7
Snap Bean Breeding

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The terms snap beans (*Phaseolus vulgaris* L.), string beans, garden beans, and fresh beans are more or less synonymous, referring primarily to beans produced for consumption as a fresh or processed vegetable as opposed to a dry bean seed (pulse). Snap bean seed can also be used in the dry state like the dry bean types (pinto, kidney, pink, small red, etc.).

Snap beans are an important and stable component of the vegetable diet consumed by Americans (about 7 lb/capita), exceeded only by sweet corn, tomatoes, cabbage, and green peas(*114*). Over the past 20 years fresh per capita consumption has declined from 3 to 1.5 lb, whereas processed usage has increased from 3.8 to 5.5 lb. Canned consumption increased from 3 to 4 lb, whereas frozen usage went from 1 to 1.5 lb per person.

While the indeterminate tall climbing vine is genetically dominant and adaptatively superior in the wild, most snap beans grown in the United States today are determinate bush types. Home gardeners and some fresh-market growers still use a few vine types; however, vine types probably constitute less than 5% of the total acreage. Tall vine types are sometimes called pole beans because poles are often used as trellises, whereas short vine types are also referred to as half-runner types. Scarcity of labor and the high cost of hand picking led to the development of mechanical harvesters in the mid 1950s. Virtually all commercial operations are now mechanically harvested.

In 1980 about 370,000 acres of snap beans were harvested commercially in the United States with an approximate farm value of $192 million(*113*). Of that, canned beans were

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harvested from 214,970 acres (av. 5460 lb/acre) for a value of $82,580,000. Beans for freezing were grown on 59,580 acres (5700 lb/acre) at a worth of $27,095,000. Fresh-market beans (3200 lb/acre) were produced on 95,700 acres with a farm value of $82,541,000.

Beans as a vegetable are produced and used in a number of different ways. Most of the beans for processing (canned, frozen, freeze-dried) are round podded, while fresh-market cultivars are often flat or oval podded. Yellow-podded cultivars (wax beans) comprise about 15% of the total pack. Home gardeners, particularly in the northeast, also use certain cultivars in the green shell (shell bean) stage, i.e., large but still soft immature seeds.

The major U.S. processing areas (*113*) are Wisconsin (83,900 acres), New York (49,000 acres), Oregon (32,000 acres), Michigan (14,600 acres), and Tennessee (13,700 acres). The rest of the acreage is scattered throughout the country. Most of the fresh-market beans are produced in Florida (48,000 acres) and seed production (40,000 acres) is concentrated in south-central Idaho (*112*). The total annual production of snap bean seed, about 80 million lb, has an approximate farm value of $32 million. Most of the U.S. seed crop is used domestically, but an increasing proportion has been going to Europe in recent years.

Europeans generally consume more beans (especially fresh) than Americans, and European seedsmen traditionally have produced seed for Europe in East Africa. During the past ten years, several large European seedhouses have also established production operations in south-central Idaho. Most U.S. cultivars are not suited to European conditions because of susceptibility to anthracnose and halo blight, and the European preference for smaller sieved pods than the American processors use.

ORIGIN AND GENERAL BOTANY

The common bean is of New World origin, principally Central and South American (*60*). In the wild state, beans or near relatives are found from the lowland, warm, humid tropics, to the cold, high-altitude, short-season mountains, and the hot, arid deserts. Generally, however, the common beans with which we are most familiar are those cultivars that fit into a relatively narrow ecological zone.

Smartt (*107*,p.19) in describing the domestication of *Phaseolus* species, states that "there is no doubt that *Phaseolus vulgaris* is the most successful American bean followed by *P. lunatus* L. (lima), *P. coccineus* L. (scarlet runner), and *P. acutifolius* A. Gray (tepary) in that order. It is perhaps no coincidence that there is a rough correlation between the extent to which their habitat preferences and those of man coincide and their advance under domestication." The beans grown in North America are usually day-neutral, determinate bush types (*91*) that fit the temperate-zone requirements of warm soil (13°–21°C), moderate air temperatures (24°–29°C), especially during bloom, adequate moisture (10–18 in.) distributed more or less evenly throughout the growing season, a relatively neutral, fertile, well-drained soil, and adequate sunlight. Outside this optimal zone in North America for the common bean, other species of *Phaseolus,* some of which are near relatives but adapted to wider environmental extremes, are often substituted. In the Southeast during the hot humid part of the summer, lima beans and cowpeas [*Vigna unguiculata* (L.) Walp.] are grown more often than the common bean. In the hot semiarid zones of the Southwest, the tepary bean produces more reliably than the common bean, and at the colder moist extremes (the Northeast), selections within *P. coccineus* like the scarlet runner bean are used as garden varieties.

Several closely related species of *Phaseolus* (all $2n = 22$) can be hybridized to common bean (*107*). Honma (*55*) succeeded in crossing tepary with common bean and the resulting cv. Great Northern 27 sel. 1 carries resistance to common blight (CB) incited by *Xanthomonas campestris* pv. *phaseoli* (Smith 1897) *comb. nov.* from the cross. This germplasm was used by Schuster and Coyne (*92*) as a source of CB resistance. Giles Waines, at the University of California, Riverside (personal communication), has crossed tepary to common bean to transfer drought tolerance into common bean. Many breeders have utilized *P. coccineus* to obtain bacterial disease resistance, tolerance to colder climates, root rot resistance, and bean yellow mosaic virus (BYMV) resistance. Lorz (*65*) working in Florida showed common bean could be crossed with a number of closely related species of *Phaseolus*. Mok *et al.* (*76*) studied the barriers to interspecific hybridization using tissue culture and biochemical techniques.

In view of the largely unutilized genetic diversity within common bean for commercially desirable characteristics, bean improvement by interspecific hybridization should be left to scientists who specialize in this area of complex basic research. The same must be said of induced mutations, tissue culture screening, and protoplasmic fusion as means of crop improvement.

Domestication of Natural Mutations

Bush-type beans are almost never found in the wild. The determinate bush habit, so widely adapted to mechanical-harvester requirements, was most certainly derived from mutants as was the apical dominance found in commercial types (*107*). Similarly the convenience and commercial value of the stringless character (*1*) and the round pod shape (*2*) were quickly recognized and incorporated into breeding programs within the past 100 years. As little as 20 years ago, garden beans were usually referred to as string beans, a term still used today even though virtually all cultivars are now stringless. The term "snap" originated from the way fresh garden beans were broken or snapped into short segments by hand in preparation for cooking.

The high pod wall fiber content of most wild legumes is necessary for the way in which legume pods dehisce easily (even forcibly) when dry. This is a natural dispersal mechanism that favors survival of the species in the wild (*107*). However, a high pod wall fiber content is undesirable in a table vegetable, and premature shattering of a seed crop is economically unacceptable. Plant breeders have systematically selected against these wild traits. Again, most likely low fiber content originated in mutations that ancient civilizations were able to recognize, perpetuate, and utilize (*107*).

Some wild forms of *Phaseolus* like *Phaseolus polystachyus* can be either perennial or annual. A few perennial forms (none of which are found in the United States) form large fleshy tubers. Many of the related species, as well as many forms of *P. vulgaris* in the centers of genetic diversity, have a short-day photoperiod requirement, which precludes their culture in North America since they would not flower until fall and thus be killed by frosts before maturity. Steve Temple and Jeremy Davis, Plant Breeders at CIAT (Centro Internacional de Agricultura Tropical, Cali, Colombia), are transferring useful genetic characteristics like cold tolerance and flood tolerance into day-neutral germplasm lines so they can be more easily utilized by temperate-zone breeders (personal communication).

Gigantism (i.e., larger stems, leaves, pods, and seeds) is another distinction usually differentiating the wild from cultivated forms of the *Phaseolus* species. "Plants in the wild will by natural selection tend to adopt the strategy of producing the largest number of seeds possible" (*107*, p. 15). The gigantism found in domesticated forms is usually only

compensatory. The increased pod and seed size in the domestic cultivars is offset by a reduction in the number of pods and seeds. Final total yield limits are about the same as the wild form.

The survival value of hard-seededness, a type of dormancy induced by the water impermeability of the testa (*107*), is another wild trait that the domestic cultivars do not require. In fact, the variability in emergence and the difficulties hard seed present in cooking make this characteristic a disadvantage in the domesticated forms.

Plant Patent Requirements

Excellent botanical descriptions of *P. vulgaris* L. (chromosome number $2n = 22$) and its related species are presented by Smartt (*107*), and so they are not repeated here. Of more immediate relevance to the North American bean breeder is the description required by the USDA Agricultural Marketing Service (*111*) which administers the National Plant Variety Protection Act of 1970. This legal description (for garden beans and/or dry beans) becomes part of the registration procedure and eventually the basis for granting a patent.

This four-page description [Form LPGS-470-12(2-79)] is basically comparative rather than absolute. This is in recognition of the effect local environmental factors can have in the expression of genetic potential. It is also important that the descriptions be comprehensible, not only by nonscientific people involved in the production and commercialization of beans, but also by the legal profession and juries in the event of litigation over patent infringements.

The essence of patentability is a recognizable novelty, the variability of which can be described. Production performance or end-product quality characteristics are not part of the currently required description. Included are relative (compared to a known standard cultivar) descriptions of maturity, physical measurements, and comparative descriptions of the plant habit, leaves, flowers, pods, seeds, and pigmentation. Disease, insect, and physiologic resistance factors are also included. It was felt that requirements for grow-out trials or performance characteristics would be expensive, could be hard to administer, and would unduly delay release of new cultivars, thus cutting several commercially productive years from the 17-year patent.

FLORAL BIOLOGY AND CONTROLLED POLLINATION

The American Society of Agronomy and the Crop Science Society of America have recently published *Hybridization of Crop Plants* (*9*). "Each crop chapter specifically discusses parental material; plant culture; floral characteristics; artificial hybridization or self-pollination; natural hybridization; seed development, harvest and storage; and techniques for special situations."

The introductory chapters, plus the detailed chapter by Bliss on the common bean, make any attempt to repeat such information here completely unnecessary.

MAJOR BREEDING ACHIEVEMENTS OF THE RECENT PAST

Since the release of the first round-podded cultivar in 1865 and the first stringless cultivar in 1870 (*131*), the most significant breakthrough in snap bean improvements came with Bill Zaumeyer's (USDA, retired) release of the cv. Tendercrop (*134*) in 1958. Tendercrop set new industry standards for several plant and pod characteristics, and is still used today by the frozen bean processing industry. In 1970, 46% of the green-podded bush types had

Tendercrop germplasm in their ancestry (*132*). Besides having large, fleshy, bright-green, smooth, straight, round pods, Tendercrop has a relatively slow rate of seed and/or fiber development once it reaches maturity, thus giving some "holding ability" to harvest operations if delayed by weather or equipment problems. Tendercrop has a strong upright, relatively narrow plant habit, which holds pods primarily in the upper two-thirds of the canopy. This feature reduces spoilage of pods. Tendercrop was the first high-quality processing cultivar with a concentrated pod maturity, i.e., a majority of the pods were ready to pick at the same time. This is a prime requirement for the success of mechanical harvesting of green beans, which was commercially perfected about the same time.

Another factor that influenced cultivar development in the past three decades was the rapid increase in popularity of frozen foods. Frozen vegetables in the United States have become popular primarily since World War II. Most canning or fresh market cultivars used in the 1940s and 1950s were light to medium green, which were quite unattractive as a frozen product. With the introduction of Tendercrop, the frozen food processors had a product with a uniform and very appealing bright-green color.

In the early 1950s, bean canners became aware of a darkening of the liquid in cans of dark-seeded cultivars that had been harvested on the late side of optimal maturity. This represented a potential buyer's barrier, and so when Mel Parker of Gallatin Valley Seed Company discovered and released an off-white seeded mutant (GV-50) from Tendercrop, it became an immediate success (*131*). Earlier white-seeded cultivars had not been accepted because of poor seed quality. The cv. Gallatin 50 was the leading canning cultivar for about 10 years, until replaced by the white-seeded cv. Early Gallatin.

Prior to the late 1950s when beans were picked by hand two to six times during the season, yields for bush types ranged from 3000 to 8000 lb/acre (*41*), while pole beans went as high as 18,000 lb/acre (*66*). At the time of the introduction of the first mechanical harvesters, a yield of 5000 lb/acre was considered necessary from a once-over destructive harvest in order to be economically feasible. While national average processing yields are only slightly above that today, beans for processing are not as mature as they were 25 years ago and this makes yield comparisons difficult. Progressive grower returns are usually 10,000–12,000 lb/acre at the "optimal" harvest stage of 50% one- to four-sieve pods, and 50% five-sieve and larger. The integration of recent improvements in cultivars, equipment, disease control, and cultural practices indicate yields as high as 40,000 lb/acre are possible. Therefore, as these advances are commercialized, average yields of 10,000–15,000 lb/acre should be realized by the turn of the century, at least for those areas with supplemental irrigation.

