-below protein concentrations and for the lowest-yielding entries to have the highest protein concentrations. The oat breeder searches for those unique genotypes that have both high grain yields and high or above-average protein percentages. From both the practical and the genetic points of view, both grain yield and protein concentration must be considered before the agronomic and breeding value of a genotype can be determined. Consequently, many oat breeders use protein yield, expressed as weight of protein produced per unit area, as a single trait that reflects both grain yield and protein percentage.

**Concurrent Selection.** The breeder usually is able to prevent or minimize undesirable correlated responses by selecting for acceptable or desired levels of several key traits concurrently. However, rate of gain for any one trait will likely be less than when only one criterion for selection is used. Two key challenges facing the oat oat breeder are combining (a) high grain yield and stiff straw and (b) high grain yield and high protein percentage. Both combinations are strongly influenced by physiological processes during growth and development.

Alternatives to concurrent selection include tandem selection for individual traits followed by hybridization among superior types and concurrent selection. While this procedure has worked well for combining certain agronomic and disease traits, generally it has not been successful for combining high grain yield and high groat protein percentage. For groat protein, concurrent selection for grain yield, stiff straw, disease resistance, and protein percentage among progenies from crosses between elite breeding stocks may be the most efficient short-range procedure to follow.

An option to be considered for long-range improvement in protein percentage is concurrent selection in two separate programs. In one program, selection for yield, straw strength, and disease resistance receives primary emphasis, and protein percentage receives slightly less emphasis. In the second program, protein percentage receives primary emphasis, with slightly less emphasis on yield, standability, and disease resistance. Based on additive gene action, intercrossing superior lines from these two programs should favor the generation of superior combinations of genes. The procedure avoids severe dilution of desirable traits in one parent due
to a low level in the second parent, such as when the cultivated oat is mated with the wild species *A. sterilis*. *A. sterilis* has a high protein percentage, but is inferior for many agronomic traits.

**Influence of Shattering on Protein Concentration.** One more point needs to be made in relation to the many physiological processes and morphological traits that affect grain filling and grain quality in oats. Breeders have concentrated on *A. sterilis* as a breeding stock, initially as a source of crown rust resistance and more recently as a source of high protein percentage. However, Lyrene and Shands (1974) found that *A. sativa* fatoid and *A. sterilis* shatter-types always had 2 to 3 percentage points higher groat protein than their nonshatter sister plants. Similarly, Reich and Brinkman (1984) reported that groat protein percentage was significantly higher in shattering than in nonshattering *F₂* progenies from *A. sativa* × *A. fatua* crosses in 1 of 2 years. It is possible that the shatter trait causes a premature termination of carbohydrate deposition in the endosperm, which in turn results in higher protein percentages. This hypothesis remains untested at this time.

**Summary.** Each of the breeding and selection procedures discussed in this section has some advantages and disadvantages, and often the choice of a procedure depends on the preference of the breeder, the objectives of the breeding program, and available land, greenhouse, and labor resources. Superior cultivars can be developed from any one or from a combination of the procedures. The identification of superior genotypes requires careful observation and testing at a number of locations for several years. These testing phases are absolutely essential and require a major amount of time and other resources. Because of this, only lines that are clearly superior should be continued, otherwise the breeding program will become cluttered with mediocre material that has little chance of producing superior cultivars.

**FIELD-PILOT TECHNIQUES FOR GENOTYPE EVALUATION**

Early generations, preliminary yield trials, and advanced yield trials constitute the three main performance-evaluation categories. Evaluation for grain yield is generally deferred until *F₅* or *F₆* when most lines are homozygous and homogeneous.

