CHAPTER FOUR

Barley

A. Earl Foster

Barley (*Hordeum vulgare* L.) is considered the oldest cereal grain cultivated for food. Cultivation of barley antedates historical records, and its origin remains unknown (Harlan, 1968). Archaeological evidence from Egypt shows that barley grains were used by the inhabitants around 16,000 B.C. (Wendorf et al., 1979). Characteristics of the barley kernels found by archaeologists are very similar to those of present-day barley. Evidence of early barley culture has been found in other places, including Ethiopia, Tibet, Afghanistan, and the Near East.

There are two main types of cultivated barley: two-rowed and six-rowed (Fig. 4-1). Each type has three spikelets at each rachis node (one central and two laterals), and each spikelet contains one floret. Groups of spikelets are arranged in an alternate and opposite fashion on the rachis. The lateral spikelets of two-rowed barley are sterile and the central is fertile, resulting in two rows of kernels on the rachis. All florets of six-rowed barley may be fertile, resulting in six rows of kernels when viewed from the top of the spike. Harlan (1968) suggested that two-rowed barley preceded six-rowed barley in evolution because the two-rowed character occurs in a wild ancestor, *H. spontaneum* Koch. The six-rowed trait may have resulted from a mutation because the two-rowed character is controlled by an allele that is dominant to the allele for six-rowed, and dominant to recessive mutations are much more frequent than the reverse.

Early immigrants to North America brought barley with them, and it became a part of their agricultural production as they moved to new areas. Four groups of barley became established (Weihe and Reid, 1958):

1. The *Manchurian-O.A.C. 21-Oderbrucker group* probably came from Manchuria or neighboring countries. These cultivars became established in humid sections of the Upper Mississippi Valley,
south of the Great Lakes, and in Canada. They are six-rowed barleys with the spring growth habit.

2. *The Coast group*, of North African origin, was introduced into California from Mexico. They are large-kerneled six-rowed cultivars with the spring growth habit, but are commonly sown in fall or winter in California and Arizona.

3. *The two-rowed group* consists of two principal types with the spring growth habit, the Hannchen type of European origin and the Compana-Smyrna type of Turkish origin. The Compana-Smyrna type can be grown in areas of marginal rainfall. Although early settlers introduced two-rowed barley into eastern United States and Canada, hectarage of this group now is concentrated in the Pacific Northwest, in intermountain areas of the West, to some extent in the Great Plains, and in the prairie provinces of western Canada.
Before the 1890s, two-rowed barley was grown extensively in Ontario for export as malting barley to the United States. However, protective tariffs set by the United States eliminated this market and farmers in Ontario switched to greater yielding, but poorer quality six-rowed cultivars.

4. *The Tennessee-Winter group* is of unknown origin, but may trace to the Balkans-Caucasus region or Korea. This group consists of six-rowed cultivars with the winter growth habit. Winter barley is grown primarily south and east of a curved line running from central New York through central Missouri, southern Nebraska, and south to Texas. Other production areas include the Pacific Northwest and some intermountain areas of western United States.

**TYPES OF CULTIVARS**

**Mode of Propagation**

Cultivated barley species are naturally self-fertilizing. Each fertile floret contains three stamens and a pistil enclosed in the lemma and palea. Anthesis begins in florets near the center of the spike and progresses to the top and bottom. Anthesis usually begins while the spike, excluding awns, still is partially to totally enclosed in the flag leaf sheath (Fig.4-2). However, environment and genotype influence timing of anthesis. Anthers usually dehisce before extrusion, and much of their pollen is shed within the floret, resulting in nearly 100% self-pollination. Degree of cross-fertilization depends on the environment and proximity of other barley plants. Relatively cool temperatures, adequate soil moisture, and abundant sunlight, as may be found in irrigated barley fields in Arizona, favor spike extrusion from the flag leaf sheath before pollination. Florets thus exposed are more subject to cross-fertilization, but the percentage may still be less than 1%. Cross-fertilization in barley nurseries of the northern United States and Canada seldom has been observed, unless male-sterile plants are present. Seed-set on male-sterile plants seldom exceeds 10 to 15% in the upper Midwest or Canada, but may reach 95 to 100% in Arizona. Cross-fertilization on male-sterile plants can be improved in the upper Midwest by selection of appropriate male and female genotypes.

**Past and Current Cultivar Types**

Efforts to improve barley by breeding, rather than selection, are seldom mentioned in early barley literature. 'Horsford,' released about 1880, is the first barley cultivar known to result from planned hybridization in
North America. Most barley breeding programs were initiated after 1900, and most cultivars that originated from hybridization were not released until after 1920. In the early 1900s, numerous introductions from abroad were made by the U.S. Department of Agriculture (USDA), the Canadian Department of Agriculture, and, to a lesser extent, private individuals. These introductions were not pure-line cultivars, but rather a mixture of numerous types; an example of which is the cultivar ‘Manchuria.’ Introductions were distributed to various researchers who tested the materials, made selections, and released cultivars (Poehlman, 1977).

The predominant type of barley grown in North America is six-rowed, and breeding programs have been in place much longer for six-rowed than for two-rowed barley. It was not until about 1940 that introduced two-rowed cultivars began to increase in hectarage in intermountain areas of northwestern United States and slightly later in prairie provinces of western Canada. Current six- and two-rowed cultivars nearly all are awned with a covered caryopsis. Hooded six-rowed spring and winter cultivars are grown only in a few areas where they are used for hay or feed (Fig.4-3). Awnletted six-rowed winter cultivars are grown in the U.S. Atlantic Coast states. Hulless six-rowed cultivars are grown for livestock feed in Utah and Saskatchewan.
All currently grown barley cultivars are pure lines. No hybrid barleys are available, but the Cargill company had a large hybrid program using the cytoplasmic-genetic male-sterility system. Their program was discontinued in January 1986. Use of chemical hybridizing agents to facilitate production of hybrid seed is being investigated by some commercial companies.

In addition to the use of morphological differences for classification of barley cultivars as two-rowed or six-rowed types, winter or spring growth habit, and hulled or hulless, they also can be classified as malting or feed type. Most of the barley grain produced in the United States and Canada is used to feed livestock and poultry. Feed or nonmalting cultivars have

Figure 4-3  Hooded six-rowed barley.
been developed with the major goal of high yield for producers. Although breeders of feed barley give attention to good agronomic type and resistance to prevalent diseases, they seldom have been concerned with feed quality. The neglect of feed quality is related to difficulties in screening breeding material for quality traits, to the lack of a good definition of quality that changes with species and age of target animals, and to the lack of a premium in the marketplace for feed barley with improved quality. The lack of tests for feed quality resulted in failure to identify ‘Steptoe’ as a cultivar with poor feed quality before its release. ‘Steptoe’ is one of the best-yielding cultivars when grown in the Pacific Northwest and intermountains states. The barley breeding programs in Alberta, Saskatchewan, and Montana emphasize the quality of feed. An objective of the Alberta program is to develop high-lysine barley grain. High lysine has been associated with smaller kernels, abnormal starch development, and reduced yields. However, Munck et al. (1985) reported that high-lysine lines with plump kernels and normal yield had been found. Feeding trials have shown that currently grown malting cultivars make very good barley for feeding, resulting from favorable amounts of soluble protein and carbohydrates and relatively less fiber (Harrold, 1985).

Principal areas of malting barley production in the United States are the Upper Mississippi Valley states of Minnesota, North Dakota, and South Dakota, the western intermountain states of Colorado, Idaho, Montana, and Wyoming, and the Pacific Northwest states of Washington and Oregon. Nearly all six-rowed malting barley is produced in the Upper Mississippi Valley area and most two-rowed malting barley is produced on irrigated lands farther west. Production of malting barley in Canada is concentrated in the western prairie provinces of Alberta, Manitoba, and Saskatchewan. Six-rowed malting cultivars are grown in all three provinces and two-rowed malting cultivars are grown primarily in Alberta and Saskatchewan. Production of two-rowed malting barley gradually is increasing in Canada. The most extensively grown cultivars in the major barley producing areas are listed in Table 4-1.