The recently developed Multi-D Harvester (Chisholm Ryder Company) made possible high-density bean culture as proposed by Andy Duncan, Oregon State University (OSU), in the mid-1960s, and described by Mack and Stang (*67*). High-density (174,200 plants/acre) culture (narrow rows with widely spaced plants within the row) is contingent upon reliable chemical weed and disease control. Besides high-density planting arrangements, which make optimal use of available sunlight, water, and nutrients, other cultural practices like amount and frequency of irrigation (*73*), and deep soil chiseling to reduce soil compaction (*75*) also seem to be important, especially under conditions favorable to root disease.

Two additional areas of cultivar improvement had significant impact on a national scale. The first was the transfer of pod quality characteristics from pole-type Blue Lake cultivars like FM-1, to bush types adapted to mechanical harvesting. The second was the revolution in market garden (fresh-market) cultivars led by Harvester.

W. A. Frazier, OSU, was one of the prime movers behind the transfer of the Blue Lake pod to a machine-harvestable bush. His OSU-1604 is still widely used in the Willamette Valley 10 years after its release. Yields of 8–10 tons/acre are not unusual for OSU-1604, and it has most of the Blue Lake pod quality factors for which the Willamette Valley is famous. The pole-type Blue Lake cultivars commanded a market premium for many years, not only because of the distinctive Blue Lake flavor, but they were also well suited for the institutional trade. Cut-style Blue Lake canned beans remain firm and with relatively little carpel separation or skin sloughing after long hours on a restaurant or institutional steam table. By contrast, canned Tendercrop types have a bland flavor and do not retain an attractive appearance for long under steam table conditions.

Art Sprague, Del Monte Corp., and Walt Pierce, Asgrow Seed Co., were also among the early proponents of the Blue Lake movement. While the Del Monte cultivars are available only to their own growers, emulation of their unquestionable high quality and yield ability became the objective of many other bean breeders. Two other distinctive features of the Del Monte cultivars included a tendency for a large number of fruiting lateral branches (instead of a few strong central stalks as in Tendercrop), and a profusion of flowers that bloomed over an extended period. The heavy branching provided many flowering nodes, thus the high yield potential and the extended flowering period provided some protection against "split sets" (expanded and uneven distribution of pod maturities) caused by blossom drop during periods of high temperatures during bloom.

Asgrow cvs. BBL 47, 240, 274, and 290 generally introduced Blue Lake types to the rest of the U.S. industry (Midwest and East). As mentioned earlier, the Del Monte cultivars were only available to Del Monte growers, and the OSU cultivars were generally not well adapted outside the Willamette Valley, primarily because of their extreme sensitivity to heat during bloom.

Pierce's cultivars were also successful outside the Willamette Valley because of their distinctive improvements in machine harvestability and in plant efficiency over the earlier OSU and Del Monte cultivars, although they were still not as easy to harvest as Tendercrop. Processors and growers, being used to the high field recovery rate (90–95%) of machine-harvested Tendercrop types, were appalled at leaving 2–3 tons/acre in the field (70%) recovery) when using the early OSU or Del Monte cultivars. Even though machine-harvested yields of the early Blue Lake cultivars were higher than those of the Tendercrop types, the increase in broken-off branches, clusters of unseparated pods, and dirt (from trying to harvest too close to the ground) for a long time kept the midwestern and eastern processors from adopting the Blue Lake types. The increased trashiness often slowed through-the-plant flow by several tons per hour thus increasing unit production costs considerably.

Pierce's cv. Harvester, released in the mid-1960s, was well adapted to mechanical harvesting and replaced many of the previously used hand-picked types, thus becoming the fresh-market and shipping bean industry standard for many years. Fresh-market pods are generally light to medium green, round (a few are oval or flat) in cross section, and heavily pubescent. The pubescence presumably reduces pod blemishes from wind scarring and damage during shipping. A convenient field test of this criterion is the ability of a pod to cling to a cotton shirt.

The requirement for an attractive appearance on a Chicago grocer's shelf, after shipment from Florida and being handled several times, imposes different quality standards on fresh-market cultivars, which generally make them unsuitable for processing. A fresh-market or shipping pod must have enough pod wall fiber to retain its shape and fresh

appearance 7–10 days after harvest, even with some desiccation incurred during shipment, storage, and display.

A review of major breeding achievements would not be complete without mention of Mel Anderson (Rogers Brothers Seed Co.). Anderson's cultivars dominated the industry for many years and were often produced in larger volume than all others combined. In 35 years of bean breeding, he developed more than 40 new cultivars, including Earligreen, Earliwax, Slendergreen, Slimgreen, and Improved Tendergreen. In 1970, the Bean Improvement Cooperative presented Anderson, Frazier, Parker, Pierce, and Zaumeyer with the Meritorious Service Award, in recognition of their outstanding contributions to the U.S. snap bean industry for about 40 years.

CURRENT GOALS OF BREEDING PROGRAMS

To be successful, a new snap bean cultivar must please the grower, the seedsman, the processor, and finally the consumer. Excellence in one or more of these categories can create a temporary demand for a new cultivar, but a serious deficiency invariably invites replacement. The fact that few new cultivars remain popular for more than 5–7 years attests that we have not yet found the "perfect bean for all seasons."

There can never be a perfect bean, because (1) different end uses have different requirements, and (2) as we approach the current objectives for any particular end use, we broaden our horizons and set higher goals. With the above in mind and before a cross is ever made, bean breeders need to determine not only what is needed by the particular segment of the market they are aiming for now, but what else will be needed in 10–15 years when the new cultivar is introduced. Few breeders have the time or opportunity to acquaint themselves thoroughly with all the important aspects of each segment of a particular market, and all of its regional idiosyncrasies dictated by such things as climate, available labor or equipment, cultural practices, and the time demands of other crops, to name just a few. Thus breeders must rely heavily on a variety of information sources from which to define 10-year objectives. In the commercial arena, they are assisted by regional seeds salespeople who are most familiar with the problems encountered by local growers, shippers, and/or processors. They are also assisted by managerial economic considerations of such factors as present- and future-market analysis, anticipated population shifts, and anticipated transport and labor costs. Current literature and attendance at meetings of scientific societies and the Bean Improvement Cooperative biennial meetings, keep breeders abreast of technological advances in all the related scientific fronts. Finally, commercial breeders must integrate all this information into an ongoing program that focuses maximum effort on those goals most likely to succeed financially in the shortest possible time. This may leave many research voids, especially in areas of long-range needs. It is the role of public breeders to address these problems.

Hence, the following analysis of current goals will touch on the diversity of types needed to satisfy the many and varied end uses, consider some of the common objectives sought by all breeders, and speculate on current commerical goals of private breeders and some of the long-term futuristic goals of public breeders.

Seed Characteristics

Improved seed quality is one of the greatest needs of the bean industry. Good seed quality, uniform emergence, and early seedling vigor are prerequisites to consistent and maximum production at harvest. Variable seedling emergence and vigor can result from inherent

genetic characteristics or from improper seed harvest, storage, and/or handling conditions (*17,104*).

Dickson and Boettger (*25,26*) reported that seed coat thickness, tightness of adherence of seed coat to cotyledons, and a solid contact between cotyledon faces contribute to resistance to mechanical damage. Hoki (*54*) showed that the size and shape of the seed are important factors in resistance to mechanical injury.

Beside breeding for seed characteristics that contribute directly to resistance to mechanical injury, breeders might consider selection for plant and pod characteristics that indirectly lead to improved seed quality. Westermann and Crothers (*122*) showed that snap beans grown for seed also respond to high-density culture. Silbernagel (*102*) suggested that direct harvesting of snap bean seed grown under high-density culture would eliminate many of the problems contributing to decreased seed quality that are associated with the present windrow system. Windrowed beans are cut below the soil line and laid on the soil surface to dry, where they may be exposed to moisture, causing molds following rains, or subsequent overdrying. The rubber-belt thresher proposed by Silbernagel strips dry pods from standing mature plants. The rubber belts extract seed with a minimum of mechanical damage; and since the plants are not windrowed, there is less seed spoilage from stains and molds during rainy weather. To facilitate optimization of the system for high-density culture followed by direct seed harvest, breeders should select for a very concentrated pod maturity, numerous small vertically oriented leaves, and a strong, upright, narrow plant habit.

Plant Characteristics

The term "Tendercrop plant type" is synonymous with a strong upright, relatively narrow habit, stiff enough to remain upright with the weight of a mature crop, but with very few pods touching the ground.

With the current trend to high-density culture, the "ideal" plant type would seem to be a miniaturized Tendercrop but with Blue Lake pod quality, that is, about 16–18 in. instead of 20–24 in. tall, and correspondingly upright and narrow with numerous small leaves (5 × 8 cm) instead of the larger leaves on Tendercrop. The smaller plant should give a slightly higher harvest index, even with "luxury levels" of fertilizer to obtain maximum pod yields. The small, vertically oriented leaves should present a greater total photosynthetic surface because light can penetrate deep into the canopy.

The force of the mechanical harvester, which strips pods and leaves off the main stems and branches, requires a strong plant with a well-anchored root system (*96*). However, some breeding lines, even with a very thick main stem, show a tendency to break easily at the primary leaf node area. This is often noticed when handling plants in making single-plant selections. The heritability of this character has not been studied, but these "weak-kneed" types should be ruthlessly eliminated.

Small leaf size can be found in the USDA Plant Introduction Service Accession (PI 165426. This PI line was reported by McClean *et al.* (*70*) to be resistant to rhizoctonia root rot and the root-knot nematode, and is the genetic basis for several improved bush-bean-type breeding lines from Charleston by Deakin and Dukes (*22*) and Wyatt *et al.*, (*126, 128*), with resistance to these problems. A small black-seeded selection from this PI line (which has a mixture of seed types) was later found also to be resistant to the root rot organisms, *Fusarium, Pythium, Thielaviopsis,* some races of rust, and cold–wet emergence conditions (*98*). However, in numerous crosses with this line, small leaves

have not been recovered in commercial-type breeding lines with otherwise acceptable horticultural characteristics. There seems to be a strong association between small leaf size and small pod size. Dickson (*33*) released a small-leafed bush type (L-1). However, it is not known whether the general association between small leaves and small pods has ever been broken.

Disease Resistance

Recent reviews (*94, 106, 133*) on breeding beans for disease resistance, which list sources of resistant germplasm and disease-screening techniques, are thorough and so only a brief summary of current highlights will be covered here.

Viruses

Most snap bean cultivars in the United States carry dominant *I* gene resistance to bean common mosaic virus (BCMV) (*106*). In view of the presence of new strains of BCMV capable of causing a lethal systemic necrotic reaction in these cultivars (*35*), breeders should combine the *I* gene resistance with either *bc-1*^{2}, *bc-2*^{2}, or *bc-3* resistance (*34*) in order to have broad resistance to both the necrotic and mosaic mottle reactions.

Curly top virus (CTV) resistance is needed for some of the western seed production and processing areas. Resistance is probably due to two epistatic dominant factors (M. J. Silbernagel, unpublished). Sources of resistance include Apollo, Blue Mountain, Goldcrop, and Wondergreen.

Peanut stunt virus (*72*), bean strains of the cucumber mosaic virus (CMV), and BYMV strains are occasionally epiphytotic on the east coast. Resistance to a few strains of BYMV is known (*86*), but more studies are needed on the genetics of resistance to a wide range of specific strains that have not even been identified.

Foliar Fungi

Rust *Uromyces phaseoli* (Reben) Wint. is a serious problem in East Coast fall crops of snap beans. Several sources of resistance to different strains are known (*133*). A recent USDA germplasm release PR-190 by Freytag in Puerto Rico, and BARC-1 by Meiners and Silbernagel (USDA, Prosser, Washington) are resistant to most of the prevalent strains. Another USDA breeding line by Silbernagel, 8BP-3 (a small-sieve whole-pack type), is also resistant to some races of rust, as well as anthracnose (*ARE* gene), BCMV (*I* gene), CTV, and some strains of BYMV. The Rogers Brothers Seed Co. cv Resisto is tolerant to several races of rust. The Wisconsin breeding line BBSR-130 is resistant to rust as well as to four other diseases (*42*).