**Early Generations (F₂ through F₅)**

Early generation materials may be space-planted or thinly seeded on a population (cross) basis, or planted in hills or short rows on a line basis.
(pedigree method). A field may be marked into rows, ranges, and alleys (Fig. 9-9) before planting, although use of wheel-tracks or other guide marks made the previous trip across the field can eliminate the need for prior row marking. Marking a field in both directions creates a grid for planting hills. Planting equipment includes tractor-mounted (Fig. 9-10) or hand pushed cone seeders (Fig. 9-11) and hand-pushed funnel seeders (Fig. 9-12). A maize jabber can be used to plant hills. Regardless of the methodology used, field-nursery layouts must be in harmony with the equipment used for row marking, planting, pest control, and harvesting. Pest control is essential and must be performed in a timely manner.

**Hand-Planted Progeny Rows.** In preparation for planting, seeds from individually harvested panicles are placed in coin envelopes at the time of threshing, which usually occurs during winter months. The breeder inspects the seed in each envelope before planting, and often discards up to 50% of the selections based on grain quality.

For hand-planting individual rows in ranges, the rows are arranged in numerical order along each alleyway. A typical sequence of steps is as follows. The field is marked, the rows are opened with cultivator shovels mounted on a garden tractor, a stake is placed every 10 rows, the seed is
planted by hand in row number sequence, and the rows are closed with a hand-pushed garden planter that has had the planting shoe removed. A 1.5-m alley and a 3.0-m range, made up of two tiers of 1.5-m rows planted back to back, are convenient dimensions. A susceptible oat that serves as a rust spreader is planted between the two tiers of each range. Records are maintained for each cross and each line, and performance characteristics such as heading date, plant height, and disease reactions are recorded for each line (row).

*Tractor Planting with Seed Trays.* Seeds of individually harvested panicles may be placed directly into the seed-tray cups (Fig. 9-13) at the time of threshing, which generally precludes seed inspection by the breeder after harvest. Consequently, seed inspection for grain quality must take place in the field, on a line basis rather than a plant basis, at selection time. For planting, the seed trays are inserted into a tractor-mounted tray feeder, and the seeds in the cups in one tray row are planted into four separate rows, each 35 to 90 cm long. The rows planted from a tray usually are arranged in narrow blocks eight rows wide (four rows
Figure 9-11  Hand-pushed cone seeder. (Courtesy of W. O. Scott, Emeritus Professor of Agronomy, Univ. of Illinois, Urbana.)

Figure 9-12  Hand-pushed funnel seeder. (Courtesy of Ronald A. Bunch, Department of Agronomy, Univ. of Wisconsin, Madison.)
Figure 9-13  Seed tray with four cells per row. (Courtesy of Precision Machine Co., Lincoln, Nebraska.)

down and four rows back) with a 30- or 60-cm space left between the eight-row blocks (strips) for planting a disease spreader. A 1.8-m space can be left between sets of two strips for pest control equipment. Using this method, the materials are positioned in column-type blocks rather than in horizontal ranges. Book records are maintained on a cross basis and usually are less systematic and less detailed than for the pedigree system.

Preliminary Yield Trials

Regardless of breeding method used, the breeder usually generates a large number of $F_3$ to $F_7$-derived lines that need to be screened for the first time for grain yield. Segregation for kernel color, plant height, and other traits may still occur in $F_{4:5}$ lines, so caution must be exercised if the plants in an $F_{4:5}$ line are cut and threshed in bulk and homogeneity is a necessity. Most $F_7$-derived lines are homozygous and homogeneous for most visible traits and can be entered in preliminary yield trials. Because the amount of seed available is limited, initial evaluations may take the form of smaller, replicated plots or larger, nonreplicated plots.
**Small Plots.** Small-plot sizes and seeding rates commonly used include the following:

*Row length:* 3.0 m  
*No. of rows per plot:* 1 or 2  
*Distance between rows:* 30 cm  
*Grams seeded per row:* 9.5  
*Length harvested/row:* center 2.4 m  
*Number of replicates:* 1 to 3

If average seed weight is 34 mg, the 9.5-g amount provides 280 seeds per 3.0-m row, a seeding rate of 89.6 kg/ha (2.5 bushels/acre). The actual amount seeded per row needs to be adjusted upward if average seed weight exceeds 34 mg or if a 96.0 kg/ha (3.0 bushels/acre) seeding rate is desired. Where two or more replicates are used for a preliminary test, the lines can be randomly positioned within each replicate or they can be planted in the same order in all replicates. A nonrandom planting order may be used because analyses of variance often are not performed at this early stage of testing, record keeping is simplified, and high selection intensities of 30 to 50% minimize the possibility of discarding superior lines.