EXTENT AND NATURE OF BREEDING PROGRAMS IN NORTH AMERICA

Public Programs

The number of researchers engaged actively in barley breeding has diminished markedly in the past 30 years. Reasons for personnel attrition include (a) changes in USDA policy to more basic research; (b) the devastating effect of barley yellow dwarf on barley hectarage in winter barley-producing states and California, resulting in changes in crops
Table 4-1  Leading Barley Cultivars Grown in Major Production Areas

<table>
<thead>
<tr>
<th>North-central</th>
<th>Intermountain</th>
<th>Western</th>
<th>Prairie Provinces</th>
<th>Eastern Provinces</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robust*</td>
<td>Steptoe</td>
<td>Steptoe</td>
<td>Bonanza*</td>
<td>Leger*</td>
</tr>
<tr>
<td>Morex*</td>
<td>Klages*†</td>
<td>Kamiak†</td>
<td>Klages*†</td>
<td>Birka*</td>
</tr>
<tr>
<td>Azure*</td>
<td>Hector†</td>
<td>Boyer†</td>
<td>Johnston</td>
<td>Rodeo†</td>
</tr>
<tr>
<td>Hazen</td>
<td>Moravian III*†</td>
<td>Heski†</td>
<td>Conquest*</td>
<td>Laurier</td>
</tr>
<tr>
<td></td>
<td>Piroline*†</td>
<td>C.M. 72</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Prato</td>
<td></td>
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</tbody>
</table>

*Classed as acceptable malting cultivar.
†Two-rowed cultivar; all other cultivars are six-rowed.
‡Winter cultivar.

grown and research responsibilities; (c) increased emphasis on crops with greater income value; and (d) cutbacks in agricultural research funding by state and federal agencies. Major breeding programs now are concentrated in those states and provinces where substantial barley hectarage remains. In the United States, the main spring barley breeding programs are in Idaho, Minnesota, Montana, North Dakota, Oregon, Utah, and Washington. Active barley breeding programs in Canada are found in Alberta, Manitoba, Ontario, Prince Edward Island, Quebec, and Saskatchewan, with major efforts in the western prairie provinces, where about 90% of the production takes place. The USDA is involved actively in breeding programs in Idaho and Montana and Agriculture Canada is involved in the programs of Alberta, Manitoba, Ontario, Prince Edward Island, and Quebec. Substantial winter barley breeding programs are found in Georgia, Idaho, Oregon, Virginia, and Washington.

Private Programs

Barley breeding programs by commercial companies in the United States essentially were nonexistent before passage of the Plant Variety Protection Act in 1970. Before that time, it was not economically feasible for companies to develop and release cultivars of self-pollinating crops such as barley because, after the initial sale, there was no way for a company to recoup its investment. Cultivars released by private companies before 1970 usually resulted from introduction of cultivars or selections from European countries.

Major private barley breeding programs currently are conducted by
six companies. Anheuser Busch purchased the barley germplasm and hired the barley breeding staff of Nickerson American Plant Breeders. Their cultivars are targeted for the six- and two-rowed malting barley areas in Canada and the United States. Western Plant Breeders have targeted their cultivars for Arizona, California, and other western states in the United States. Their cultivars have been grown for nonmalting purposes. Cargill was concentrating on development of hybrid nonmalting barley for the Upper Mississippi Valley in the United States. Although their major effort was devoted to the cytoplasmic-genetic male-sterility system proposed by Ahokas (1978), they also were investigating use of chemical hybridizing agents to facilitate production of hybrid seed. It is likely that all private and some public programs have investigated or soon will investigate the use of chemical hybridizing agents. Northrup King has developed cultivars that are grown primarily in California for nonmalting uses. CIBA-Geigy developed two nonmalting cultivars for eastern Canada using the doubled-haploid breeding procedure. Their program recently was purchased by Thompson Bros. who are continuing the research. King Grain also is developing nonmalting cultivars for Ontario and other eastern provinces.

BREEDING OBJECTIVES FOR CULTIVAR DEVELOPMENT

Priority given to various characters will vary among research projects and with the intended use of the grain. Priority given to breeding for disease resistance is related to prevalence and severity of specific diseases. Emphasis given to malting quality depends on the intended market of the grain.

High grain yield must receive top priority. Yield will be affected by many other characters, such as resistance to lodging, shattering, and prevalent diseases. At the same time, emphasis must be placed on selection for such marketing factors as test weight, kernel plumpness, and kernel color.

A breeder must establish a mental image of the ideal plant or ideotype and work toward that goal. For example, the ideotype may have high yield, strong and short straw, plump kernels, medium maturity, high test weight, no shattering, lax head, thin hull, smooth awns, short rachilla hairs, resistance to prevalent diseases, good kernel color, and good malting quality. At least one of the parents of the cross must possess the character desired in the ideotype. The breeder should not rely on transgressive segregation to provide improvements for specific characters, but must be prepared to capitalize on new genetic variability when it occurs. The ideotype must be achieved by a succession of steps because breeders have not yet succeeded in developing their ideal ideotype. Progress toward the ideal has been made for many characters. Wych and Rasmus-
son (1983) compared barley cultivars released over a 40-year period and documented progress in malting quality characters and grain yield. They attributed 73% of the yield increase in commercial production to genetic improvement of cultivars.

Some of the most important characters are controlled by multiple genes and are considered quantitative characters. Grain yield, lodging resistance, plant height, kernel plumpness, test weight, maturity, kernel protein percentage, winter hardiness, malt extract, diastatic power, alpha-amylase activity, and resistance to some diseases are examples of quantitative characters. Aleurone color, awn type, rachilla hair length, hull color, deciduous awns, shattering resistance, resistance to stem rust (incited by *Puccinia graminis* Pers. f. sp. *tritici*), dwarfness, day-length sensitivity, hull adherence, growth habit, resistance to barley yellow dwarf virus, spike compactness, and seed dormancy are examples of qualitative characters controlled by one or two gene pairs.

Establishing priorities for a group of characters does not establish the order in which the breeder selects for them during cultivar development. Selection should be made for the most heritable characters in the F$_2$ or F$_3$ generation, while selection for characters controlled by multiple genes usually is delayed until F$_2$- or F$_3$-derived lines are in observation rows or yield trials. For example, aleurone color, growth habit, dwarfness, spike compactness, awn type, and stem rust resistance are examples of characters that can be selected in the F$_3$ generation. Characters that can be selected for in F$_2$- to F$_3$-derived lines include plant height other than dwarfness, heading date, kernel plumpness, shattering resistance, kernel color, resistance to spot blotch (incited by *Cochliobolus sativus* (Ito & Kurib. in Kurib.) Drechs. ex Dast.), net blotch (incited by *Pyrenophora teres* Drechs.), scald (incited by *Rhynchosporium secalis* (Oud.) J. J. Davis), and barley yellow dwarf virus, and the malting quality factors extract, protein, and diastatic power. Burger and LaBerge (1986) have described various tests that are available to evaluate experimental lines for malt quality.

Yield, test weight, straw strength, and deciduous awns are evaluated in replicated trials. Also, those characteristics previously evaluated in progeny rows should be reexamined in the replicated trials because more accurate assessment can be made in larger plots. Evaluation of lines in replicated trials for malting or feed quality should be made after selections are made for yield and other characters because quality tests would not be justified on lines that will be discarded on the basis of other characters.

Malting quality characteristics of importance are kernel plumpness, total malt protein, soluble protein, extract, fine/coarse difference, diastatic power, and alpha-amylase (see Table 4-2 for definitions of these characteristics).

Barley researchers are fortunate to have much information available on barley genetics. The *Barley Genetics Newsletter*, published annually,
Table 4-2 Malt Quality Characteristics

<table>
<thead>
<tr>
<th>Quality</th>
<th>Definition and Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plump kernels</td>
<td>Kernels that remain on a slotted sieve with rectangular openings of 2.4 \times 19.1 mm. A high percentage of plump kernels is desired because it indicates that kernels contain favorable amounts of starch.</td>
</tr>
<tr>
<td>Total malt protein</td>
<td>A measure of the amount of nitrogenous substances in the malt. Brewers want 11.0 to 13.5% protein in malt.</td>
</tr>
<tr>
<td>Soluble protein</td>
<td>A measure of soluble nitrogenous substances in the malt. Brewers want at least 5% soluble protein in malt.</td>
</tr>
<tr>
<td>Extract</td>
<td>That portion of the malt that is soluble in the wort. This percentage is a measure of fine-grind extract on a dry-weight basis, and ranges from 76 to 82% in malting cultivars.</td>
</tr>
<tr>
<td>Fine/coarse difference</td>
<td>The difference between fine-grind extract and coarse-grind extract. It represents the degree of modification that has taken place during malting. Differences of less than 2% are required by brewers.</td>
</tr>
<tr>
<td>Diastatic power</td>
<td>A measure of beta-amylase and other diastase enzymes present to convert starches to sugars. This is expressed in degrees Lintner. Increasing numbers represent greater diastatic power.</td>
</tr>
<tr>
<td>Alpha-amylase</td>
<td>An enzyme that is part of diastatic power which liquifies starch. A value of at least 35 dextrinizing units (DU) is required by brewers.</td>
</tr>
</tbody>
</table>

maintains an up-to-date list of known genes and current linkage maps for the seven barley chromosomes. Researchers should use the Newsletter as the primary source of information on simply inherited characters.

STEPS IN CULTIVAR DEVELOPMENT

Choice of Parents

Barley cultivars historically have been developed for certain geographic areas. For example, cultivars developed for eastern Canada are different from those developed for the prairie provinces. Cultivars for eastern Canada all are considered feed types and must have resistance to different diseases from those in the prairie provinces. Thus, a breeder must decide on the target area for potential new cultivars. Secondly, the breeder must determine the potential market use of new cultivars: feed or both malting and feed. After these decisions have been made, the breeder must choose germplasm from which the desired types of cultivars can be derived by recombination.
Developing Segregating Populations

Crosses must be made between those parents which, in combination, possess the traits desired in a new cultivar. A population of F₂ plants large enough to contain the desired recombinants must be grown from each cross. A breeder can expect to improve only a few traits in one cycle of crossing and selection. If a breeder is expecting to select for six unlinked characters, and the desired condition for any character is expected to occur 25% of the time, only one F₂ plant in 4096 is expected to have all the desired traits. The breeder should be realistic about the progress that can be expected from a given cross.