Root Rots

Fusarium root rot, *Fusarium solani* (Mart.) Appel & Wr. f. sp. *phaseoli* (Burk.) Snyd. & Hans., is widespread and can reduce yields in the Northwest by as much as 25–50% (*100*). It is also serious in New York (*83*). No resistant commercial snap bean cultivars are yet available, but Dickson and Boettger (*28*) released a number of breeding lines with a moderate degree of tolerance to fusarium and/or pythium root rot. Resistance to fusarium root rot seems to be due to several quantitative genes (*10, 50*), and it is apparently independent of resistance to thielaviopsis (*52*) and pythium root rots (*129*). Cultural practices, biological control practices, and seed treatment can reduce the severity of root rot injury and increase production levels (*97*). Breeder–pathologists are tending toward

the opinion that a high degree of physiologic resistance may not be necessary for effective field tolerance.

Several breeding lines with resistance to rhizoctonia root rot caused by *Rhizoctonia solani* Kuhn [*Thanatephorus cucumeris* (Frank) Donk] have been released over the past several years from the Charleston, South Carolina, USDA Vegetable Breeding Laboratory by McLean *et al.*, (*70*), Deakin and Dukes, (*22*), and Wyatt *et al.* (128). Most of these are colored-seeded types (*21*). Several also carry resistance to the root-knot nematodes (*126*). *Rhizoctonia* is prevalent in many southeastern production areas (*77*) with warm soils. Prasad and Weigle (*85*) reported on a number of breeding lines and cultivars with tolerance to *R. solani*.

Resistance to several *Pythium* spp. has been found in white-seeded sources by York, Dickson, and Abawi (*24, 129*) and by Hagedorn and Rand (*43, 45*). The Wisconsin breeding lines RRR-46 and -36 are resistant to *Pythium* and to the recently described aphanomyces root rot of beans caused by *Aphanomyces euteiches* f. sp. *phaseoli* Phend. & Hag. (*81*). Resistance to *Pythium* is needed almost anywhere snap beans are grown.

Resistance to *Thielaviopsis basicola* (Berk. & Br.) Ferr. seems to be available in several sources of root rot resistance (*51, 52*). However, since it does not usually cause serious damage by itself, little effort has been devoted to incorporation of this resistance into snap beans, even though it can be found in most production areas. Someone needs to determine if early season injury by thielaviopsis root rot predisposes plants to more serious injury by other root rots.

Bacteria

Repeated halo blight epidemics incited by race 2 of *Pseudomonas syringae* pv. *phaseolicola* (Burkholder 1926) *comb. nov.* in the major U.S. seed production areas (Idaho and California) in the past 15 years have finally persuaded U.S. breeders to emulate the European breeders in the development of resistant cultivars. Most resistant snap bean cultivars, like Noorinbee (*87*) and RH-13 (*40*), are foreign introductions, except for the halo-blight-resistant breeding line Nebraska HB-76-1 (*19*). Little or no effort has been made to develop snap bean types with resistance to bacterial wilt [*Corynebacterium flaccumfaciens* pv. *flaccumfaciens* (Hedges 1922) Dowson 1942], or common blight *Xanthomonas campestris* pv. *phaseoli* (E. F. Smith) Dowson, because they are rarely serious problems in the United States. Brown spot (*P. syringae* pv. *syringae* van Hall 1902), however, is severe and widespread in Wisconsin and Minnesota. Recent germplasm releases by Hagedorn and Rand of Wis BBSR-130 (*42*), and WB-BSR-17 and -28 (*44*) are highly and moderately resistant, respectively. This resistance needs to be combined with aphanomyces and pythium root rot resistance for reliable production in the Midwest. Epoch, a Wilbur Ellis Blue Lake type cultivar, is tolerant to brown spot.

Insect Resistance

Very little is known about resistance to insects in beans, and I know of no cultivars with identified resistances. Insects are usually controlled through the use of insecticides; however, with governmental regulatory procedures for the production and use of pesticides becoming progressively more restrictive, we may increasingly have to turn to genetic control. Seedcorn maggot resistance has been reported in New York (*116*) and Washington (*47*). Cultivar differences in insect preference have been reported for mites, thrips, and aphids (*48*). Likewise, sources of resistance to leaf-hopper burn (*Empoasca*) are also

known (*31*). Resistance to Mexican bean beetle is being studied in the Southeast (*127*) and differences in tolerance to lygus bug stings on pods have been observed in Washington (*46*). These factors should be bred into production cultivars to reduce the need for pesticide applications.

Environmental Stress Tolerance

Relatively little effort has gone into the introduction of factors for environmental stress resistance in snap beans. There is, however, a growing awareness among breeders and research administrators that environmental stress extremes directly cause a large part of the annual fluctuations in legume production. When production levels fluctuate, supplies, demand, and prices often vary out of proportion to actual crop losses. Thus, environmental stress tolerance is needed as much for market stability as for ultimately raising area and national yield levels.

Environmental stresses for which tolerance is needed include cold and/or wet emergence conditions, temporary drought and/or flooding, acid or alkaline soils, high or low temperatures during bloom, photoperiod sensitivity, N_2 deficiency, and air pollution. A cultivar with such tolerances likely would have a wide range of adaptation.

Breeders can tentatively identify drought-tolerant materials by selective water management (*135*) in trial plots. Usually the better materials are coming from root rot breeding programs, where a low nitrogen stress is combined with water stress to identify those lines also able to fix more of their own nitrogen (*11*). Studies in Idaho indicate some cultivars may lose the ability to fix atmospheric N_2 when all selection takes place in nurseries with high levels of supplemental nitrogen (*123*). The snap bean cv. Canyon was found to have the lowest rate of N_2 fixation, while Viva Pink had the highest (*124*). Viva, whose parentage includes a wild bean from Mexico (PI 203958) with a high rate of N_2 fixation ability, was developed by selection in root rot nurseries stressed for supplemental nitrogen and water (*12*). Viva was also reported by D. H. Wallace (Cornell University, personal communication) to have one of the highest harvest indices (*118*) of several dry bean cultivars tested, even though it was not purposely selected for harvest index, only production under multiple-stress conditions.

In recent years, many wild sources of disease resistance have been crossed with modern snap bean cultivars. Thus the opportunity exists for recovery of not only root rot resistance, but root vigor, drought and flood tolerance, and effective N_2 fixation by rhizobium nodulation as well. This field stress system also lends itself well to the identification of germplasm that does not require seed treatment fungicides and/or insecticides. This ability will become more important as environmental concerns limit the availability and/or use of agricultural pesticides.

Soil Compaction Tolerance

A vigorous root system may be less restricted by the so-called plow pan often found at the 10- to 12-in. depth in field soils compacted by heavy equipment. When roots of snap bean cultivars are confined to this zone where most root rot organisms are found (*13*), the severity of root rot damage is increased, and unless frequent irrigations are maintained during hot periods, yields are reduced. The frequent irrigations are deemed necessary by growers to promote secondary root formation to replace those rotted off by root rots. However, too frequent irrigation also aggravates the severity of root rot damage (*100*), and keeping the soil surface moist for long periods of time promotes white and gray molds

(*75*). Thus deep-penetrating, rot-resistant roots could contribute toward water conservation and at the same time reduce the potential losses due to white and gray molds.

Air Pollution Tolerance

Tolerance to air pollutants is almost mandatory under some eastern seaboard conditions. Fortunately, tolerance is found in a wide array of commercial snap bean cultivars (*89*). Screening of segregating populations under metropolitan eastern or California conditions would be highly desirable. Alternatively, choosing parents that are well adapted to polluted conditions would greatly increase the probability of finding tolerant materials in unscreened late-generation selections.

Tolerance to Low and High Temperatures

Since photosynthetic surface area and fruiting nodes are prerequisites for pod production, early seedling vigor is essential to realization of maximum yield potential. In the cool environment of a spring planting, the ability to imbibe, emerge, transport water, and photosynthesize at slightly lower than normal temperatures would support the desired early branching and rapid leaf surface area development.

The need for cold tolerance in beans has been recognized for some time, especially in places like England (*3*) and Canada (*61*). It now appears that research on cold tolerance in bean should be divided into at least three apparently independent phases: (a) the imbibition–emergence phase, (b) the vegetative development phase, and (c) the reproductive phase.

The effects of temperature on reproductive development in beans have been known for some time. However, only recently have any serious efforts been initiated toward the incorporation of genetic tolerance to both high- and low-temperature stresses during bloom into improved cultivars. Farlow (*37*) found that the difference in ability to tolerate cold during flower development between two Australian cultivars was primarily due to a difference in incidence of ovule abortion. The rate of failure of the female reproductive organs was progressively higher as temperatures were reduced from 21° to 10°C. This resulted in fewer pods per plant, fewer seeds per pod, and more crooked pods. Dickson and Boettger (*29*) also observed that low night temperatures (8.5°C) cause "split set" in snap beans. They found that fewer pods and/or seeds per plant were produced at a night temperature of 8.5°C than at 18°C.

Sensitivity to high temperatures during bloom is one of the principal reasons why beans are not grown in much of the Southeast during June, July, and August. According to Farlow *et al.* (*38*) high daytime temperatures (>35°C) reduce pollen production and/or viability. The resulting split sets can be a serious problem to both the bean processor and the bean seed producer. Much additional information is needed to clarify the effects of high night temperature and the possible interactions with relative humidity and to identify cultivar × time × temperature threshold differences. Marsh *et al.* (*68*) and Weaver *et al.* (*120, 121*) are developing cost-and space-effective screening procedures to identify resistant individuals in segregating populations. Sources of tolerance to high temperatures during bloom have been reported (*6, 78, 103, 125*), but little is known about the mode of inheritance. It is possible to recover heat-tolerant single-plant selections from advanced-generation hybrid populations derived from a heat-tolerant breeding line. Silbernagel (*99*) released the heat-tolerant breeding line 5BP-7 in 1979. In 1982 (*103*) he released a pair of isogenic lines (derived from a cross with 5BP-7), one of which is sensitive and the other

resistant to high temperature during bloom. These are being studied by Marsh *et al.* (*68*) to determine the nature and inheritance of heat tolerance. Tolerance appears to be simply inherited.

Numerous mechanisms and/or modifying factors for heat tolerance may be involved. Work by Farlow (*37, 38*) on the nature of temperature stress tolerance during reproduction in beans should have a great impact on future bean breeding. The widespread application of the information provided by these two papers in the development of new commerical cultivars may be a major contribution toward breaking the so-called yield barrier in bean production.

Flood Tolerance

The sensitivity of bean roots to oxygen starvation has been known for some time. Miller and Burke (*74*) and Noor *et al.* (*79*) have shown that the stress of temporary near-anaerobic conditions induced by flooding can alter root metabolism and greatly increase sensitivity to fusarium root rot. Resistance to temporary flood conditions is available (*63,79*), but little is known about its genetic inheritance or economic importance.

Some confusion exists as to the effects of sensitivity to cold emergence conditions vs. sensitivity to flooding and/or oxygen starvation. Ladror *et al.* (*63*) recently studied the interacting effects of cultivar, initial seed moisture content, temperature, oxygen content, and flooding. Much of the reduced emergence and seedling vigor, presumed to be due to O_2 starvation or low temperature during seed imbibition, appears to be due to flooding.

As the importance of temporary flooding injury to emergence and/or root rot resistance is better understood, tolerance to flooding should receive increasing attention from breeders.

Response to Cultural Practices

Response to Optimum Fertility

While yield stability due to disease and insect resistance and tolerance to environmental stresses is important, it is only meaningful when combined with high yield and processed quality. All too often, pest- and/or stress-resistant cultivars are not impressive in the absence of those pests and/or stresses. The cv. Red Mexican UI-36 is very sensitive to fusarium root rot. However, in soils free of root rot it responds extremely well to high fertility levels (*14*). Therefore, growers keep using it because without severe root rot it often outyields similar cultivars with root rot tolerance. Snap bean breeders need to maintain genetic factors for maximum productivity and quality under good growing conditions, as well as stress and disease conditions.

Response to High-Density Culture

In the early 1960s workers at Oregon State University and Cornell University (Geneva) began asking why beans were grown in 30- to 36-in. rows, thus wasting all that space between rows. They concluded that originally the wide rows were for the passage of horses, and later tractor tires and equipment used in cultivation. Now that we have effective herbicides and fungicides that can be applied by air or through overhead sprinkler systems, tractors are often not needed in the field between planting and green bean harvest. Spacing studies by Mack and Stang (*67*) showed that maximum production was obtained when each plant had an average of 36 $in.^2$ of space in a nearly equidistant

arrangement. Subsequent commercial experience has shown that populations of 160,000–170,000 plants/acre in various spacing arrangements can yield 8–12 tons/acre. This is a dramatic increase from the 4–6 tons/acre that the better Willamette Valley growers currently obtain with 32-in. rows. Current cultivars are not ideally suited to this production practice, and the characteristics that presumably would contribute to even more efficient and higher production levels are being identified.