In most cases, lines in the preliminary, small-plot yield test are grown at only one location, and only a portion of the lines are harvested. Harvest is accomplished by using a small-plot mower (Fig. 9-14), a small binder (Fig. 9-15), or a small combine (Fig. 9-16). If lodging is extreme, the plants may have to be hand-pulled. If drying is necessary before threshing, the bundles should be bagged to avoid seed mixtures. If the plants are mature and dry, the harvested bundles may be threshed the day of harvest (Fig. 9-17). When there are two or more replicates of an entry, the plots of each entry frequently are grouped together before threshing, and replicate 1 is threshed last so that it has the least chance for seed mixtures and becomes the primary source of seed for future tests.

Approximately 60 g of seed are needed for planting a three-replicate test with two 3.0-m rows per plot. Because a 1.5-m progeny row usually yields 120 to 160 g of seed, the excess seed of a few of the most promising lines can be planted in observation or increase blocks of 4, 8, or 12 3.0-m rows for added scrutiny and purification. The 120 to 160 g of seed would allow four-row plots, but this would double the area of land needed for preliminary evaluation of genotypes.

Hill plots may be used for preliminary yield trials, which allows for more replications with a given amount of seed and land area. However, coefficients of variability of 15 to 20% or higher are not uncommon for hill-plot yield tests. A typical trial would have hills positioned on a 30-cm grid with 30 seeds planted per hill.
Figure 9-14  Small mower with a 30-cm cutter bar and a cradle to help gather the cut stems. (Courtesy of Ronald A. Bunch, Department of Agronomy, Univ. of Wisconsin, Madison.)

Figure 9-15  Small-plot binder. (Courtesy of Ronald A. Bunch, Department of Agronomy, Univ. of Wisconsin, Madison.)
Augmented Design. An augmented randomized complete-block design can be used for preliminary tests of oat lines in a single replication (Federer, 1961). In the oat breeding program at the University of Illinois, each block in the design has 20 entries, consisting of 17 test lines and three check cultivars. Each of the check cultivars is placed at random in each block. The check cultivars, which are common to all blocks, provide an estimate of error that can be used to adjust the performance of test lines for block effects. All plots of the check cultivars must be harvested, but any test line found to have major defects can be discarded before harvest. Often more than 50% of the test lines are discarded before harvest. A computer program has been developed to analyze data from the augmented complete-block designs (Beal et al., 1965).

Advanced Yield Trials

Plot Size. Tractor-planted plots used for advanced yield trials range in size from a conventional four-row nursery plot with each row 3.0 m long and 30 cm between rows to large plots planted with a grain drill with rows...
15.0 to 17.5 cm apart. Large drill plots 1.8 m wide and 7.6 to 24.4 m long are common. If plots are seeded by hand, three-row plots with rows 5.5 m long and 30 cm apart offer an alternative to four-row plots.

*Planting.* To duplicate common farm practice, spring-sown yield trials must be planted as soon as the soil becomes dry enough to prepare a firm seed bed. After soil preparation, the field is marked into ranges and alleys, and for breeding-nursery tests, the entire field may be row marked. Most yield-test drills now are equipped with a feeding device which dis-
perses the seed from a central container into the drill tubes. This allows for easy and rapid clean-out between plots so that different genotypes can be planted sequentially in trips across the field without fear of seed mixtures.