Selection of the Desired Type

Identification of those plants in the segregating populations that have the best combination of desired characters requires that plants are grown in an environment where the traits can be expressed. Plants seldom are found with all the desired traits, so the breeder must select the best plants that are available. Normally, about 0.5 to 2.0% of the F₂ plants are selected and advanced to the next generation. The F₃ and F₄ generations can be managed in several ways, including progeny rows or bulk populations. If populations are inbred by the bulk or single-seed descent methods, plants ultimately must be evaluated in progeny rows where selection for quantitative traits is more effective than on a single-plant basis.

Testing

After selections have been made on a progeny-row basis, the lines must be evaluated in replicated yield trials. Yield trials should be conducted at several locations over several years to identify superior lines. Inferior lines are discarded. The best lines are evaluated on a regional basis in cooperative nurseries to determine their areas of adaptation.

Seed Increase

The final step in cultivar development is seed increase and distribution. Sometimes seed increase is handled by the breeder, and some organizations have other people who are responsible for that task. The seed increase must be done so the line is not contaminated with seed of other cultivars or by foreign pollen.
SOURCES OF GENETIC VARIABILITY

Types of Parents and Populations

Examination of pedigrees from many cultivars that have been grown extensively in the United States and Canada shows that most parental material consisted of cultivars or elite experimental lines adapted to their area of production. These adapted lines and cultivars make up the elite germplasm that a breeder will use. Unadapted or exotic germplasm makes up a very small part of the parental stocks. Breeders have discovered that crossing to exotic germplasm results in progeny that are less desirable than the adapted parent. There are so many genes segregating in such a cross that the chances of finding desirable segregates is remote, even in very large populations. A breeder cannot expect to obtain malting cultivars from single-cross populations involving one nonmalting parent, even though it is adapted to the area. Malting barley cultivars have many genes contributing to quality, and barley breeders have accumulated this array of favorable genes by many cycles of crossing and selection. As a result, introducing genes from a nonmalting cultivar reduces the high level of quality expected in malting cultivars. Crosses between adapted cultivars, even those which share some common background, does not seem to limit genetic diversity and has resulted in improved yield and malt quality. This accumulation of desirable genes has not been accomplished in one step, but rather through several cycles of selection in which the best-adapted types of one cycle were used as parents to form new populations for the next cycle. This successful procedure can be likened to recurrent selection, in which genotypes are intercrossed that are high yielding, disease resistant, agronomically desirable, and of high quality.

Although the beginning breeder should be cautious in use of exotic germplasm, such germplasm can provide new sources of disease resistance or other desired characters, such as semidwarfness or resistance to barley yellow dwarf virus. Incorporation of one of these characters into adapted germplasm involves backcrossing and selection. Care must be taken to retain the desired genes in the backcross program, particularly for quantitative characters controlled by multiple genes. Only after the character is incorporated into an adapted background should a cross be made to another adapted parent for the direct selection of a new cultivar. Most breeders have several of these ancillary programs in progress to provide new genetic materials for the main program.

Germplasm with genes for disease resistance or some other desired character is available from the curator of the USDA collection of barley in Beltsville, Maryland, and from the Canadian counterpart in Ottawa, Ontario. These collections contain over 30,000 pure-line accessions and 21 composite crosses. The composite crosses have been developed for
specific purposes, and are registered with the Crop Science Society of America. For example, CCXXXV has various sources of resistance to scald, leaf rust (incited by *Puccinia hordei* Otth.), and powdery mildew [incited by *Erysiphe graminis* (DC.) ex Merat f. sp. *hordei* Em. Marchal], and CCXXXIV has tolerance to soils with high pH and high aluminum. Composite crosses can be grown in the area where the breeder can select for plants with the desired genes and then make crosses to adapted parents. It is highly unlikely that a selection from an unadapted composite cross could be released as a new cultivar. However, many composite crosses carry a gene for genetic male sterility, and over time the population should shift naturally in the direction of adapted genotypes.

**Population Development by Hybridization**

Barley is a self-fertilizing plant, and artificial hybridization requires removal of anthers from florets of the female plant (Starling, 1980). Basic tools needed for crossing are a scissors and a forceps. Although inexpensive tools can be used, small stainless-steel scissors of surgical quality with a 3-cm blade make the job much easier. Stainless steel forceps, 10 cm in length with small tips, make emasculation easy and fast. A cord with the scissors and forceps attached to either end and extended around the back of the worker’s neck helps keep tools accessible.

A list of all planned matings and their objectives should be prepared prior to crossing. All emasculations and pollinations can be recorded on the list as they are completed. Several spikes of the female parent usually are pollinated by the same male genotype to ensure that enough *F₁* seeds are obtained. The number of *F₁* seeds needed will depend on the desired size of the *F₂* population. If the breeder wants 2000 *F₂* plants from a certain cross, and expects a minimum of 100 seeds per *F₁* plant, then 20 hybrid seeds are needed. Extra *F₁* seeds are desirable because adverse weather conditions or other disasters may result in loss of *F₁* plants.

Emasculation must be accomplished while anthers are immature, preferably 1 to 2 days before they normally dehisce. Ability to identify the proper emasculation stage is gained through experience. In the absence of previous experience, a good place to start is when awns begin to emerge from the collar of the flag leaf (Fig.4-2). Each cultivar varies slightly in its morphological development at anthesis, and temperature, moisture, light intensity and duration, and soil fertility also affect timing of anthesis. After physically examining several tillers in different developmental stages, the breeder can estimate which ones will have flowers at the proper stage for emasculation.

The spike is enclosed by the flag leaf sheath before emasculation. The flag leaf sheath is cut off immediately above the tip of the spike. The cut
sheath can be unrolled from around the spike and bent downward at a point just below the spike. At this stage of development, the rachis and peduncle are very fragile and the spike will need gentle support from the worker’s fingers (Fig. 4-4). Workers should be cautioned not to twist the rachis or peduncle during emasculation because they are damaged easily, resulting in death of the spike. Lateral florets of both two- and six-rowed barley and very small central florets at the base and tip of the spike are removed carefully with a forceps.

Emasculation can be accomplished by physically removing anthers with a forceps. There are two techniques for this procedure. One is called the slit method and involves using a sharp forceps to slit the back side of
the lemma, followed by insertion of the forceps through the slit and removal of the three anthers. A more common technique is to cut off the tips of the florets just above the anthers. In good light, the green anthers can be distinguished faintly through the lemma. The anthers are removed with a forceps, and care must be taken not to damage the stigma. All florets on the spike must be emasculated to prevent self-pollination. The worker should develop a regular pattern of emasculation to ensure that no florets are missed. One technique is to always emasculate from the bottom to the top of the spike. This practice reduces the chance of pollen shed from anthers prematurely ripened by heat from the worker’s fingers. The tips of all the florets should be cut off on one side of the rachis and the anthers removed before using the same procedure on the opposite side of the rachis. An alternative emasculation technique, called the clip method, involves cutting off the top one-half of the floret to remove about one-third of the green anther. Green anthers disturbed in this manner normally do not shed viable pollen.

After all florets have been emasculated, the flag leaf sheath is returned to its original position around the spike. The leaf sheath performs a dual function of lending support to the peduncle and rachis and preventing desiccation of the florets. Glassine bags or dialysis tubing can be placed over an emasculated spike to prevent entrance of foreign pollen and to maintain humidity around the spike. The worker should attach a small jewelers tag to each emasculated spike indicating the date or emasculation. The worker’s initials can be recorded on the tag, if more than one person is emasculating.

Emasculated florets are ready for pollination when the lemma and palea open slightly. This stage occurs 2 to 3 days after emasculation, but pollination can be delayed for up to 7 days after emasculation in favorable environments. Tips of emasculated spikes normally are extruded from the flag leaf sheath by the elongating peduncle and workers can observe when florets should be receptive without opening the flag leaf sheath (Fig. 4-5).

For pollination, a spike is selected in which anthers have begun or are ready to dehisce, and the tips of the florets are cut off to expose the anthers. Mature anthers usually will extrude from the trimmed floret as the filaments elongate (Fig. 4-6). Workers will discover that anthers extrude best on bright sunny days. Extrusion of anthers on cloudy days in greenhouses often can be improved by providing supplemental lighting. Pollen usually is shed in the morning; therefore, most workers make pollinations in the morning and emasculations later in the day. Maturity of anthers can be accelerated by exposing a spike to sunlight or a heat lamp.