Rapid uniform emergence and seedling development are the first requirements. The ideal plant type for high-density culture is a strong central upright stalk, with three or four narrow-angled branches, a high yield of pods all close to the same maturity, borne high on the outer periphery of the bush for ease of mechanical harvest. Pods should separate easily (unbroken), with no pod clustering or broken-off branches being carried into the picker. Leaves should be small, and oriented toward the sun to allow maximum light interception and penetration through the canopy. Plants should be 16–18 in. tall and strong enough not to lodge when heavy with crop. Vigorous roots resistant to diseases should anchor the plant well enough not to be pulled up by the harvester. The roots should nodulate profusely and be capable of high rates of early-season nitrogen fixation. At the early pin bean stage, when natural nodulation declines, the plant should respond to supplemental nitrogen fertilizer by maximizing pod development and yields, instead of renewing vegetative growth. Finally, the ideal bean should be compatible to minimum tillage practices. This would probably require *Pythium* resistance, since *Pythium* populations seem to increase under minimum tillage practices.

SELECTION TECHNIQUES FOR SPECIFIC CHARACTERS

General Considerations

Since there are many different markets for which beans are produced, there is no one set of selection criteria for specific characters that is applicable to all needs. Also, the environment under which the breeding, screening, and selection work is done may differ from the commercial production area environment; and there may be genotype–environment interactions. Therefore, it is essential to maintain trial nurseries for disease screening and plant/pod-type evaluation in both the seed production and the vegetable crop production areas.

After intensive early-generation screening for resistance to locally prevailing diseases in each area, there should be enough genetic diversity left for plant and pod characteristics in segregating populations to recover most of the desired agronomic–horticultural recombinants. Another reason for alternating early-generation disease screening between seed production and processing (or shipping) areas is that each area may have a completely different set of diseases related to the prevailing respective environments. In the western desert area where most seed production is concentrated, resistance to BCMV and CTV is highly desirable, although CTV is never a problem in the major processing or market garden (shipping) areas. Likewise, fusarium root rot causes the most serious root rot in the major northwest seed production areas, but in Wisconsin *Aphanomyces* and *Pythium* are the major root rot incitants. Rhizoctonia root rot is quite widespread in all production areas, but is apparently only economically serious in California, Arkansas, and the eastern seaboard from Maryland to Florida. Tolerance to cold–wet late-April planting conditions in Oregon may not be needed in an Arkansas mid-May planting. Blossom drop (split set),

due to high temperatures during the flowering period, may prevent bean production through much of the Southeast during July and August, but is only an occasional problem in Wisconsin or New York. The ability to grow and set well under cool growing-season conditions may be desirable in cultivars destined for Canada or England, but is almost never needed in Arkansas. However, the Florida shippers who grow beans in December and January could use cold-tolerant cultivars. Thus, since no one test location represents all growing areas, most commercial breeders maintain trial grounds in four or five locations around the country. And since a breeder can only be in one place at a time, considerable regional technical support and collaboration is needed to plant and evaluate the early, midseason, and late crop responses within any given major production area.

Detailed multiple-harvest and location information is needed to evaluate advanced-generation materials properly (this will be covered in the section on Trials of Advanced Lines). The local evaluator assists the breeder in screening segregating populations for disease resistance and in selecting for desired plant and/or pod characteristics. However, the green-pod production area is usually not a good seed production area because of wet fall weather.

If seed from wet areas is returned to the breeders' trial grounds in the seed production area, there is a possibility of contaminating the rest of the breeding lines with seedborne pathogens, some of which may represent new strains and/or higher degrees of virulence, because they may have been screened on resistant or tolerant germplasm populations. Moreover, most evaluators in the green-pod production areas are not equipped with seed harvesting, drying, cleaning, and storage facilities. There are two ways of handling this problem: (1) seed being returned from any trial ground outside the breeder's nursery should first go through an isolation nursery (always a good basic procedure), or (2) only the trial information and not the seed should be returned. Option 2 (progeny testing) involves making numerous single-plant selections (SPS) in segregating populations in the breeder's (seed production area) trial grounds. The following generation each SPS is subdivided. Part of it remains in the breeder's trial grounds, and part goes to a green-pod production area trial. The evaluator in the green-pod production area trial records disease reactions and relevant plant and/or pod characteristics. If a particular SPS is well adapted and homozygous resistant in the green-pod production area trial, then further SPS can be made in the breeder's own trial grounds (in the seed-producing area), since the breeder knows SPS are resistant to a particular disease in the green-pod production area trial, and that the seed harvested will be free of seedborne problems. Furthermore, the green-pod production area trial evaluator does not need to worry about harvesting poor-quality seed in wet weather.

Cooperative and Regional Testing

Breeding programs differ in both the technically trained manpower capability and in the natural environment adequate to screen cultivars or segregating populations for more than a few factors. To offset these limitations, some public breeders, through the sponsorship of regional projects like WR-150 (*117*) (Genetic Improvement of Beans for Yield, Pest Resistance, and Nutritional Quality), screen materials for each other, usually under natural conditions. Other breeders (public and private) exchange materials for testing on a personal cooperative basis. Some provide only information, while others return resistant selections and comments to the originator. Private seed companies, large enough to afford regional test nurseries and trained personnel, do this within their own organization. Either

way, regional testing of early-generation materials is important to the development of new cultivars that are not only resistant to various factors but widely adapted and highly productive.

When to Screen

Simply inherited factors can be recovered and stabilized at a relatively early (F_2 or F_3) generation. Conversely, the more complex the inheritance of the character sought and the lower its heritability, the longer (F_5 to F_8) rigorous selection should be delayed. However, even though selection efficency may be low in early generation for complex characters with low heritability, those characters should not be ignored in early generations. Postponement until F_8 with no selection pressure would build up populations to unmanageable proportions. Conversely, too much selection for other things may reduce or eliminate the genetic variability for the particular character sought. Thus selection pressure for complexly inherited characteristics, like root rot resistance, should be low in early generation to eliminate only highly sensitive individuals.

Controlled Screening Pressure

The severity or intensity of screening pressure applied to a segregating population depends both upon the level and complexity of the available resistance. If a high level of resistance is available and easy to recover, like *I* gene resistance to BCMV, then highly virulent strains like NL 2, 3, and 4 (*34*) should be used to eliminate all but the most resistant. If, however, the highest level of resistance available is an intermediate tolerance to something like halo blight, race 2, that is easily eliminated with more virulent isolates (halo blight, race 3), then the use of less virulent isolates (race 1) should be considered in order to be able to detect multiple sources of low-level tolerance, which might later be recombined in a search for accumulative or transgressive resistance. The combined higher level resistance might then be detected by screening with progressively more virulent isolates (race 2, then 3). If races or strains of a pathogen that differ in virulence are not available, then inoculum concentration or environmental conditions (temperature, moisture, inoculum density, etc.) might be manipulated to control the degree of screening pressure. Of course, under field conditions precise control of disease severity is not always possible. Greenhouse or growth chamber conditions are usually needed to obtain repeatable levels of controlled disease pressure.

Overreliance on only the highest level of resistance available to the most virulent isolate(s) might tend to shift the breeding population toward single-factor (and less stable) vertical resistance, while the use of all available factors, even resistance to low or intermediate levels of pathogenic virulence, might broaden the population resistance base toward multiple-factor or a more horizontal (and stable) form of resistance. Intercrossing of low-level tolerant lines might pyramid several sources of resistance to produce recombinant individuals with horizontal resistance levels that might then be able to tolerate more virulent pathovars under field conditions.

A screening program should be based on a thorough knowledge of the available variability in both the pathogen virulence and/or race specificity, as well as the host resistance. A lot of field-screening effort can be wasted trying to stabilize resistance to a pathogen like BYMV when the breeder is unaware there are many different strains and that they are not necessarily the same each season or testing cycle.

Field vs. Greenhouse Screening

Considerations of time, space, expense, and the requirements for large numbers often dictate that screening be done under field conditions. However, the need to know specifically to which strain(s) of BCMV, rust, halo blight, or anthracnose a breeding line has resistance eventually requires some confirmation with identified pathogens under controlled greenhouse or growth chamber conditions. Screening for certain characteristics that occur for only a short time period and/or need to be done at a specific stage of growth (like tolerance to cold–wet imbibition or heat during bloom) usually is best done under controlled conditions.

Single vs. Multiple-Disease Screening

Whether to screen for resistance to a single disease or to screen simultaneously for resistance to several diseases is a largely unresolved question. Many diseases (as well as different test conditions) are known to affect the expression of another disease; but if the purpose is to combine as many simply inherited factors (like BCMV and rust resistance) as quickly as possible, then simultaneous multiple-factor testing is sometimes the most efficient procedure.

However, with more genetically complex factors for resistance, like root rot, it may be better to rely on single-factor relay or parallel tests (*Fusarium, Pythium, Rhizoctonia, Aphanomyces*) in order to increase the probability of recovery of resistant individuals to each disease in small populations. If more than one of these resistance factors are needed in a single cultivar, eventually they have to be combined through hybridization and tested under artificial and/or natural mixed-pathogen conditions. By that time, however, the breeder knows which factors are present by previous single-disease testing, and the multiple-disease screening is merely a confirmation test, in which the emphasis can then also be turned to selection for plant and pod characteristics.

Disease Resistance

All breeding programs must at some point be concerned with diseases. A great deal of detailed information on screening and genetics is available in several current reviews [e.g., Schwartz and Galvez (*94*), Zaumeyer and Meiners (*133*), and Silbernagel and Zaumeyer (*106*)] and so only a brief summary will be presented here.

Virus Disease Screening

Most bean viruses encountered in the United States, while naturally transmitted by insect vectors, can also be mechanically transmitted. These include BCMV, BYMV, peanut stunt virus, alfalfa mosaic virus, southern bean mosaic virus, bean pod mottle virus, red node virus, and legume strains of CMV. Details of inoculum storage, preparation, and inoculation procedures are similar for all mechanically transmitted viruses. The methods described by Drijfhout *et al.* (*36*) for BCMV apply to any of the above. Basically, fresh, young, infected tissue is desiccated rapidly with silica gel (under refrigeration if possible), sealed against air and moisture, and kept frozen for 1–2 years. When needed, a small amount (¼ g) is ground in 2 ml 0.01 *M* neutral phosphate buffer (cold), poured through a double layer of cheesecloth, and used to inoculate a virus-susceptible buildup host. Test plants can be lightly dusted with 400- to 600-mesh carborundum prior to inoculation to facilitate cell penetration. Young tissues are best for inoculation (primary

leaves when ½ to ¾ expanded). The severity of some virus diseases is intensified by holding the test plants in the dark 24–48 hr before inoculation. At greenhouse temperatures of 24°–28°C, symptoms are usually expressed in 10–14 days. When producing inoculum for screening segregating populations, susceptible virus buildup hosts usually reach the highest virus titer 2–3 days before symptoms appear (8–10 days after inoculation). When large amounts of inoculum are needed, infected tissue in buffer (1 g : 5 ml ratio) can be ground for 1 min in a Waring blender. Buffer and blender jar should be prechilled to 2°–5°C; and after screening through double-layered cheesecloth, the inoculum can be further diluted 1/100 with chilled buffer. For large-scale field or greenhouse inoculations of segregating populations, the carborundum can be added to the diluted inoculum at the rate of about 1 g/liter. The inoculum can be applied by a pressurized paint sprayer (50–100 psi) or with a hand-held 400- to 500-ml plastic bottle, over the neck of which a piece of Parafilm and several layers of cotton gauze are held by a rubber band [Francisco Morales, International Center for Tropical Agriculture (CIAT), personal communication]. The Parafilm is punctured with a pin until the desired amount of liquid keeps the gauze moist enough for inoculation use, but not to the point of runoff. The young leaves being inoculated are held in place by a firm plastic sponge or several layers of paper towels held in one hand by the applicator, while the damp gauze is lightly stroked over the leaf with the other hand. Under greenhouse or screenhouse conditions, susceptible individuals are easily identified in about 2–3 weeks. Symptomless plants should be inoculated a second time (on the youngest trifoliolates), especially if they are to be saved for seed production or counted in an inheritance study. Symptomless field plants should likewise be given a second inoculation (about 2 weeks after the first) to guard against escapes and late emergers being harvested as resistant. Final resistant selections (at young to full-pod stage) can be marked with wire flags, numbered tags, or simply a hand-held spray can of bright-red or fluorescent-orange paint. It is important to be sure that apparently resistant plants showing no leaf or growth depression symptoms also do not exhibit pod symptoms.