A hand-pushed cone or funnel seeder (Figs. 9-11 and 9-12) may be used to plant yield trials at locations where a mechanical planter is not available. For hand planting, three-row plots 5.5 m long are commonly used.

Harvest. Near maturity, the center two rows of a four-row nursery plot are shortened from a planted length of 3.0 m to a harvested length of 2.4 m to remove the alley effect. The center row of a three-row plot 5.5 m long is shortened to 4.9 m. The plots may be harvested with a small mower (Fig. 9-14), small binder (Fig. 9-15), or a small combine (Fig. 9-16). Similar maturity among entries is required for binder or combine harvest because these machines are not easily maneuvered and must proceed across ranges at harvest, unless land availability allows for wide alleys between ranges.

Design and Location. Yield trials generally are conducted in different regions of each state, the number depending on soil types, temperature gradients, rainfall patterns, and resources. A randomized complete-block design with three or four replicates is usually employed for tests with fewer than 40 entries. A partially balanced lattice design with four replicates usually is used for large tests with 64, 81, or 100 entries. Entry means are adjusted for block effects which usually exist within replicates of this size.

Computers are used for a wide assortment of operations within oat breeding programs, including randomization for planting plans, field-book records, planting-packet, stake, and harvest-bag labels, data analyses, and report preparation. Data recording devices are available for field or other uses, and they allow the transcription of data from tape directly into microcomputers or mainframe units.

PROCEDURES FOR SEED PRODUCTION

Methods for Producing and Maintaining Breeder Seed

A successful breeding program must include an effective method for providing an adequate supply of high quality, genetically pure seed for farmer production. Most cultivars of oats originate in public programs; therefore, the emphasis in this section is on the procedures used to
increase and maintain seed of public oat cultivars. Specific procedures differ among breeders, but the ultimate aim in all cases is to develop and use a set of procedures that will ensure an abundant supply of genetically pure seed of improved oat cultivars.

In a typical public oat breeding program, the oat breeder provides the initial supply of pure breeder seed of the new cultivar to an agent who has responsibility for increase and maintenance of the seed. In most states, the Agricultural Experiment Station or its designated agent has this responsibility. The designated agent may be under the direct control or even a part of the organization responsible for the public oat breeding program, or the agent may be an independent private company or corporation operating via a contract or memorandum of agreement. Regardless of the specific arrangement, the designated agent must have the skills, capability, and resources to increase and maintain an adequate supply of genetically pure seed of the cultivar. The breeder seed provided by the breeder is increased by the designated agent to provide foundation seed for distribution to seed growers.

Extreme care must be exercised in all phases of seed production to avoid mechanical mixtures with other cultivars of oats or other crops. Planting, harvesting, and seed conditioning operations are particularly vulnerable to mechanical mixtures. Although oats are highly self-pollinated, some natural crossing will occur; therefore, breeder seed fields should be isolated from other cultivated or wild oats that might outcross with the cultivar. The Association of Official Seed Certifying Agencies requires isolation of 3 m between oat cultivars. Isolation also will help prevent mechanical mixtures that might occur during the harvest operation. Breeder seed fields must be carefully rogued to remove plants that are not typical of the cultivar, as described by the oat breeder.

Even with extreme caution and close supervision, genetic and mechanical mixtures will sometimes occur, so the breeder seed must be purified from time to time. This purification must be done under the direct supervision of the oat breeder. Typically, purification is accomplished by selecting several hundred individual panicles from the cultivar to be purified. Seed from each panicle is planted in an individual short row or hill plot. The rows or hills are carefully examined several times during the growing season and those that are not typical of the cultivar under purification are removed. At maturity, the remaining rows or hills, all of which are judged to be typical of the cultivar, are bulk harvested to provide the new source of purified breeder seed of the cultivar. The purified seed is further increased, again under close supervision of the oat breeder, and when a sufficient quantity is available, is designated the official and sole source of breeder seed of the cultivar. This general procedure is repeated until there is no longer need for seed for commercial production of the cultivar.
Commercial Seed Production and Marketing