One procedure of pollination is to collect pollen from the male parent on a folded glassine bag and transfer it by tips of forceps onto the stigma of each emasculated floret, one by one. A second procedure involves the transfer by forceps of single mature anthers to one or two emasculated
florets. The stigma of the female can be touched gently with the anther to promote pollen dispersal. The remains of the anther can be left in the female floret. The approach method is a third procedure of pollination in which entire spikes of the male parent can be placed above an emasculated female spike in the same glassine bag. Pollen may be shed over several hours or days, depending on environmental conditions. In the approach method, male spikes can be removed from the donor plant, and the peduncle placed in a vial containing water. The vial can be taped to a support stake next to the female plant. Tapping the bag periodically can aid in pollen dispersal.

A fourth pollination technique is called the *twirl method*. With this
method, the closed end of the glassine bag is cut off and a spike from the male parent that is shedding pollen is inserted upside down. The worker spins the peduncle of the male spike between thumb and forefinger, and pollen is released over the exposed female florets. The male spike is removed, the glassine bag secured, and a record of the male and female parents is entered on the tag. If the number of male spikes is limited and plants are in pots, more than one female spike can be enclosed in a glassine bag and pollinated simultaneously with one male spike. Workers should cleanse hands and tools with alcohol or soap and water when changing from one male genotype to another.

In all but the approach method of pollination, flag leaf sheaths of the female are placed around the pollinated spike to provide support and prevent desiccation. Kernel shape is more normal when the spike is enclosed by the leaf sheath. Under humid conditions, glassine bags can be removed about 1 week after pollination to help prevent fungi from infecting developing kernels.

Researchers may need to stagger planting dates of male and female parents so they will flower at the same time. Staggering planting dates under field conditions may be more difficult than in greenhouses, but selec-

Figure 4-6  Barley spike with anthers extruding is a source of pollen.
tively pruning early plants may force some spikes to develop later. Relative heading dates of cultivars grown under greenhouse conditions may not coincide with heading dates of the same cultivars grown under field conditions. The fall greenhouse environment of reduced light and altered day length can change the normal differential noted for heading dates of cultivars in the field. Therefore, additional planting dates of male and female parents will help ensure that all desired crosses can be made.

Breeders working with winter barley in the greenhouse must vernalize their seedlings. The length of time required for vernalization is somewhat genotype dependent, but 35 days at 3 to 5°C usually is sufficient. Potted seedlings can be placed in vernalization chambers, or petri dishes containing germinated seeds can be kept in a refrigerator for the prescribed time before transplanting.

Culms of barley grown in greenhouses or growth chambers are subject to lodging and need support. Plants grown in pots can be supported by using metal or bamboo stakes and plant ties (Fig. 4-7). Plants grown in soil beds can be supported by string or twine attached to stakes anchored at the ends of the rows.

When crosses are made in a greenhouse or growth chamber, adequate lighting and good soil fertility are essential. Supplemental light in

Figure 4-7 Barley plants supported by bamboo stakes. Glassine bags protect emasculated spikes from foreign pollen and desiccation.
greenhouses is necessary in Canada and the northern United States during the fall and winter growing seasons. Although incandescent and fluorescent lighting are adequate to induce flowering, fixtures with 1000-W mercury vapor or sodium halide bulbs provide enough light for good plant growth and pollen development. Low light intensity results in poor anther development, which makes crossing difficult or impossible.

Barley develops most rapidly under long-day or short-night conditions. Greenhouse crops grown during the fall and winter flower more rapidly if supplemental light is provided in the early morning or early evening to make a 15-hour day. Alternatively, the same goal can be accomplished by interrupting the night with 1 or 2 hours of light.

Crossing under field conditions can be successful in areas like Arizona where storms seldom occur during the crossing and maturation period. The relatively cool days and long nights extend the period when crosses can be made. In many northern areas where barley is grown during the summer months, warm temperatures and long days cause rapid plant development, and crossing in the field is limited to a few days. Areas such as the Upper Mississippi Valley of the United States and some barley growing areas in Canada are subject to summer storms. These storms damage or destroy spikes covered with glassine bags, even when supported by stakes. Therefore, most breeders in storm-prone areas do not attempt to cross barley in the field.

When F₁ or other seeds are planted shortly after harvest, they may not germinate because of postharvest dormancy. Dormancy can usually be broken if the seeds are dried, placed on wet blotter paper in a petri dish and allowed to imbibe, and transferred to a refrigerator at 2 to 4° C for 4 to 5 days. Removal of the lemma and palea also breaks dormancy of most genotypes.

**Mutagenesis**

Barley has been subjected to many different mutagens, including ionizing radiation and chemicals. Radiation causes more chromosomal breakage than chemicals and is not used widely at present. Ethyl methane sulfonate (EMS) and sodium azide are two chemicals that have been used successfully to induce different types of mutants in barley. Some examples of cultivars that have been developed directly or indirectly through mutation breeding and the mutant character they possess include: 'Samson' (short straw); 'Boyer' (short straw); 'Mari' (early maturity); 'Atem' (mildew resistant); 'M-737' (low beta-glucan); and 'Galant' (proanthocyanidin-free).

Mutagenesis is not a breeding procedure used to the exclusion of others, but is considered a tool to increase genetic variability. Most muta-
tions are deleterious; therefore, rigorous selection must be practiced when evaluating mutant populations. Anderson and Reinbergs (1986) discuss mutation breeding and have further references on the subject.

BREEDING PROCEDURES

Barley improvement by selection in heterogeneous natural populations has occurred for many centuries. Selection initially was done by nature, and later by people who grew barley as a food or feed crop. Initial introductions into the United States and Canada were not pure cultivars, but rather a mixture of genotypes. The practice of growing mixtures still can be observed in Ethiopia, North Africa, the Middle East, and Tibet, where landraces are a blend of several genotypes. Not until late in the nineteenth century were artificial hybridization and selection used for cultivar development. After the rediscovery of Mendel's work, artificial hybridization became common.

Most barley breeders use a combination of breeding strategies to develop new cultivars. The particular strategy will depend on objectives for a given cross. A breeder may use backcross, bulk, pedigree, recurrent selection, single-seed descent, doubled-haploid, and composite-cross procedures in various parts of the overall program.

Backcrossing

This breeding procedure is useful when easily identified characters controlled by one or two genes are to be added to an existing cultivar or elite line. Backcrossing is most attractive for characters that can be identified in the F₁ or F₂ generation. Examples of characters suitable for backcrossing include earliness, short stature, absence of proanthocyanidin, and aleurone color. Genes for resistance to diseases, such as loose smut or barley yellow dwarf virus, are less suitable for a backcross program because resistant plants may not be identified until the F₃ or F₄ generation. This slow cycling of backcross generations discourages some breeders from backcrossing because the recurrent parent may be outdated by the time the program is complete. However, it is important to incorporate genes for qualitative characters into adapted genotypes that can be used as parents.

An example of a cultivar that was developed by backcrossing is 'Erbet' (Table 4-3). 'Erbet' was derived by transferring a gene for earliness from 'Prior' into the cultivar 'Betzes' (Hockett and Eslick, 1972). Selection for the earliness of 'Prior' was made in each backcross F₂ generation.
Table 4-3 Development of the Cultivar ‘Erbet’ by the Backcross Method

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1958</td>
<td>Field</td>
<td>Cross made of ‘Prior’ × ‘Betzes.’</td>
</tr>
<tr>
<td>1959</td>
<td>Field</td>
<td>Grew F₂ plants, and made the first backcross between ‘Betzes’ and selected early heading plants.</td>
</tr>
<tr>
<td>1960</td>
<td>Field</td>
<td>Grew BC₁,F₂ plants, and made the second backcross between ‘Betzes’ and selected early heading plants.</td>
</tr>
<tr>
<td>1961–1964</td>
<td>Greenhouse and field</td>
<td>Repeated the procedures used for the first and second backcross to obtain the third through sixth backcross.</td>
</tr>
<tr>
<td>1965</td>
<td>Field</td>
<td>Grew BC₄,F₂ plants, selected early heading individuals.</td>
</tr>
<tr>
<td>1966</td>
<td>Field</td>
<td>Grew BC₄,F₄ progeny rows, bulk harvested 39 desirable rows.</td>
</tr>
</tbody>
</table>

*Information provided by Hockett (1985).

The original cross was made in 1958 and the final selection was made in 1967.