CTV is only transmitted by the sugarbeet leafhopper *Circulifer tenellus* Baker (*7*). It is a difficult insect to rear and work with, and so field exposure under natural conditions is the best way to screen for resistance. Susceptible sugarbeets planted in mid-March are used as a trap crop in western areas, where the insect overwinters on wild mustards in desert waste areas. As the mustards mature (mid-May), the insects migrate. Strips of two (22 in.) susceptible sugarbeet rows spaced 23 ft apart allow eight rows of beans spaced 22 in. apart to be planted between the beet strips. Beans planted during mid- to late May usually emerge in early June. By then leafhopper populations are increasing, especially if the weather has been hot and dry (*16*). By early July, a high percentage of the susceptible controls are usually infected, and resistant individuals in segregating populations are easily identified. Again, final selection is best delayed until the fresh-pod stage of maturity.

Bacterial Disease Screening

Whereas viruses are usually spread by insects, water and wind are the most common means of spreading bacterial diseases within the crop season. Between seasons, since they are all seedborne, humans transport them from one growing area to another, in spite of phytosanitary regulations.

The two *Pseudomonas*-incited diseases halo blight and brown spot both thrive under cool–wet growing conditions. However, the *Xanthomonas*-incited diseases common

blight and fuscans blight [*Xanthomonas campestris* pv. *phaseoli* (var. *fuscans*)] are more prevalent under hot–humid conditions. Bacterial wilt is also favored by high temperatures, but usually under dry stress conditions.

Since the primary damage caused by the pseudomonads and xanthomonads is to leaves and pods, most screening techniques have been developed to evaluate resistance at the late-bloom or early-pod stages of growth. This requires a lot of space and time, which usually means field testing if large numbers are to be screened. In order to reduce the labor required in inoculating large segregating populations, sometimes every third row (a highly susceptible cultivar) is inoculated, which serves as a spreader source to the adjacent test rows.

Planting contaminated seed, as described by Poryazov (*84*), is an easy means of establishing infected spreader rows. If natural spread is not dependable enough, frequent use of an overhead sprinkler system or a power sprayer can be used to supplement natural spread. If the weather does not cooperate, a lot of effort can be lost in field plots.

Greenhouse or growth chamber tests can be controlled to ensure good testing conditions, but since indoor space is usually limited, it is difficult to work with large populations. Inoculation of seedlings in the crookneck stage (*101*) with a hypodermic syringe is time and space efficient for halo blight and brown spot screening (*101*). Schuster and Coyne (*92*) reviewed procedures to standardize screening of beans with the xanthomonads. Most inoculation methods use pressure sprays or vacuum to achieve leaf tissue infiltration. Needle punctures or cuts are also used in a variety of ways to achieve inoculation. Inoculum concentrations can influence disease reactions; most reported optima are in the range of 10^6–10^8 cells/ml. Symptoms develop in 10–20 days and are usually expressed on a 1 to 9 scale, with usable tolerance being in the 1 to 2 range.

Resistant and susceptible control cultivars are used as references to evaluate the degree and range of resistance found in the segregating population. In early generations, typically 5–10% of the test population might be saved for seed production. An increasing proportion of resistant survivors is saved for seed with each cycle of recurrent selection.

Inoculum is grown on YDC agar, which contains 15% agar plus 10 g yeast extract, 10 g dextrose, and 15 g $CaCO_3$ per liter. Forty-eight to 72-hr petri plate cultures are washed off the agar with sterile water or 0.01 *M* $MgSO_4$. Ouen Huisman (University of California–Berkeley, personal communication) found less bacterial cell disruption by osmosis in 0.01 *M* $MgSO_4$ than in water. For long-term storage under liquid culture, use 0.1 *M* $MgSO_4$ on agar slants or wash off and store without the agar. Stored inoculum should be revived and checked for virulence before being increased for screening use.

Excellent information on sources of resistance, inoculation techniques, rating systems, and heritability of resistance is reviewed by Schuster and Coyne (*92*) and Yoshii (*130*). Additional information as well as germplasm and cultures are available by contacting the authors of articles in recent annual reports of the Bean Improvement Cooperative.

Screening for Resistance to Foliar Fungi

The principal foliar infecting fungal diseases in the United States, in order of descending importance, are rust caused by *U. phaseoli* (Reben) Wint. [*Uromyces appendiculatus* (Pers.) Unger], white mold caused by *Sclerotinia sclerotiorum* (Lib.) de Bary, gray mold caused by *Botrytis cinerea* Pers. ex Fr., and anthracnose caused by *Colletotrichum lindemuthianum* (Sacc. & Magn.) Scrib. The latter three also destroy stem and pod tissue. Disease establishment and spread are favored by moderate temperatures (17°–27°C), >95% RH, and periods of wetness. Rust and anthracnose can infect plants at any stage of

development when climatic conditions (cool and wet) are favorable; however, white and gray mold usually are not a problem until after bloom. For disease establishment, the mycelia produced by ascospores and conidia of white and gray mold require a food base (usually spent blossoms) before they can invade living stem, pod, or leaf tissues.

Gray Mold No genetic gray mold resistance has been identified, but not much effort has been exerted looking for it. Some disease escape, due to plant architecture, may be operational under conditions of low disease pressure. In view of the importance of gray mold in Oregon and the lack of satisfactory chemical control, some effort should be made to find genetic resistance. The principles and methods employed to combat white mold should be a likely starting point for a campaign aimed at genetic control of gray mold. An Integrated Pest Management (IPM) bean program at Oregon State University, coordinated by Rick Weinzerrel (Corvallis, Oregon, personal communication) is attempting to develop the background information needed for practical control with minimal environmental pollution. The IMP approach, coupled with even a moderate level of genetic tolerance, should be successful for white as well as gray mold.

White Mold It was long assumed that the only differences in genetic response to white mold in beans were due to different architectural configurations which allow a drier, warmer microclimate under the canopy (*8, 53*). Now that the details of environmental requirements for disease establishment and spread are more clearly understood, workers in Nebraska and New York have been able to differentiate between physiologic tolerance (*58*) and avoidance mechanisms related to plant architecture (*20*). No germplasm is entirely resistant; however, Hunter *et al.* (*59*) have been able to identify partial resistance with a limited-term inoculation method. They found that an ascospore spray procedure was less reliable than placing mycelium colonized pieces of celery or bean pod in contact with a host test plant internode for 15 hr at 21°C and >95% RH. After this disease exposure, the 3-week-old test plants are transferred to a greenhouse and rated for disease severity on a 1 to 9 scale 6–10 days later. Certain *P. coccineus* lines, and to a lesser degree some *P. vulgaris* lines, show physiologic resistance by taking longer to die. More recent work by Dickson *et al.* (*32*) shows this technique can be used to classify segregating hybrid populations for genetic tolerance to white mold. Many researchers believe a combination of genetic tolerance, architectural avoidance, judicious use of chemicals, cultural practices, and perhaps biologic control agents provide a realistic basis for long-term cost effective management of the disease.

Rust Vargas (*115*) recently reviewed the status of breeding for rust resistance. The high degree of pathogenic variability in the bean rust fungus has inclined many workers toward efforts to base long-range control on a program of combining horizontal (or non-race-specific) resistance factors. The components of horizontal resistance are such factors as reduced numbers of infections, decreased pustule size and spore production, late or slow rusting, increased resistance with plant maturity, longer incubation period, and slower rate of pustule development. Research workers at CIAT in Cali, Colombia, have taken the lead in coordinating an International Bean Rust Nursery (*93*). Schwartz and Temple (*95*) suggested a CIAT breeding strategy for the development of rust resistance. In the United States, Meiners, (*71*) and, since his retirement, Stavely (*108*), in Beltsville, Maryland, have coordinated a Uniform Bean Rust Nursery for bean breeders. Efforts are underway to establish a uniform set of host differentials and a standardized disease rating system for race identification. Generally the scale developed by Ballantyne (*5*) is used.

Inocula collected from diseased plants can be kept frozen (sealed against moisture) for up to 2 years. The usual inoculation procedure consists of a spore suspension in water containing a few drops of Tween 20 detergent as a dispersant, sprayed onto foliage during cool–wet periods or evenings. Cordoba *et al.* (*18*) compared four inoculation methods and found that 0.12 g freshly collected uredospores diluted in 1.0 g of talc and dusted on the premoistened plants gave the most consistent results. Moderate numbers of uniform pustules are needed for effective separation of resistant segregants. In greenhouse tests, inoculated plants are held 18–24 hr in a mist chamber at 18°C before transfer to a greenhouse bench. Under field conditions, inoculation may be directly on the test plants or on highly susceptible spreader rows planted at frequent intervals (every third to tenth row). Spreader rows should be planted early and inoculated 1–2 weeks before the test plants emerge to provide ample inoculum for natural spread. A mixture of local races is usually used to screen segregating populations.

Anthracnose Snap bean breeders or seedsmen in the United States have not been concerned with breeding for anthracnose resistance because the disease has been controlled for about 50 years by producing seed in semiarid areas of the Intermountain Region (between Rocky Mountains and Cascade Mountains) of the western states (Idaho, Washington, California). The arid summers, coupled with phytosanitary regulations restricting the introduction of infected stocks into the seed production areas, have been successful in virtually eliminating the disease from U.S. production.

In Europe, however, anthracnose is a common problem. The seed production areas of eastern Africa, where most European snap bean seed is grown, are also frequently contaminated. Consequently, the Europeans have made a concerted effort to find and breed sources of anthracnose resistance into their processing cultivars. American seedsmen need to incorporate anthracnose resistance into cultivars aimed at the European market.

Hubbeling (*56*) in 1957 found that the Cornell line 49-242 was resistant to all then known races of anthracnose. Mastenbroek (*69*) in 1960 found that resistance in C49-242 was due to a single dominant factor (*ARE* gene). For about 20 years this gene was used very extensively by the Europeans to develop a large number of resistant cultivars.

In 1973 Leakey and Simbwa-Bunnya (*64*) found a strain in Uganda that attacked the *ARE* gene. Other isolates were later discovered in Brazil (*80*) and in Germany (*90*) that also overcame the *ARE* gene. New races were also found in Malawi (*4*), but none of those overcame resistance in C49-242. There are several resistant breeding lines (Mex 222 and 227) that control the new strains however (*39, 49*); thus these new genes (*Mex-2* and *-3*) will eventually be combined with the *ARE* gene for more stable polygenic resistance.

Hubbeling (*57*) presented a useful key to anthracnose strain identification using differential bean cultivars. He suggested ways of combining the various sources of resistance to develop multigenic broad resistance. He also indicated that the old way of spray inoculation of the young seedlings just after emergence would allow better detection of more minor factors for disease resistance than seed inoculation or root dipping. Chaves (*15*) and Tu and Aylesworth (*109*) suggest various methods of inoculation and screening for anthracnose resistance.

Pure culture isolates often lose the ability to sporulate unless cultured on bean pod agar or sterilized bean pods or leaves. Use only spores suspended in sterile water (not mycelium) to transfer the culture. For inoculation, a water suspension of 200 conidiospores per milliliter is sprayed onto the emerging seedlings, which are kept at 100% RH and about 18°–21°C for 2–3 days. Symptoms develop in 8–10 days.

Field inoculation can be accomplished by sowing every third nursery row with infected seed 2 weeks before planting the test materials. Disease development is favored by daily, light overhead irrigation during dry weather periods.

Screening for Resistance to Root Rots

Root rots are probably the most ubiquitous chronic diseases of snap beans in the United States, and receive the least attention by commercial breeders for good reason—they are extremely difficult to control genetically.

There is little research data available on the actual costs of these diseases in terms of reduced yields, quality, or increased costs of production due to the use of fungicides or cultural practices like subsoiling or extra irrigations. However, in the seed production areas of the West (*100*), I would estimate yield losses alone are in the range of 500–1000 lb/acre (20–40% of potential).

Average industry snap bean seed yields are about 1500 lb/acre on old bean land. In soils free of root rot, it is not unusual to produce over 2500 lb/acre. The seed industry is so used to 1500 lb/acre that it is generally accepted as normal.

Breeding for root rot resistance is difficult because of (1) the lack of high levels of stable resistance in horticulturally acceptable plant and pod types, (2) the general association of colored seed coats and late maturity with resistance (until recently), (3) a lack of clarity as to the genetics of resistance (which generally has a low degree of heritability) or the nature of resistance, (4) and a lack of reliable screening techniques. The last item will be addressed in this section, primarily by describing the methods found most reliable over a period of years. However, much more work on screening methodology is still needed.