In many states, the increase and distribution of seed of oat cultivars for commercial production is done by a foundation seed association. For example, in Illinois, this service is performed by Illinois Foundation Seeds, Inc., which is a private corporation. The service is performed in accordance with a memorandum of agreement between the Illinois Agricultural Experiment Station and Illinois Foundation Seeds, Inc. In other states, the management of the foundation seed association is a direct function of the Experiment Station or the Agronomy Department.

Most states have a seed certifying agency whose responsibility is to certify the genetic purity of cultivars. As with foundation seed associations, the organizational structure of the certifying agencies varies from state to state. In Illinois, responsibility for seed certification rests with the director of the Agricultural Experiment Station, but the director has delegated that responsibility to the Illinois Crop Improvement Association via a memorandum of agreement.

The seed certifying agency in each state makes field and laboratory inspections of all foundation seed lots, and only lots that meet or exceed the established standards for genetic purity for the foundation class of seed are certified. Foundation seed that meets the standards for certification is sold to certified seed growers for increase and sale to farmers as a class of certified seed. Fields of certified seed are inspected by the certification agency, and only seed that meets or exceeds the minimum standards for the certified class of seed can be labeled and sold as certified seed of the cultivar.

Oat cultivars are eligible for protection under the Plant Variety Protection Act (Public Law 91-577) which became law December 24, 1970. This law was enacted to encourage the development of novel varieties of sexually reproduced plants and to make them available to the public, providing protection available to those who breed, develop, or discover them and thereby promoting progress in agriculture in the public interest.

The act makes it possible for the developer to secure legal protection for a new plant cultivar which reproduces sexually by seed. To receive a certificate of protection, the cultivar must be distinctive, uniform, and stable. Protection continues for 17 years from the date of issue of the certificate. The owner of the cultivar may also specify that seed of the protected cultivar shall be sold only as a class of certified seed. The Act places strict limits on the reproduction and selling or offering for sale of a protected cultivar by anyone other than the owner. Several recently developed oat cultivars have been issued certificates of protection with the specification that they be sold only as a class of certified seed.
FUTURE PROSPECTS FOR CULTIVAR DEVELOPMENT

The challenge facing oat breeders in both developed and developing countries is to develop cultivars that maximize the probability of producing high yields of high quality grain under specific management systems in specific environments. Oat germplasm is constantly being improved, and superior cultivars for farm production are continually being developed using conventional breeding procedures. Two considerations for the future are hybrid oats and the use of genetic engineering to facilitate cultivar development.

Hybrid oats are not available and the prospect is not bright. Neither cytoplasmic male sterility or a suitable chemical gametocide have been discovered, and the potential for wind transfer of pollen from male to female parents remains untested.

Oats are amenable to anther culture, but the results obtained have not yet contributed to oat cultivar development. In contrast to barley and wheat, haploid oat plants whose chromosomes could be doubled to create an instantaneous pure line have not been obtained via anther culture. Other genetic engineering techniques such as selection and regeneration of plants from cell cultures, fusion of protoplasts, or use of various vectors for DNA transport either have not been tried or have not been successful with oats. Systems for selection of mutants with increased lysine, threonine, or methionine have been devised (Green and Phillips, 1974), and it is possible that increased efforts could lead to biochemical improvements in oats.

Oat improvement goals are long-term and require much patience. Excellent germplasm is available, new knowledge is emanating from basic research, and new techniques are being developed and evaluated. These factors indicate that further genetic improvement of oats will be achieved in the future.

REFERENCES


Briggle, L. W., R. T. Smith, Y. Pomeranz, and G. S. Robbins. 1975. Pro-


Reich, J. M., and M. A. Brinkman. 1984. Inheritance of groat protein per-