Single-Seed Descent

The single-seed descent procedure attempts to maintain a high level of heterogeneity among a large number of plants in a population as they are brought rapidly toward homozygosity. The basic procedure is to remove one or two seeds from the spike of selected F₅ plants, grow the F₅ plants and again remove one seed from each spike for advancement. This procedure can be followed through the F₄ or F₃ generation, at which time the entire spike is harvested and the seed is planted in a progeny row for evaluation. Breeders may use single-seed descent with fall and winter greenhouse crops to advance material toward homozygosity and reduce
Table 4-4  Development of the Cultivar ‘Morex,’ Illustrating Use of Single-Seed Descent

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Activity*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1969</td>
<td>Fall greenhouse</td>
<td>Cross made of ‘Cree’ × ‘Bonanza.’</td>
</tr>
<tr>
<td>1970</td>
<td>Winter greenhouse</td>
<td>Grew F₁ plants.</td>
</tr>
<tr>
<td>1970</td>
<td>Field</td>
<td>Grew F₂ plants; harvested individual spikes from selected plants. One kernel from each selected spike was put into a bulk.</td>
</tr>
<tr>
<td>1970</td>
<td>Fall greenhouse</td>
<td>Grew F₃ population and one kernel from each spike was harvested and put into a bulk.</td>
</tr>
<tr>
<td>1971</td>
<td>Winter greenhouse</td>
<td>Grew F₄ population and harvested plants individually.</td>
</tr>
<tr>
<td>1971</td>
<td>Field</td>
<td>Grew F₅ progeny rows and harvested individual spikes within selected rows.</td>
</tr>
<tr>
<td>1971–1972</td>
<td>Winter, Mexico</td>
<td>Grew F₆ progeny rows. Selected rows were harvested individually in bulk and the seeds were returned to Minnesota.</td>
</tr>
<tr>
<td>1972</td>
<td>Field</td>
<td>First-yield evaluation of the F₅-derived lines in the F₇.</td>
</tr>
<tr>
<td>1978</td>
<td></td>
<td>‘Morex’ released to farmers.</td>
</tr>
</tbody>
</table>

*Information provided by Rasmusson (1985).

the overall time needed to develop a new cultivar. ‘Morex,’ released by Minnesota (Rasmusson and Wilcoxson, 1979), is an example of a cultivar for which single-seed descent was used in the F₃ and F₄ generations (Table 4-4).

**Bulk Method**

The bulk method is an efficient way to advance material in segregating generations because it requires comparatively little time from the breeder. With this method, seed from all F₃ plants of a cross is harvested in bulk and a sample of the bulk is planted in a plot of approximately 0.01 hectare. Seed from the F₅ plants in a plot is harvested in bulk, and a sample is planted in a plot the following year to produce F₆ plants. This cyclic procedure can be continued until the plants reach the desired level of homozygosity. Many breeders make spike selections within the F₅ or F₆ population, and plant progeny rows the following year. One advantage of
the bulk method is that natural selection should reduce the frequency of the unadapted types in the population. The breeder has the option of modifying the basic procedure and can impose selection during any generation, but the selection should not be so restrictive that population size of the bulk is reduced. 'Heartland,' released by Agriculture Canada (Therrien et al., 1985), is an example of a cultivar developed by the bulk method (Table 4-5).

Pedigree Selection

The pedigree method allows a breeder to maintain a continuous record on selected material, from the F₂ generation to the time seed is bulked to start yield trials. Each F₂ plant selected from a cross is identified by a cross and selection number. Progeny rows are grown from each F₂ plant and selections are made among and within the F₃ progeny rows. The three to five F₂ plants selected within a row are identified by number, seeds from each plant are grown in F₄ progeny rows the next year, and row and plant selections again are made. This procedure can be continued until the desired level of homozygosity is reached, but seldom continues past the F₅ or F₆ generation, at which time seeds within selected rows are bulked and used to plant yield trials. The number of plants selected within a progeny row should be greatest in the F₄ and may be reduced in later gen-

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Activity*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974</td>
<td>Fall greenhouse</td>
<td>Cross made of 'Klondike' × BT416.</td>
</tr>
<tr>
<td>1975</td>
<td>Winter greenhouse</td>
<td>Grew F₁ plants.</td>
</tr>
<tr>
<td>1975</td>
<td>Field</td>
<td>Grew F₂ populations; harvested the plants in bulk and selected the largest seeds for the next planting.</td>
</tr>
<tr>
<td>1975–1976</td>
<td>Brawley, California</td>
<td>Grew the F₃ population in rows, harvested the plants in bulk, and selected the largest seeds for the next planting.</td>
</tr>
<tr>
<td>1976</td>
<td>Field</td>
<td>Grew the F₄ population, individually harvested all seed from selected plants.</td>
</tr>
<tr>
<td>1977</td>
<td>Field</td>
<td>Grew F₅ progeny plots (three rows each) and harvested selected plots individually in bulk.</td>
</tr>
<tr>
<td>1984</td>
<td></td>
<td>'Heartland' was licensed and released.</td>
</tr>
</tbody>
</table>

*Information provided by Wolfe (1985).
Table 4-6 Development of the Cultivar ‘Beacon’ by the Pedigree Method

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1963</td>
<td>Winter greenhouse</td>
<td>Cross made of ‘Conquest’ × ‘Dickson.’ The cross was designated C63-5.</td>
</tr>
<tr>
<td>1963</td>
<td>Growth chamber</td>
<td>Grew F₁ plants of C63-5.</td>
</tr>
<tr>
<td>1963–1964</td>
<td>Mexico</td>
<td>Grew F₂ population and harvested individual spikes from 212 selected plants.</td>
</tr>
<tr>
<td>1964</td>
<td>Field</td>
<td>Grew F₃ progeny rows of C63-5-1 to C63-5-212. F₃ plant selections were made in 19 rows.</td>
</tr>
<tr>
<td>1964–1965</td>
<td>Mexico</td>
<td>Grew 38 F₄ progeny rows, including C63-5-74-1 from which ‘Beacon’ was derived. Spike selections were made within desirable rows, including C63-5-74-1.</td>
</tr>
<tr>
<td>1965</td>
<td>Field</td>
<td>Grew F₅ progeny rows, including C63-5-74-1-1 from which ‘Beacon’ was derived. Spike selections were made within desirable rows, including C63-5-74-1-1.</td>
</tr>
<tr>
<td>1965–1966</td>
<td>Mexico</td>
<td>Grew F₆ progeny rows, bulk harvested C63-5-74-1-1-2, which became ‘Beacon.’</td>
</tr>
<tr>
<td>1966–1972</td>
<td>Field</td>
<td>State and regional yield trials of the F₆-derived line. ‘Beacon’ was released.</td>
</tr>
<tr>
<td>1973</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Recurrent Selection

One of the best sources of parental material a barley breeder has exists in the elite lines that have been developed over time. These lines have many of the best agronomic, disease resistance, and quality traits that can be found for the area. Continuous cycles of selection and intercrossing of the best lines in the breeding program, including some additions of other cul-
tivars and lines from other breeding programs that show good adaptation, is a type of recurrent selection. Each cycle of selection in barley is relatively long because populations are inbred to the F<sub>4</sub> or F<sub>5</sub> generation before lines are derived for evaluation of agronomic, disease resistance, and quality traits during several years.

**Doubled-Haploid Breeding**

There are several methods of developing doubled haploids (Choo et al., 1985), but the most commonly used procedure is based on the phenomenon that seeds with the haploid number of chromosomes (n = 7) develop when a *H. vulgare* ovary is fertilized with pollen from *H. bulbosum*. The breeder emasculates an F<sub>1</sub> plant that resulted from a cross between two *H. vulgare* parents, and pollinates the stigma with pollen from *H. bulbosum*. A gradual elimination of the *H. bulbosum* chromosomes during early mitotic divisions results in a haploid embryo. The developing haploid embryo must be cultured on artificial media to survive. The haploid plant can be converted to a homozygous diploid by appropriate treatment with nitrous oxide or colchicine. For efficient use of this breeding method, large numbers of florets must be pollinated with *H. bulbosum* pollen because only 5 to 10 doubled haploids survive from pollination of 100 florets (Kasha and Reinbergs, 1981). Reinbergs et al. (1976) suggested that as few as 20 doubled-haploid lines were sufficient to evaluate the potential of a cross. Thus, a breeder would pollinate a minimum of 200 florets per cross to obtain 20 lines. The main advantage of this procedure is that homozygous lines are developed in one generation and yield testing can begin whenever seed supplies are adequate. Disadvantages of the procedure include the requirement for laboratory and growth-chamber facilities and special training for technical personnel. Appropriate *H. bulbosum* stocks must be obtained because some are more efficient than others in effecting this phenomenon. At least three cultivars, 'Mingo' and 'Rodeo' in Canada and 'Gwynan' in Wales have been developed using the doubled-haploid technique. 'Mingo' was developed using the procedure outlined in Table 4-7 (Ho and Jones, 1980).