Environment and Medium Most of our critical root rot screening work is done in a growth chamber where temperature, moisture, and lighting can be controlled. The chamber is kept at 60–70% RH and is unlighted until the beans emerge (about 5–6 days). High-intensity fluorescent lights provide about 1000 fc at 12 in. above the test medium surface for a 14-hr period daily.

Our testing medium is one part fine-grade quartz sand to three parts fine, horticultural-grade perlite (v/v). The medium is screened after each test, autoclaved 8 hr, and reused indefinitely. We use aluminum pans about 23 in. long × 18 in. wide × 4 in. deep. Each pan holds 20 liters of medium and has drain holes in the bottom. The predampened planting medium is 3 in. deep, and six rows of 20 seeds are planted 1.5 in. deep. The rows are 3.5 in. apart and the seeds ⅛ to ¼ in. apart in the row.

Replication and Incubation Time Most tests with untreated seed (ten seeds per test line) are inoculated at planting and rated for disease severity 14 days later. Each pan contains test lines and two control cultivars, one resistant [NY 2114-12 (*119*)] and one susceptible (Goldcrop) to the pathogen being used. Three to six 10-seed replicates are needed for an accurate estimate of the root rot index for a test line. However, seed of a single plant selection is often in short supply and large numbers of lines need to be tested. Thus it is not always possible to do three replications per line. If the line rates well in comparison to the controls, it may be repeated a second or third time; however, highly susceptible test lines are usually discarded after the first test, unless there is another reason for retaining that particular line.

The 2-week time period from planting to evaluation is important from several points of view. Primarily the seedlings are young enough to survive transplanting for greenhouse

seed production. Disease pressure must be sufficient in this time period clearly to separate susceptible from resistant lines. This is monitored by the disease index of the controls. On a 0 to 100 scale, susceptible controls are usually in the 60–80 range, while resistant controls are in the 20–30 range. Disease pressure regulation is primarily a function of inoculum density, temperature, and moisture. The requirements for each root rot disease are slightly different.

Rating Root Rot Severity At the end of the 2-week disease exposure period, emergence is recorded. The seedlings are dug, washed, and rated on a 0 to 5 scale as follows: 0, no disease; 1, trace; 2, fairly extensive hypocotyl and/or root surface lesions; 3, extensive external and slight internal decay (but still with some functional solid tissues); 4, severe external and internal decay with little or no functional hypocotyl or primary root tissue remaining (may be surviving on new secondary roots); 5, dead or dying, including those seed that rotted before emergence from *Pythium* or *Rhizoctonia*. *Fusarium* and *Aphanomyces* are not seed rotters. Be careful to distinguish between hard seeds that fail to emerge and those that are rotted due to the disease under study or secondary bacteria that invade dead seed. The disease index is calculated as follows:

$$\frac{100[0(\text{no. at } 0) + 1(\text{no. at } 1) + 2(\text{no. at } 2) + 3(\text{no. at } 3) + 4(\text{no. at } 4) + 5(\text{no. at } 5)]}{(\text{total plants}) \times (\text{no. of disease categories} - 1)}$$

where the sum of the products [(number of plants in each disease category) × (numerical value of that category)] is multiplied by 100. That product is divided by the product of the total number of plants times one less than the number of disease categories used. This system allows for comparisons among researchers who use different disease severity ratings (e.g., 0–4, 1–5, 1–9) by putting all results on a 0 to 100 basis.

What to Save Category 0 is immune, 1 is highly resistant, 2 is moderately resistant, 3 is moderately susceptible, 4 is very susceptible, and 5 is highly susceptible. Plants with a rating of 0 or 1 are usually considered resistant enough to save for seed production. However, within a sample there may be enough variation due to various factors, especially late emergence, that the evaluator might be tempted to keep too many boderline 1s or 2s that are escapes. In order to differentiate between possible escapes and genetic resistance, it is necessary to concentrate on saving apparently resistant selections primarily from those test lines with an average disease index (DI) lower (more resistant) than the arithmetic mean of the two controls. Thus, if the resistant control DI = 25 and the susceptible control DI = 75, the control average DI =50. Those test lines with DI $\leq$ 50 are more likely to contain genetically resistant segregants.

The resistant survivors are transplanted to a greenhouse bench for seed production. The seed is increased the following season in a field nursery, where it is exposed to BCMV and CTV screening. Selection for plant and pod type from greenhouse-increased seed is often misleading because of the variable vigor of plants obtained from greenhouse-grown seed. Most of the seed from this field increase is grown in the root rot field the following season, where selection pressure for plant and pod type is applied. The seed harvested from the field root rot nursery is again screened for resistance to individual root rots in the growth chamber–greenhouse (winter season) to complete the testing cycle. Part of the seed of each bulk or SPS may be tested against *Fusarium* and/or *Pythium* one winter greenhouse season, then *Rhizoctonia* and/or *Aphanomyces* the following winter. We do

not have the facilities or technical assistance to test for all four root rot pathogens each season.

Controls The New York breeding line 2114-12 [Wallace (*119*)] is our most *Fusarium*-resistant control. It is also resistant to *Thielaviopsis, Rhizoctonia,* and *Pythium* (*83*), but it is sensitive to cold–wet imbibition. Line PI 165426 (black seed) is not quite as resistant to *Fusarium,* but it is also a very useful control because of its combined tolerance to cold–wet emergence conditions and root rots.

Oliver Norvell's PI 203958 (N-203) is also resistant to *Fusarium, Rhizoctonia,* and *Pythium,* but less so than NY-2114-12. The Wisconsin root-rot-resistant breeding lines 36 and 46 are resistant to *Aphanomyces* and *Pythium.* Susceptible controls might be any of the following: Early Gallatin, Tendercrop, Puregold, or Goldcrop.

Inoculum Preparation and Application Essentially we use a modification of the Del Monte method for *Fusarium* screening (Roger Schmidt, San Leandro, California, personal communication). *Fusarium solani* f. sp. *phaseoli* sporulates readily on V-8 juice as follows: Add one part V-8 juice to four parts distilled water, autoclave, and dispense (20 ml) into sterile petri plates. Transfer a loopful of macroconidia or a small piece of sporulating culture medium aseptically to each plate. Rotate plate to mix inoculum throughout the medium. After 8–10 days at room temperature, blend the sporulating mycelial mats for 1 min (no longer) in a Waring blender, pour through double-layered cheesecloth, and adjust the macroconidia concentration in the effluent liquid to 200,000/ml (D. W. Burke, USDA, Prosser, Washington, personal communication). Usually several isolates are mixed to reduce chances of loss of virulence or strain specificity (although none has been reported for the bean *Fusarium*). This preparation is applied uniformly over the seed lying at the bottoms of the six trenches in each tray (described above) formed in the planting medium just prior to planting. A small hand-operated pressure pump is used to spray the inoculum at the rate of 1.0 ml/seed onto the trench walls and seed. After spray inoculation, the ridges are flattened causing the spore-laden trench walls to come together above the seed row. The trays are watered lightly (daily) and placed in the growth chamber at 21°C.

Aphanomyces euteiches f. sp. *phaseoli* and most *Pythium* spp. produce abundant oospores and/or sporangia on corn meal agar after 8–10 days at room temperature. For each 20-ml petri plate, add 100 ml distilled water and blend for 0.5 min in a Waring blender. The mixture is poured through double-layered cheesecloth and the oospore containing effluent is diluted to a concentration of 1000–4000 oospores per milliliter (Bill Pfender, University of Wisconsin, personal communication). This mixture is sprayed onto the seed in trenches at the rate of 1.0 ml/seed, in the same procedure described above for *Fusarium.* However, the growth chamber is kept at 26°C for *Aphanomyces* and 16°–20°C for *Pythium.* The trays are watered lightly by overhead sprinkler once daily until emergence and then to slight excess twice daily until evaluated.

Rhizoctonia solani inoculum standardization is more difficult. This pathogen can be cultured on finely granulated vermiculite particles permeated with V-8 juice, which are mixed into the perlite–sand test medium at the rate of 3% v/v. This method is also useful for *Pythium ultimum.*

The following inoculum preparation recipe is from John Kraft (USDA, Prosser, Washington, personal communication). Put 400 cc vermiculite into a 500-ml widemouthed Erlenmeyer flask, cap with aluminum foil, and autoclave 4 hr at 15 lb pressure. When flasks are cool, add 200 ml of a V-8 juice–distilled-water mix (1:4) to each flask, and

autoclave another 2 hr. Inoculate the cooled flasks aseptically with a small bit of petri-plate-grown agar culture on two sides (opposite) of the vermiculite mass. Shake each flask daily to help spread the inoculum. After 10–12 days at room temperature, the flasks are well permeated by mycelial growth and the inoculum mass may be difficult to remove without cutting into smaller pieces with a long spatula. These are rubbed through a ⅛-in. mesh wire screen (hardware cloth) just prior to use. One liter (3% v/v) of this inoculum is mixed for 10 min in a small cement mixer with 30 liters of the predampened perlite–sand testing medium. The untreated seed is planted as described above, watered lightly, and placed in the growth chamber at 25°C. The *Rhizoctonia* tests are watered to slight excess daily until evaluated.

The *Pythium* tests, like the *Aphanomyces* tests, are watered once daily until emergence and then to slight excess twice daily until evaluation. The mobile zoospores produced by *Aphanomyces* and some species of *Pythium* travel in a film of water, and so slightly saturated conditions are optimal for uniform disease expression.

After the breeder has combined resistance to several of the root rots, it might be more efficient to screen for two pathogens at the same time. Dickson and Boettger (*27*) have combined *Fusarium* and *Pythium* screening. Workers in Wisconsin (*43, 81, 82*) have combined *Aphanomyces* and *Pythium* testing. Pieczarka and Abawi (*83*) tested several different disease combinations. In general, most combinations should be satisfactory except *Rhizoctonia* with *Pythium* or *Aphanomyces*. *Rhizoctonia* is a hyperparasite of *Pythium,* and so it would possibly do the same to *Aphanomyces* since it is also a member of the Pythiaceae.

The rest of this section will focus on selection methods for seed, seedling, root, plant, and pod characteristics. Included in these selection procedures will be considerations of environmental stress tolerance (heat, cold, drought), cultural practices (mechanical harvesting of green pods and/or seeds, high and/or low fertility levels, herbicide compatibility), and harvestability factors (maturity, trash, plant flow, and case recovery).

Seed Characteristics

Single plant selections and small bulks can be compared for seed yield and quality. Those lines with comparatively low yield, highly variable seed size and shape, shrunken poorly developed seed, or a high proportion (> 2%) of seed coat rupture should be categorically discarded, providing there is no other overwhelming reason to keep a particular line. The remaining lines are then given Dickson's (*23, 25*) nick test for tightness of seed coat adherence, the frequency of transverse cotyledon cracks, and thickness of the seed coat. Next, the best candidate lines are given a seed test for rate of water imbibition as recommended by Dickson and Boettger (*30*). They found a too-rapid rate of water uptake to be correlated with poor stands and weak seedlings and suggested elimination of both problems by selection of semihard seed. The procedure I have adopted is as follows: Apparently sound seed (previously dried to 6% seed moisture) is soaked for 12–24 hr at room temperature. Those lines that take up water within a few hours are discarded. Only those that imbibe after about 12 hr are saved as semihard seed with delayed imbibition, which was found to be correlated with resistance to mechanical injury (*30*). Those that are still hard after 24 hr are discarded as hard seed.

Resistance to mechanical damage is also rated with the same previously dried lot of seed (6% compared to a 14% moisture control lot, fresh-weight basis) dropped several times onto an inclined steel plate from about 2 m (*26*). The smaller the seed quality

difference between dropped and not-dropped seed of the two moisture levels, the more tolerant the line is to mechanical injury. Seed damage can be estimated by comparing the percentage of broken seed and the percentage of hairline cracks found via the water test or by standard germination tests. The seed coat crack (water) test is done with several replications of 100 apparently sound seeds placed in water at room temperature. After 2–3 min, those with hairline seed coat cracks wrinkle in the vicinity of the crack. Sound seed takes much longer to begin imbibition through the micropyles or hilum (*62*).

The standard germination test (*110*) consists of several hundred seeds in wet sand (20% moisture), perlite, or vermiculite, or in rolled paper towels at about 21°C. After 7 days, those seedlings with the equivalent of at least one sound primary leaf, one cotyledon, a normal shoot and root tip, and that are at least half the normal size, are counted as germinated. If more detailed information is required, the seedlings can be classified as to the percentage of healthy, vigorous, normal (HVN) seedlings (*98*). Then the product of percentage emergence multiplied by percentage HVN seedlings is used to develop a seed quality estimate (SQE). Lines can be even more critically evaluated by the seed quality index (SQI), which is the product of the seed emergence index (percentage emergence × rate of emergence) × the percentage of perfect seedlings (*98*).

Seedling Characteristics

In the field, seedling stand counts and early-season vigor can be estimated on a 1 (excellent) to 9 (poor) scale. It is helpful to note the frequency and types of seedling abnormalities. There may also be noteworthy differences in response to herbicides, or differential reactions to an unusually cold or hot, wet or dry emergence period.

Root Characteristics

Roots are usually examined in conjunction with evaluation for disease and/or insect damage. However, this same material may be also rated for root size and vigor. Because little is known about what constitutes an ideal root system, a simple 1 (best) to 9 rating system, relative to the most successful cultivars in a given situation, may be a safe starting point. Besides the obvious absolute size (by weight, length, and/or volume), the rate of root development is perhaps its most important characteristic. This is especially true under adverse environmental extremes of heat–cold, drought–flood. The rate may be estimated in terms of gain per day relative to 1 g of initial seed weight (*3, 97*). This would differentiate between two lines with identical absolute root size and apparent vigor, but which had different initial seed weights. A large vigorous root is usually associated with a large vigorous seed, but snap bean processors do not necessarily want a large-seeded cultivar. Therefore, if a small-seeded cultivar develops as large and vigorous a root system as a large-seeded cultivar, within a limited time period, its roots had to develop at a faster rate.

Next in importance may be a cultivar's ability to rapidly regenerate secondary roots along the basal portion of the hypocotyl and to replace those lost to various biotic or abiotic factors. This characteristic may be an important supplemental or contributing factor to root rot (or insect) tolerance under field conditions.

The roots can also be given a quick evaluation, 1 (best) to 9, to estimate the relative amount and size of the rhizobial nodules.

Plant Characteristics

The single most important plant characteristic the breeder looks for is a strong upright plant habit (or architecture). The plant habit must be stiffly upright and strong enough to hold the pods well off the ground and to withstand mechanical harvesting without breaking. By growing beans in high density under sprinkler irrigation, the weak plants are identified. Care must be taken to avoid selecting those which remain standing under these conditions only by virtue of low yields.

Plant height may vary from 16 to 35 in. depending on cultivar and growing conditions. Most commercial snap beans developed for 36- to 40-in. rows are 20–22 in. tall at harvest. However, underhigh-density culture (6- to 18-in. rows and 2–6 in. between plants), many of these same cultivars are too weak and are thus unable to keep the pods off the ground just before harvest.

For high-density culture, cultivars are needed that respond to optimal fertility levels and cultural practices by increased pod fill and higher yields, rather than excessive renewed vegetative growth. The cv. Early Bird and the USDA breeding line 8BP-8 respond in this way. Under normal row spacing (32–42 in.) and fertility, these types will be 16–18 in. tall at harvest. They should be produced on good land at optimal fertility and moisture levels. On poor soils, plants may be too short and pods too close to the ground for mechanical harvesting.

Flowering should be profuse and spread over a period of about 7 days. Fruiting nodes should be high enough above the soil (mid to upper part of the plant) to keep pods free of spoilage from soilborne organisms. Flowering branches and/or peduncles should be relatively short and strong to prevent pod weight at harvest from bending them to the ground.

If the breeder is field screening for high-temperature setting ability, plantings should be timed so that most of the bloom period is likely to occur when daily maximum temperatures are over 35°C. If the breeder wants to screen for the ability to fill pods well (no seed skips), blooming plants should be exposed to low night temperatures of 10°C. Growth chamber or phytotron screening is much more reliable, but generally less available.

As a general rule, any plant that is well adapted to high-density culture will also perform satisfactorily under "normal" conditions. However, not all plant habits suitable for "normal" row spacing will respond well under high-density conditions. Therefore, the breeder should consider making selections for plant and pod characteristics under high-density, high-fertility conditions, as well as currently used plant spacings and fertility levels.

Pod Characteristics

Selection for pod characteristics in the field is complicated by differences in maturity, and so it is rarely possible directly to compare lines and/or cultivars at the same time. Moreover, even among plants within any particular line, the potential harvest period extends over 4–6 days, during which time the yield, sieve size distribution, and raw-pod quality are constantly changing. An awareness of where a line is, in terms of this harvest period, is important in order to temper the selection criteria relative to the pod characteristics. The length of this harvestable period and how rapidly the raw-pod quality

changes is referred to as a cultivar's "holding" ability. From flowering to harvest, pods increase in sieve size and weight to an optimum harvest point where yields level off and then begin to decline as quality (in terms of percentage of seed, percentage of fiber, and flesh firmness) starts to deteriorate. During the early potential harvest period, quality is high (dark, small-sieved, firm pods), but yield is low. Late in the potential harvest period yield is high, but quality may be borderline or low. A breeder making selections estimates whether a line is in the early or late stages of potential harvestability, but the actual determination of yield potential, percentage sieve size distribution, and holding ability can only be accomplished by sequential replicated yield trials at several dates and plantings, in several locations, for 2–3 years.

Because the potential harvest period during which selection for pod characteristics can be made is relatively short, most breeders schedule different nursery plantings to mature at different times. In this way, they are able to look at more materials at the right time. Most breeders need extra helpers during this fleeting period to assist in making selections.

Plants in many nurseries set up for selection work are spaced 4–6 in. apart in the row to facilitate access and to allow each plant equal opportunity to express its full potential. Rows usually vary from the 22-in. spacing used in the seed production areas of the West, to the 30- to 40-in. spacings most frequently used in the major processing areas.

With the increasing trend toward high-density culture for processing, some breeders are also making selections in narrow rows (11–18 in.) with spacing of 3–6 in. within the row. Care must be exercised in any situation to avoid selection of plants that are on ends of rows or near an open space within the row. These are usually more vigorous and productive because they are able to take advantage of additional light, fertilizer, and/or water because of the reduced population competition.

Ideally each plant should be judged when the pods are at the balanced optimum between yield and quality. Since this is not always possible, a considerable amount of "guesstimation" is required by the evaluator making selections. The evaluator must imagine what the pods on this plant looked like a few days ago if it is over prime, or if the plant is slightly immature, what the pods may look like a few days later when the plant is at its prime.

The pod selector looks first for maximum yield potential, concentrated maturity, and proper placement on the bush. Pods should be well above the soil, with most borne in the mid to upper part of the plant and mostly on the outer periphery in order to be well adapted to mechanical harvesting (or even hand-picking). Once the selector determines a plant has the above qualifications, the pods are critically examined. The selector looks for pods that are straight, smooth, and round; with uniform internal and external color.

Pod cross-sectional shape is classified as round, heartshaped, slightly oval, to oval or flat. Unfortunately, a given cultivar or selection rarely retains the same cross-sectional shape in all sieve sizes. Therefore, roundness is usually relative to sieve size and type. Most Tendercrop-type cultivars are round podded in 2–4 sieve, but may be "crease-backed" (narrower suture to suture vertical diameter than in horizontal diameter) in 5–6 sieve. To avoid this, some breeders select a slightly oval to heart-shaped pod in 3–4 sieve, so that at full maturity (5–6 sieve) the pod is round in cross section instead of creasebacked. Basically, the objective is to have mostly round pods when the line "peaks-out" in terms of optimum yield, sieve size distribution, and processed quality. Cultivars differ in the rate of reversion to a flat pod shape (presumably by mutation). Seed companies spend a lot of time and effort trying to reduce the frequency of this defect, by

roguing (physically removing off-type plants during the growing season), single-plant selection, and mechanical precision sizing (Calvin Lamborn, personal communication, Gallatin Valley Seed Co., Twin Falls, Idaho). Most have established tolerance limits for each stage of seed production increase, aimed at providing the processor with less than 2% flats in the final processing crop. At the breeder's seed stage, a maximum of eight plants per thousand is a good rule of thumb. Seedlots of most cultivars have to be replaced every 3–5 years, to keep the frequency of flats (and string mutants) within acceptable limits.

Processors object to flats because they are usually overmature in relation to the round-podded sieve size with which they are found. The presence of strings also seriously lowers quality grades.

DESIGN OF THE COMPLETE BREEDING PROGRAM

The typical bean breeding program includes a broad scope of specific and nonspecific objectives, each at various stages of planning, execution, revision, and completion.

The principal nonspecific objective is to identify a wide range of useful genetic diversity for plant, pod, and seed characteristics, pest and disease resistance, environmental stress tolerance, physiologic capabilities, etc.

Sources of genetic diversity include the breeders' own collections, many accessible public and/or private breeders' collections, current and old cultivars, and heirloom collections, often maintained by the National Seed Storage Laboratory (Fort Collins, Colorado), and a vast collection of exotic or wild materials available through the USDA Western Regional Plant Introduction Station (Pullman, Washington) and CIAT (Cali, Colombia).

Another nonspecific aspect of any breeding program is a working knowledge of the inheritance of the available genetic diversity. This develops through experience and study of lists of genes, and other literature citations that enable the breeder to review what is known about the inheritance of particular characters. The germplasm committee of the Bean Improvement Cooperative (BIC) has compiled such a list of bean genes and literature citations. The latest bean gene "catalog" is in the 1982 BIC Annual Report (*88*). This list is quite comprehensive and is in the process of being reviewed, and so it will not be repeated here.

After a specific breeding objective is defined in terms of a desired phenotype, the germplasm pool is searched for the parents needed to obtain that particular goal. Sometimes the required parents first need to be developed via a preliminary or "prebreeding" program, i.e., if one of the required characteristics is only available in another species or in a wild *P. vulgaris* line from the tropics with late maturity, black seeds, fibrous pods, and photoperiod sensitivity for flower initiation.

After the required parents are identified or developed, the breeding strategy is outlined on the basis of the available genetic information (Fig. 7.1). The segregating populations from the hybridized parents are scheduled for appropriate screening to certain diseases or environmental resistance factors at specified generations. The selection for horticultural and agronomic characteristics is also scheduled for specific generations and usually in a defined environment and sequence.

When the target combination of characteristics is finally assembled in advanced-generation single-plant selections, the most promising candidates are multiplied, evaluated under a wide range of conditions, and eventually released as a breeding line or a named cultivar.

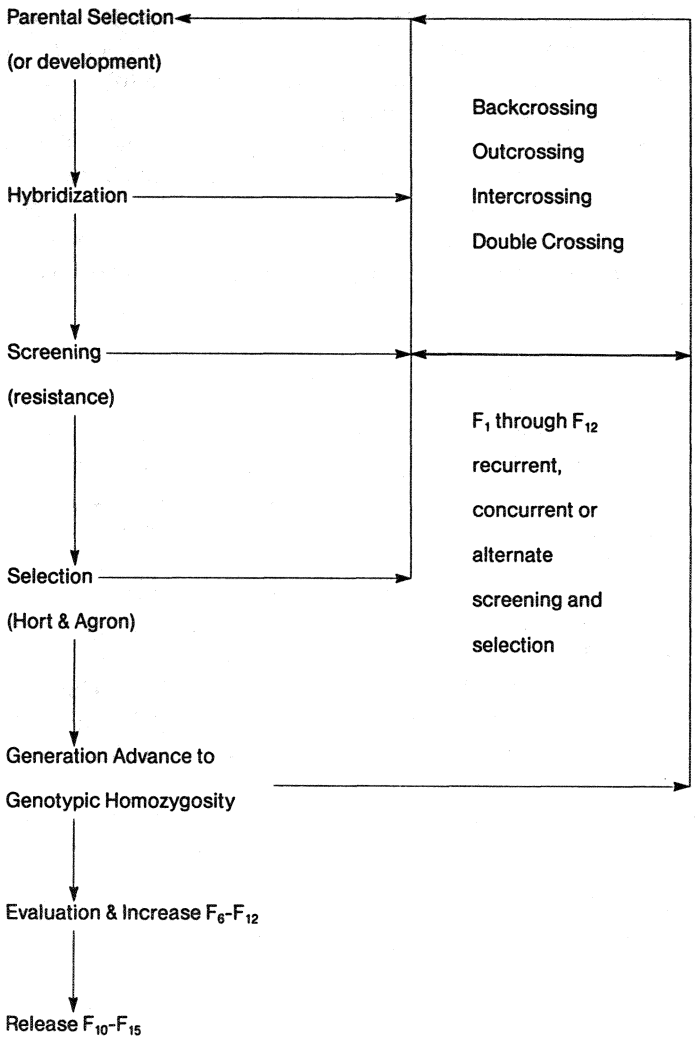

FIGURE 7.1. Flowchart of typical breeding program.