**Composite Crosses and Male-Sterile-Facilitated Recurrent Selection**

Currently, there are 44 composite crosses recorded for barley, and 21 of these have been registered as germplasm with the Crop Science Society of America. The first composites were developed by making single crosses among many cultivars or pure-line selections, bulking the F<sub>1</sub> seed, and growing the composite as a bulk for several generations. Breeders interested in the bulk as a source of germplasm could plant a plot of the
Table 4-7  Development of the Cultivar 'Mingo' by the Doubled-Haploid Method

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 1974</td>
<td>Growth room</td>
<td>Cross made of 'Vanier' × 'Laurier,' F₁ embryos transferred to culture media.</td>
</tr>
<tr>
<td>March to December 1974</td>
<td>Growth rooms</td>
<td>F₁ plants grown and pollinated with <em>H. bulbosum</em>. Embryos with the haploid number of chromosomes were cultured to produce seedlings. Chromosome number of seedlings was doubled and 200 doubled-haploid seeds were harvested.</td>
</tr>
<tr>
<td>January 1975</td>
<td>Growth room</td>
<td>Seed increase of doubled-haploid plants. Fourteen doubled-haploid lines from the cross were tested in one provincial trial.</td>
</tr>
<tr>
<td>1975</td>
<td>Field</td>
<td>Seven doubled-haploid lines were tested in five provincial trials.</td>
</tr>
<tr>
<td>1976</td>
<td>Field</td>
<td>One line was tested in provincial and licensing trials.</td>
</tr>
<tr>
<td>1977 – 1978</td>
<td>Field</td>
<td>'Mingo' was licensed and released.</td>
</tr>
<tr>
<td>1979</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Information provided by Ho (1985).

population and select plants with the desired characteristics the first year or allow natural selection to act on the population for several years before making selections. The selections usually were used by breeders as source germplasm for specific characters, but occasionally they were released as cultivars.

Genetic male sterility, first reported by Suneson (1940), facilitated the development of later composite cross populations. Breeders used one to many lines homozygous for the *msg* gene as females and many other lines as males to develop the basic populations. Presence of the male-sterile gene in the population allowed natural intermating among the plants in each generation and enabled the breeder to add genotypes with desired genes into the population at any time. Growing the population in a location for a number of years allowed natural selection to shift the population toward a predominance of adapted types, and the breeder could extract lines for use as parents.

Populations used for male-sterile-facilitated recurrent selection (MSFRS) are a modification of composite crosses. The procedure is to plant a population segregating for male sterility, and which contains the genes that the breeder wants to combine into one genotype. Crosses are made between selected plants and male-steriles. The *F₁* generation is grown and no selection is practiced. The *F₂* generation is grown in a space-planted nursery and many male-sterile and male-fertile plants are selected and crossed. Hybrid seeds are planted and no selection is practiced. The *F₂* generation again is grown in a space-planted nursery and the
crossing cycle is repeated. If the F₁ and F₂ generations are grown in different environments, for example Arizona and Montana, the time required per cycle can be reduced. This method of recurrent selection allows for recombination among desirable genotypes and prevents rapid inbreeding of the population. Individual plant selections can be made at the end of any cycle and placed in progeny rows for testing and purification. The cultivars ‘Gus’ and ‘Reliance’ resulted from selections out of CC XXXII which had been developed through MSFRS (Ramage et al., 1976).

Winter Barley

Breeding winter barley requires slightly different procedures than breeding spring barley because winter barley requires a vernalization period to initiate flowering. This extra time period limits the number of generations that can be grown conveniently each year, and the time required to develop new cultivars or incorporate new characteristics into adapted cultivars is extended. Any of the breeding procedures already described can be used to develop winter barley cultivars. The cultivar ‘Wysor,’ released by Virginia, is used to illustrate the development of winter barley cultivars (Starling, 1985) (Table 4-8).

Off-Season Nurseries

In the southwestern United States where spring barley is planted in the field during November or December, the off-season for production occurs during the hot summer months. Barley grows poorly in the greenhouse at that time. Breeders in Arizona overcome this difficulty by planting a summer nursery in Montana, and Montana breeders often reciprocate by planting a winter nursery in Arizona. Breeders in the northern United States and Canada may have winter nurseries in southern United States, Mexico, or New Zealand. When greenhouse or growth chamber facilities are available for crossing, the timetable described in Table 4-9 can be used for advancing germplasm to yield trials.

FIELD-Plot Techniques for Genotype Evaluation

Resources Used at Each Phase

Breeders designate the material in yield trials in various ways. They may use the terms YT1, YT2, and YT3, to describe those lines that have been in yield trials for 1, 2, or 3 years. A breeder will have the greatest number
Table 4-8  Development of the Winter Barley 'Wysor'

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Activity*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975</td>
<td>Greenhouse</td>
<td>Ten single crosses were made between one or more of three lines with 'Sussex' or similar parentage and one or more of eight lines with 'Surry' or similar parentage. The purpose of the crosses was to combine the disease resistance, high yield, and early maturity of the 'Sussex' group with the winter hardiness, shorter straw, better lodging resistance and test weight, and leaf rust resistance of the 'Surry' group.</td>
</tr>
<tr>
<td>1975—1976</td>
<td>Field</td>
<td>Ten F₁ populations were grown. Seeds from all populations were bulked into one lot.</td>
</tr>
<tr>
<td>1976—1977</td>
<td>Field</td>
<td>The F₂ population was grown at two locations. Selected spikes from both locations were composited.</td>
</tr>
<tr>
<td>1977—1978</td>
<td>Field</td>
<td>The F₃ population was grown at two locations. Selected spikes from both locations were bulked.</td>
</tr>
<tr>
<td>1978—1979</td>
<td>Field</td>
<td>The F₄ generation was handled similarly to the F₂ and F₃.</td>
</tr>
<tr>
<td>1979—1980</td>
<td>Field</td>
<td>F₅ plants were grown at two locations and spike selections were made.</td>
</tr>
<tr>
<td>1980—1981</td>
<td>Field</td>
<td>F₆ progeny rows were grown at one location and the best rows were harvested separately in bulk.</td>
</tr>
<tr>
<td>1981—1982</td>
<td>Field</td>
<td>Observation plots of the F₅-derived lines in the F₇ were grown at two locations. Plot 44-553 was identified as promising, and the line was given the identification number VA 83-42-63.</td>
</tr>
<tr>
<td>1982—1983</td>
<td>Field</td>
<td>VA 83-42-63 was grown in yield trials at two locations.</td>
</tr>
<tr>
<td>1983—1984</td>
<td>Field</td>
<td>VA 83-42-63 was grown in state and regional yield trials; 375 spike selections were made to develop a source of breeder seed.</td>
</tr>
<tr>
<td>1985</td>
<td></td>
<td>'Wysor' was released.</td>
</tr>
</tbody>
</table>

*Information provided by Starling (1985).

of experimental lines in the YT1 trials. The number of lines tested at this stage depends on the size of the program, but breeders should not plant more than they can evaluate and harvest properly. Sites chosen to plant yield trials should be in areas where potential cultivars will be grown. Testing lines in the area of production should expose them to prevalent diseases and allow the breeder to select the most resistant genotypes. Sites should be as uniform in soil type and fertility as possible. Comparisons with a check cultivar are made for maturity, plant height, straw strength, shattering, resistance to prevalent diseases, and yield.

The number of lines tested in YT2 trials will be much less than that
Table 4-9  Timetable for Advancing Generations from Initial Cross to the Yield Trial Stage

<table>
<thead>
<tr>
<th>Time</th>
<th>Location</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st year</td>
<td>Fall greenhouse</td>
<td>F₁ seed produced by hybridization.</td>
</tr>
<tr>
<td></td>
<td>Winter greenhouse</td>
<td>Grow F₁ plants.</td>
</tr>
<tr>
<td></td>
<td>Field</td>
<td>Grow F₂ plants and select those with desired traits; harvest one spike from each selected plant.</td>
</tr>
<tr>
<td>2nd year</td>
<td>Fall greenhouse</td>
<td>Plant one F₃ seed from each F₂ spike. Harvest one seed from each F₃ plant and bulk them.</td>
</tr>
<tr>
<td></td>
<td>Winter greenhouse</td>
<td>Grow F₄ plants and harvest one or more spikes from each plant.</td>
</tr>
<tr>
<td></td>
<td>Field</td>
<td>Grow F₁-derived lines in one-row plots. All lines from a given cross should be planted close to each other so that they all can be observed from one point in the field when selections are being made. This will enable the breeder to get an overall view of the lines in a cross before making selections among and within lines. Harvest selected F₄ plants or spikes from desirable lines or harvest the line in bulk.</td>
</tr>
<tr>
<td>3d year</td>
<td>Fall-winter</td>
<td>Increase seed of Fₓ or Fₓ-derived lines at a southern location. This increase commonly provides enough seed to plant replicated yield trials at one or two locations.</td>
</tr>
</tbody>
</table>

tested in YT1. Perhaps as many as 80% of the YT1 lines will be discarded. The number of test sites and the number of replications used for YT2 and more advanced trials can be increased over that used for YT1 trials because more seed is available, there are fewer lines, and more extensive data are required. While only one or two sites with two replications of YT1 lines may have been possible, tests at four or five sites with three or four replications are used for YT2 and more advanced tests. The testing procedure for evaluation of experimental lines can be illustrated using the six-rowed barley breeding program at North Dakota State University (Table 4-10).

Plot Types

Progeny rows planted from single spikes normally are from 2 to 3 m in length. Although progeny rows seldom are evaluated for yield, a check cultivar can be planted about every 10 rows so that experimental lines can be compared with the nearest check.