As an example of one of many possible approaches to the development of an actual breeding program, I will outline a hypothetical program for the development of an Eagle-type canner for the Midwest with resistance to aphanomyces root rots and bacterial brown spot. Eagle (Asgrow) is a popular, high-yielding, widely adapted bush snap bean with BCMV resistance. Root rot caused by *A. euteiches* Drechs. f. sp. *phaseoli* Phend. & Hag., and bacterial brown spot are serious production-limiting diseases in Wisconsin. Resistance to aphanomyces root rot has been identified in Wisconsin Root Rot Resistant #36 and #46 (*43*). Bacterial brown spot resistance was identified in several Wisconsin germplasm releases, including BBSR-130 (*42*), -17, and -28 (*44*). Wisconsin RRR 36 and BBSR 130 both have the highest levels of resistance to aphanomyces and brown spot, respectively. However, because neither line is very close to commercial snap bean "type" in terms of plant, pod, and seed characteristics, one or two backcrosses to Eagle will be necessary to recover the characteristics required for commercial acceptance.

Objective: An Aphanomyces- and Brown-Spot-Resistant Eagle-Type Canner for the Midwest

Cycle I. Parental Selection and Initial Hybridization
- Phase 1. Cross number
  - 1 Eagle (BCMV resistant) × Wisconsin 36 (aphanomyces resistant)
  - 2 Eagle × Wisconsin 130 (brown spot resistant)
- Phase 2. Grow out F_1 plants to produce F_2 seed
- Phase 3. Disease screening:
  - a. Screen cross 1 F_2 populations for aphanomyces resistance
  - b. Screen cross 2 F_2 populations for brown spot resistance
- Phase 4. Identify best plant and pod-type single plant selections (SPS) among resistant progeny of each population for next crossing cycle, save resistant F_3 seed

Cycle II. Development of Two-Factor-Resistant Eagle Populations
- Phase 1. Backcross resistant F_3 SPS from each cycle I population to Eagle; cross number
  - 3 Eagle × cross 1 (aphanomyces-resistant F_3 SPS)
  - 4 Eagle × cross 2 (brown spot-resistant F_3 SPS)
- Phase 2. Grow out BC_1 F_1 plants to produce BC_1 F_2 seed
- Phase 3. Disease screening of BC_1 F_2 populations:
  - a. Screen cross 3 BC_1 F_2 population for aphanomyces resistance; save resistant F_3 seed
  - b. Screen cross 4 BC_1 F_2 population for brown spot resistance; save resistant F_3 seed
- Phase 4. Disease screening of BC_1 F_3 populations:
  - a. Screen cross 3 BC_1 F_3 aphanomyces-resistant population for aphanomyces again, plus BCMV resistance, simultaneously
  - b. Screen cross 4 BC_1 F_3 brown spot-resistant population for brown spot again, plus BCMV resistance, simultaneously
- Phase 5. Identify best plant and pod-type SPS among phase 4 resistant progeny of each population to identify two-factor-resistant BC_1 F_4 seed for next crossing cycle

  NOTE: If phase 5 SPS materials do not yet resemble Eagle enough to provide required commercial cultivar characteristics, backcross them to Eagle again, repeating cycle II, phases 1–5 before proceeding

Cycle III. Development of Three-Factor-Resistant Eagle Populations
- Phase 1. Intercross best BC_1 F_4 aphanomyces- and BCMV-resistant SPS from cross 3 to best BC_1 F_4 brown-spot- and BCMV-resistant SPS from cross 4 and reciprocal; cross number
  - 5 Cross 3 aphanomyces- and BCMV-resistant SPS × cross 4 brown-spot- and BCMV-resistant SPS
  - 6 Cross 4 brown-spot- and BCMV-resistant SPS × cross 3 aphanomyces- and BCMV-resistant SPS
- Phase 2. Grow out IC_1 F_1 plants to produce IC_1 F_2 seed
- Phase 3. Sequential and dual-disease screening:
  - a. Screen half of each IC_1 F_2 population to aphanomyces and half to brown spot to produce single-factor resistant IC_1 F_3 seed
  - b. Screen the single-factor-resistant IC_1 F_3 populations from each test in phase 3a to the other disease to identify dual-factor resistant IC_1 F_4 seed (aphanomyces and brown spot resistance).

c. Screen the dual-factor resistant IC_1 F_4 populations from phases 3a and 3b to BCMV; save triple-factor-resistance IC_1 F_5 seed (BCMV, aphanomyces, brown spot)
d. Screen triple-factor resistant IC_1 F_5 population to aphanomyces and brown spot simultaneously; save resistant IC_1 F_6 seed
e. Field screen triple-factor resistant IC_1 F_6 population for BCMV; make numerous SPS for superior plant and pod characteristics in seed production area; save resistant IC_1 F_7 seed of superior SPS
f. Rapidly increase two generations to produce IC_1 F_9 seed
g. Field screen each SPS IC_1 F_9 population simultaneously in seed production area for BCMV, and in Wisconsin (Hancock) for dual resistance to aphanomyces and brown spot; after identifying dual-resistant, well-adapted, high—yielding lines in Wisconsin, make numerous SPS within those identical lines planted in the seed production area nursery; save triple-factor resistant IC_1 F_{10} SPS seed
h. Multiply best IC_1 F_{10} SPS for increasingly detailed evaluation in Wisconsin over next 4–5 years to identify the best candidate for eventual cultivar release.

The whole program requires a minimum turnover of about 21 generations, which at 4 months per generation would be 7 years. However, more realistically 9 or 10 years would be considered a fast time. A lot depends on how much greenhouse space, time, and technical assistance is available for this and the many other programs the breeder has going simultaneously.

TRIALS OF ADVANCED LINES

Intensive disease screening from F_2 to F_6 is usually enough to stabilize factors for disease resistance, but it also eliminates much of the phenotypic variability in the breeder's screening trials. From F_6 onward, SPS are identified that show promise for plant and pod characteristics in the field. Elimination of lines with low seed yield or with seed quality defects (evaluated between field crops) helps reduce the number of lines that return to the field each season for further seed increase and evaluation of horticultural and agronomic requirements.

Those SPS lines that survive two seasons (F_7 and F_8) of close scrutinization in observation trials are advanced in the third year (F_9) to a small-scale preliminary processing evaluation (one four-row × 20-ft replication), which has enough material to freeze and can samples from two different harvest dates. If the processed products look good, the following season (F_{10}) there should be enough seed for replicated yield trials with several dates of planting (early–midseason–late) and several sequential harvests at 2- to 3-day intervals of each planting. This may require 3–7 lb of seed. Single-row plots of 10–20 ft are replicated three to six times for each planting and harvest date. The processed samples are critically compared to standard cultivars to ensure processed quality (*41*) is as good or better than current production cultivars (Fig. 7.2). Concurrently, enough seed has to be increased for future testing in case the line continues to look good in the replicated processing trials.

At least two seasons (F_{10} and F_{11}) of detailed replicated trials are required to identify those lines that are worth sampling extensively (¼- to ½-lb observational plantings) to cooperators in many other locations in the processing areas. If a line looks good in the

Variety | Sieve Size | Date Harvested _____

Location | Canned-frozen Sample | Date Evaluated _____

Style Pack: Whole-Cut

Quality Evaluation:

Appearance:	Attractive	5	4	3	2	1	Poor
Liquor:	Clear	5	4	3	2	1	Discolored
Pod Color:	Green	5	4	3	2	1	Gray
Suture Color:	Green	5	4	3	2	1	Brown
Defects:	Low	5	4	3	2	1	High
Flavor:	Good	5	4	3	2	1	Poor
Texture:	Firm	5	4	3	2	1	Mushy
String:	No String	5	4	3	2	1	Stringy
Sloughing:	None	5	4	3	2	1	Excessive
Carpels:	No Slippage	5	4	3	2	1	Excessive

Quality Rating, Total ☐

Comments:

10 seed length	mm	
Seed Range	min-max	
Deseeded Pods Wgt.	0.00 g	
Seed Wgt.	0.00 g	
% Seed		Seed Grade
Fiber Basket #		
After Drying Wgt.	0.0000 g	
Before Drying Wgt.	0.0000 g	
% Fiber-Blender Method (diff in g)		
Fiber Grade		

FIGURE 7.2. Processed quality evaluation form.

processing areas, a processor may next run small-scale replicated trials (10–25 lb/location) or may be ready to try a 5- to 10-acre commercial run. After 2–3 years of commercial trials (F_{12} to F_{14}) enough is usually known about the line to name and promote it officially, reselect within the line, or drop it.

Often the bulk lot that was a SPS in F_6 is increased for critical evaluations simply because there is enough seed available. If the multilocation trials (F_{10} and F_{11}) indicate there is too much phenotypic variability (often the case), then the bulk seed from the

original F_6 SPS is replaced by increases from one or more SPS made in F_7 to F_{10}. These are evaluated by the same process described above, until a superior, genetically stable line is identified.

From the time an SPS increase is recognized as superior until it is adequately evaluated and increased for release takes another five to seven generations. Winter increases in the tropics or the greenhouse can speed up the process. So can double-cropping in the southwestern states, i.e., the first crop is planted in late March for harvest in July, the July-harvested seed crop is replanted immediately, and the second crop harvested in late October. Of course, there are considerable risks associated with any of these rapid-increase options.

The main objective of the small-scale processing trials is basically to be able accurately to describe the new line to a shipper or processor (potential customer). Trial data are usually expressed in terms of comparisons with a local standard. A processor needs to know the maturity, sieve size distribution, yield, and quality of a line before deciding whether it might be of use.

Yield, maturity, and sieve size data alone are absolutely worthless unless related to quality; and since different end-product uses require different quality standards, it is necessary to know the requirements of each particular customer. This is where information from area salespeople is essential to the breeders and their trial ground assistants. However, no two processors have the same requirements, and any one processor can change requirements overnight if marketing pressures warrant it. Thus an attempt has been made by Silbernagel and Drake (*105*) to enable evaluators to standardize reporting of yield, maturity, and sieve size data at the point of maximum yield and quality. This is hard to pinpoint, but basically is the point at which quality goes from fancy to extrastandard in terms of seed development (seed index). Seed development can be used because other quality factors such as suture and pod wall fiber development can be related to seed development.

Of course, quality (*41*) also includes flavor, texture, carpel separation, skin sloughing, interlocular cavitation, internal tissue breakdown, and color. However, these factors can be evaluated later in processed product trials of the better lines (Fig. 7.2) that pass the preliminary evaluations based on simpler quality-screening techniques, such as the seed index. For a 5-sieve type like Early Gallatin, this would be when the seed index for 5-sieve pods reaches 100. The seed index is the product of percentage seed by weight times average seed length in millimeters. Thus, if percentage seed in the green pods by weight is 10, and the average seed length is 10 mm, the seed index is 100. Several sequential harvests at 2- or 3-day intervals (before and after optimum harvest) are needed in order to chart the increase in yield and changes in sieve size distribution. This information, in view of changes in seed index, identifies the "optimum" harvest time in terms of any particular quality level desired by the processor. This information also suggests a line's holding ability, i.e., how long it stays in a harvestable condition. This is important if harvests are interrupted by bad weather or if for any reason the receiving plant "gets behind" during pod harvest.

Two or 3 years' data at several locations are desirable to determine if a line is worth increasing for commercial processor trials. However, most evaluators know how well their trial ground results correlate with crop development in other areas, and so local small-scale trials are not always conducted in all production areas by all companies.

Processing plants may consume 3–30 tons/hr, and so they require enough raw product (5–20 acres) to keep track of a new cultivar as it goes through the plant. Plant managers

are very conscious of how many tons/hour of their standard production cultivars go through the plant, and of their case recovery, i.e., how many cases of 303 cans are recovered per ton of raw product. A new cultivar may be outstanding in all preliminary or small-scale trials, but be eliminated on the basis of tons/hour plant flow or case recovery figures. This information is generally only obtainable after a line is in fairly large volume and considerable investment has gone into its development. Nevertheless, the majority of lines that reach this level of testing are finally named and released.

In spite of all the previous seed company testing, processors must decide whether or not a new cultivar will be to their advantage. The reactions and impressions of the company field staff, plant manager, quality control manager, and sales department manager are all considered. If there is no decisive economic incentive to change, they will usually stay with what they have. The final evaluation criterion on which the decision to change cultivars usually hinges is a reliable yield of money (profit) to the processor. One outspoken breeder for a major seed company claims to know when this goal has been achieved by observing only one evaluation statistic: signed orders for seed.

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