Various sizes of plots are used by barley breeders for yield evaluation.
Table 4-10  Procedure for Evaluation of Experimental Lines by North Dakota State University

<table>
<thead>
<tr>
<th>Stage</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>YT1</td>
<td>Three hundred and thirty lines are divided into 15 experiments of 25 entries each, including 22 experimental lines and three check cultivars. The experiments are grown in two replications at two locations.</td>
</tr>
<tr>
<td>YT2</td>
<td>Sixty-six lines selected from YT1 are divided into 3 experiments of 25 entries each, including 22 experimental lines and three check cultivars. The experiments are grown in three replications at four locations.</td>
</tr>
<tr>
<td>YT3</td>
<td>Twenty-one lines selected from YT2 and four check cultivars are planted in one experiment in three replications at four locations.</td>
</tr>
<tr>
<td>Tests after YT3</td>
<td>This experiment is called the “variety trial” and includes all important commercial barley cultivars, and advanced experimental lines from North Dakota, adjacent states and provinces, and commercial companies. When experimental lines from the North Dakota program enter the variety trial, they also are tested independently at the six branch experiment stations in North Dakota and are entered in the Mississippi Valley Uniform Regional Barley Nursery. The regional nursery is planted in eight states and one province. Experimental lines may stay in the variety trial for up to 5 years while they are being evaluated for possible release.</td>
</tr>
</tbody>
</table>

The smallest would be a two-row plot 3 m long with rows spaced 30 cm apart. The largest would be a six- or eight-row plot 10 m long with rows spaced 20 to 30 cm apart. Distance between outside rows of adjacent plots may be the same as the distance between rows within a plot, or this distance may be greater to accommodate the tires of planting and harvesting equipment and to reduce interplot competition. Interplot competition probably is greatest when genotypes in adjacent plots differ markedly in height, maturity, or straw strength. Whenever interplot competition may affect relative ranking of lines being tested, wider plots are needed and the outside rows can be used as a border and are not harvested. Otherwise, plot size should not materially affect relative rank of the lines tested. Plot size can be regulated by a combination of available seed and the type of planting and harvesting equipment. The outside of the experimental area should be bordered with plots of a common cultivar to help remove biases encountered by a lack of competition.

Soil uniformity of test sites can influence plot size. The breeder must try to keep the soil variation within replications at a minimum. This is easier with smaller plots than with larger plots. More replications of smaller plots rather than fewer replications of larger plots often is advantageous.
Experimental Designs Commonly Used

The randomized complete-block design is used more frequently than any other design for barley yield trials. This design is best suited for relatively small experiments because there is better chance to control variability among experimental units within replications. There is no maximum number of entries for this design, but coefficients of variation may increase to an unacceptable level if the number of entries per experiment exceeds 25 to 30. Several experiments of this size are necessary to evaluate a large number of experimental lines. Suitable check cultivars must be included in all experiments. Check cultivars should include the most widely grown cultivar in the test area and those that serve as standards for quality and for disease resistance.

If more than 25 to 30 entries are necessary in each replication of an experiment, a lattice arrangement can be used. Square and rectangular lattices can accommodate nearly any number of entries. Analysis of lattice designs is much more difficult than analysis of a randomized complete-block, unless a computer is available. Computer programs are more common for square than rectangular lattices. Lattices help to adjust for inherent variation that exists among experimental units within replications by reducing effective block size. A lattice arrangement is not recommended for trials in which lines are discarded before harvest. Missing plots reduce effectiveness of lattices and complicate analyses.

Equipment Used for Field Operations

The type of equipment available to the barley breeder has changed dramatically in the past 25 years. In the past, much of the equipment was designed by the breeders and fabricated in local shops because no commercial company was interested in building machines for such a small market. Today, several companies design and build sophisticated field research equipment.

Many breeders use a cone seeder for planting operations. The cone seeder can be modified easily to handle the planting of F₁ and F₂ seeds, progeny rows, and yield trials. Length of a planted row can be adjusted from 1.5 to 3 m for progeny rows and up to 25 or 30 m for space planting F₂ seeds. Figure 4-8 shows a cone seeder being used to plant progeny rows. The same seeder with different attachments can be used to plant yield trials and F₂ populations. Figures 4-9 to 4-11 show the results of planting these materials. Blank rows between F₂ populations facilitate access for selecting plants. A well-prepared seed bed is very important. However, the newer cone seeders with double disk openers, depth con-
Figure 4-8  A three-rowed cone seeder planting progeny rows. The same planter can be used to plant longer rows for yield trials.

Figure 4-9  Barley nursery of progeny rows. Each progeny row is 2-m long.
Figure 4-10  Barley nursery showing yield trial plots. Each plot is three rows 3-m long with 30 cm between rows.

Figure 4-11  Barley nursery of F₂ populations. Each population is grown in a two-row strip.
trol, and press wheels permit planting even when small stones, clods of soil, unincorporated plant residue, and excessively loose soil are present.

Precise application of pesticides in breeding nurseries is extremely important. High labor costs dictate that weeds be controlled by herbicides rather than by hand hoeing. The rate of herbicide application and its timing relative to the growth stage of the barley and weeds are important considerations. Proper application requires equipment that is calibrated carefully so that the correct volume of material is discharged from each nozzle. Application of herbicides, fungicides, or insecticides should be made only by certified pesticide applicators or under their direct supervision. Most states and provinces have extension bulletins that describe in detail procedures for pesticide application. Some barley genotypes are damaged more easily than others by certain herbicides. For example, 'Bowman' is more susceptible to damage than most other cultivars from application of diclofop [(±)2-[4-(2,4-dichlorophenoxy)phenoxy]propanoic acid], a herbicide for grassy weeds. The breeder should examine the nursery after the herbicide has been applied and note any differences in color or vigor of the plants. Application of a herbicide can act as a screen to eliminate genotypes that are susceptible to a product. All genotypes should be tested for response to those pesticides commonly used in the production area before consideration is given to their release as cultivars. Susceptible lines should be discarded.

Yield trials normally are harvested in one of two ways. One method utilizes a single- or double-row binder and a stationary thresher, usually of the Vogel type. The binder is used to cut the plots and tie the culms into bundles. The plants are cut slightly before they are ripe to prevent shattering. A large kraft-paper bag can be placed over the spikes with the aid of a funnel and secured with twine to prevent bird or weather damage while the grain ripens and dries. Several bundles can be placed together in an upright position and tied to form a shock. After the grains are mature, the bundles can be threshed with the Vogel thresher. Major advantages of using the binder-thresher technique are the near absence of admixtures, if care is taken by the operators, and ability to harvest lines with different maturities.

The most common harvesting procedure is with a plot combine, of which there are several manufacturers. The combines vary in width of cutter bar, ease of cleaning, and cleanliness of the threshed sample. Some machines can be operated by one person or they may be operated by a crew of three or four. If barley is not lodged badly, a combine crew can handle one plot every 30 seconds and still have very little seed admixture from one plot to the next. If pure seed is required, the combine can be cleaned with the aid of an air compressor before going on to the next plot. Operators soon learn where seeds are apt to remain in the machine.
Combines with augers are more difficult to clean than those with a catch pan for harvested grain. Some operators have added moisture meters and scales to obtain yield information as soon as the grain is combined. Figures 4-12 and 4-13 show a combine with these features.

Some breeding operations use single- or double-row binders to remove early-maturing plots from yield trials in which the entries have a range in maturity. Narrow alleys through yield trials make it difficult to maneuver a combine into position to cut early-maturing genotypes, and a binder is much easier to handle. If the breeder waits until all genotypes are ready to harvest with a combine, early-maturing lines may lodge or shatter. Plots cut with a binder can be threshed with the Vogel thresher or with the plot combine when later-maturing types are ready.

Single-row binders also are very useful in cutting selected rows from a progeny nursery. Another efficient method of harvesting a progeny nursery when adequate labor is available is to use hand sickles to cut the rows. A Vogel thresher generally is used to thresh progeny rows.

Figure 4-12 Plot combine equipped with (A) electronic scale and (B) moisture meter.
Considerations in Data Analysis

The general availability of automatic data processing equipment and numerous software packages makes it convenient for a breeder to use a computer for randomization and analysis of all experiments. The computer also can be used to print field books, field tags, and harvest tags.

Data taken on yield plots are recorded in a field notebook. The traits evaluated may include date of heading, date ripe, plant height, lodging, reaction to one or more prevalent diseases, shattering, spike erectness, yield, test weight, and kernel plumpness. Notes are meaningful when there is variation among the genotypes for the particular character. For example, if no lodging differential exists, there is no reason to take notes on all replications.

For purposes of analysis, it is helpful to have data on all entries in a replication. However, estimates for missing data can be made using techniques described in various statistical textbooks. Some of the statistical software packages available for data analyses are capable of handling missing data. Field notebooks should be arranged in a manner that allows
collected data to be transferred in a logical manner into a computer terminal or other device for data summarization. Small portable computers can be programmed to accept data from the operator while taking notes in the field. The data can be transferred later to a personal computer or mainframe for processing. A disadvantage of the portable computer is that the operator must be trained to remedy minor problems. Also, there is no immediate hard copy of data to refer to, but some researchers do not find this to be a problem. Data-processing equipment available to breeders makes it possible to obtain summary analyses very rapidly, enabling them to make decisions quickly on the lines to be advanced. There are many types of data processing equipment from which a breeder can choose. Changes in this type of equipment are frequent and there is concern that the machine bought today may be obsolete tomorrow. However much that may be true, the breeder can feel satisfied that the equipment in hand is much better than what was available before.

PROCEDURES FOR SEED PRODUCTION

Methods for Producing and Maintaining Breeder Seed

The degree of homozygosity in experimental lines depends largely on the generation that lines are derived for initial yield evaluation. Lines generally are derived from plants in the F₂ to F₆ generation in the pedigree method, and there is always some heterogeneity within the lines. Breeders in the United States and Canada are most concerned about having their cultivars uniform for the obvious agronomic and morphological characters. These characteristics include date of heading, plant height, awn type, rachilla hair length, aleurone color, date of ripening, two- or six-rowed spikes, and covered or naked kernels. Purification of a line for possible release as a cultivar usually follows this procedure:

1. Select up to 100 spikes of the desired type.
2. Plant each spike in a separate progeny row.
3. Carefully select among rows for the desired type and discard the off-type rows.
4. Examine plants within rows for uniformity of awn type and rachilla hair length, and discard those rows segregating for either character.
5. If lines may be segregating for aleurone color, watch for variation in kernel color between and within spikes as the kernels are maturing and retain rows homozygous for aleurone color.
6. Harvest each row separately in bulk.
7. Examine a sample of the harvested seed for uniformity of rachilla hair length and a pearled sample for aleurone color.
8. Bulk seed of uniform rows.

Purification of a line is easier when selecting for recessive rather than dominant characters because an extra generation is required to identify plants heterozygous for a dominant allele.

A breeder may have the opportunity to select for combinations of kernel characters that are different from all or most of the other cultivars grown in a region. These differences aid in differentiating between cultivars in the field and in seed samples. Maltsters want to have grain marketed in pure carload lots, and buyers rely on kernel characteristics to differentiate between cultivars. Recently, cultivars with similar kernel characters, but differing malting characteristics, have been marketed together. Some maltsters now use gel electrophoresis to differentiate between these cultivars.

Lines developed by the doubled-haploid technique need not be purified if purity has been maintained during testing. If admixtures are present, spikes of the desired type can be selected and progeny tested.

Seed should be increased in an area where outcrossing can be minimized. Outcrossing is rare on male-fertile spikes in Canada and northern areas of the United States. Outcrossing has been observed between two-rowed and six-rowed and between blue and white aleurone types in winter increase nurseries near Yuma, Arizona. Therefore, more isolation may be needed if breeder seed is increased in southern areas of the United States.

For certified seed production, the minimum distance between fields of different cultivars varies among states and provinces, but a distance of 1 to 3 m is quite common. These minimum distances were established to prevent mixtures during planting and harvest, rather than to prevent outcrossing. Land used for production of certified classes of seed also must meet certain requirements. Barley must not have been grown on the land for the previous 2 years unless it was of the same cultivar of the same or better class of seed.

**Commercial Seed Production and Marketing**

*Canada.* Before cultivars are released to growers in Canada, they must be recommended for licensing by formally appointed committees of barley breeders, quality personnel, and plant pathologists. Licenses are
issued by Agriculture Canada. A breeder may bring an experimental line
to the committees for consideration as either a malting or a feed barley.
By tradition, six-rowed malting cultivars have a blue aleurone and six-
rowed feed cultivars have a white (yellow) aleurone. Two-rowed malting
cultivars have long hairs on the rachilla. Two-rowed experimental lines
that do not meet malting and brewing quality requirements and have long
hairs on the rachilla are not licensed as feed barleys. These physical and
visual characteristics make it possible for grain buyers to determine
quickly whether or not a particular lot can qualify for the malting market.

Subsequent to licensing of a cultivar, most barley breeders in provin-
cial institutions and Agriculture Canada provide a supply of breeder seed
to Seed Canada (SeCan). SeCan is a national association of seed produc-
ers. One of their purposes is to distribute breeder seed to members who
will increase the seed and sell it to other growers. Grades of certified seed
follow the normal pattern of breeder, select, foundation, registered, and
certified. SeCan cultivars can be sold only as a class of certified seed.
SeCan collects levies on all seed sales, and will collect royalties when this
is requested by the releasing organization. Income from royalties is re-
turned to the institution releasing the cultivar and income from levies is
used by SeCan for promotion of seed stocks handled by SeCan and for
operating expenses.

United States. Seed of barley cultivars released by experiment stations in
the United States usually is distributed jointly by the state crop improve-
ment association and the private seed trade. However, seed distribution
procedures vary among states. Small quantities of seed also are offered to
experiment stations of adjacent states prior to release. Seed distributed by
crop improvement associations within a state may be allocated to coun-
ties or directly to seed producers for seed increase. The amount of seed
allocated to each county may be uniform or it may be allotted differentially
on the basis of barley hectarage in previous years or expected adaptation.
Breeder and foundation class seed usually is grown at the experiment sta-
tions or contracted by a nonprofit crop improvement association or
equivalent agency under their direct supervision. Elite seed growers are
the principal buyers of foundation seed, and these growers will sell the
registered and certified classes after increase. Some experiment stations
protect their cultivars by the Plant Variety Protection Act imposing the
restriction that the cultivar can be sold only as a class of certified seed,
and a few assess royalties.

Private companies protect their cultivars by the Plant Variety Pro-
tection Act. Hectarage planted to cultivars released by private compa-
nies is a small percentage of the total, but is expected to increase.
FUTURE PROSPECTS FOR CULTIVAR DEVELOPMENT

Cultivar development to the year 2000 will continue in those states and provinces where breeding work now is conducted. New breeding programs will not be started in areas where barley hectarage is limited because research institutions have budgetary problems and administrators will be allotting funds only to high priority research.

Breeders will place primary emphasis on improved yield of new cultivars, which can be accomplished both directly and indirectly. Indirect approaches will include incorporation of improved resistance to diseases and other plant pests and tolerance to salt, heat, and moisture stress so the plant can express fully its yield potential, or incorporation of better straw strength so farmers can direct combine and apply more fertilizer to achieve higher yields.

Other areas of emphasis are resistance to leaf rust and powdery mildew in winter barley regions of the Southeast, spot blotch and net blotch resistance in the upper Midwest, and improved resistance to barley yellow dwarf virus. The Ryd2 gene offers a fair level of tolerance to barley yellow dwarf virus, but better resistance has been found in some grass species. Leymus mollis (Trin.) Pilger and Elymus canadensis L. are essentially immune to this virus (Timian, 1985). These genera do not cross readily with Hordeum species, and transferring the Leymus-Elymus resistance will be a long-term project. The cereal leaf beetle, Oulema melanopus L., has reduced barley hectarage in Michigan and adjacent states. Germplasm with some tolerance to the insect has been developed, but improved resistance must be identified.

Various germplasm collections contain lines with an array of genetic diversity, but little is known about many of them. The difficulties in using these accessions are being addressed in the United States by a Crop Advisory Committee that is working with the curator to evaluate the entries.

More emphasis will be given to feed quality of barley in the future. Breeders will select for reduced fiber content and improved protein quality, and more emphasis will be given to hulless barley. Breeders and animal nutritionists will work together to develop screening tests that are suitable for the small quantities of seed that would be obtained from progeny rows or initial yield trials.

The impact of private seed companies on barley improvement gradually will increase. Commercial companies will place greater emphasis on hybrid barley because the opportunities for financial return are much greater than with pure-line cultivars. There have been only a few reports of substantial hybrid vigor in barley, but with the advent of chemical hybridizing agents, it will become much easier to make hybrids and have the seed quantities necessary to conduct yield trials. After high-
yielding combinations have been identified, characteristics that improve cross-fertilization can be incorporated into the parents, admittedly not a short-term project. Initial hybrids will be nonmalting types targeted for high-production areas because hybrid vigor in areas of low or erratic production probably will not be enough to justify seed cost. Hybrid malting barley will be more difficult to develop because quality constraints must be considered, in addition to agronomic and disease constraints.

The impact of biotechnology and genetic engineering on development of barley cultivars may not be apparent for many years. Barley is not one of the major crops, and biotechnology companies may concentrate attention on crops like maize, soybean, and wheat where the potential to recover investments is much greater. However, the genetic resources available and the short generation time make barley a desirable plant for biotechnological studies. Even after genetic engineers transfer a desirable gene to barley, the lines must be evaluated by conventional breeding techniques.

Genetic engineering can be instrumental in more accurate mapping of genes, and new, rapid methods to select for various traits may be developed. For example electrophoresis of certain plant extracts may provide a method to identify germplasm with good yielding ability or resistance to a specific disease. Plant breeders will have opportunities to work with genetic engineers and to utilize the information and materials they develop. Genetic engineering and plant breeding should not be considered competitors, but rather cooperators to achieve the goal of productive cultivars for producers.

REFERENCES

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