13 Faba Bean: Breeding for Organic Farming Systems

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Purposes of Breeding and Growing Faba Bean

Faba bean (*Vicia faba* L.; Ackerbohne, field bean, féverole) is a traditional and important nitrogen-fixing crop with protein-rich seeds (about 30%). In Europe, dry faba bean seeds are mainly used as a component of feed for ruminants (cattle, sheep), monogastrics (pigs), and birds (chicken, pigeon). Like pea and sweet lupine, faba bean is used as substitute of soybean. Faba bean performs very well under neutral pH, fertile, and humid conditions, and is very tolerant to summertime episodes of cool temperatures. In such environmental conditions, faba beans are very appropriate to achieve self-sufficiency with respect to the protein feed component that is demanded by organic livestock standards (Hancock et al., 2005).

Another use of faba bean is food production for human consumption. Faba bean is a traditional and important staple food crop around the Mediterranean Basin, in Ethiopia, in the Hindu Kush region, in parts of China, and in the Andean Community.

The world faba bean area in 2009 was 2.51 Mha, and average yield was about 1.6 t ha^{-1}. Main growers were China (945,000 ha) and Ethiopia (521,000 ha). North Africa and Australia produce faba beans in significant amounts. In Europe, France and the UK are the main producers with 100,000 to 200,000 ha per year. Average yield in France from 2007 to 2009 was 4.9 t ha^{-1}. Bolivia, Algeria, and Morocco were the main producers of faba bean green pods and seeds. No precise figures are known for organic production of faba beans in Europe. A total of 1.3 Mha of pulses were grown in 25 European countries, with 4.4% produced under organic conditions; in Germany, this figure was 26% (i.e., 21,900 ha) in organic production. The German faba bean hectarage (12,000 ha) in 2009 was 50% organic (AMI, 2011; Eurostat, 2011; FAOSTAT, 2010).

Farmers in the UK and France export combine-harvested beans for a premium price to food markets in the Nile Valley. The main traits to satisfy this market are: White hilum; an even, light seed color; absence of symptoms from insect or fungus attack; and absence of bean beetles. In the UK and northern parts of Germany, faba bean seed is a component of some traditional dishes (e.g., *dicke Bohnen mit Speck*). The vegetable types of beans used for these purposes are quite different from beans used for animal feeds in that they are large-seeded. Breeding objectives depend on the type of use, which is either consumption as fresh, frozen, or canned product, very young pods, or mature dry seed. Cooking quality, color and taste are major features (AEP, 2010).

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Additional uses of faba beans are as rolled and cracked grain, which is used as nitrogen-rich fertilizer in allotment or community gardens (Raupp, 2010). In certain field rotations, faba bean may serve as a catch crop, with the sole purpose of fixing additional nitrogen, or as a mixed crop, to prevent nitrogen from leaching into ground water. It may also serve as a break in crop rotations to interrupt pest, weed, and disease infection or infestation cycles. Winter-hardy types of faba bean (similar to winter pea) may also serve as a catch crop in a biogas rotation, producing biomass for silage and being followed by corn for the same purpose (Backhaus, 2009; Roth, 2010). In this chapter, we focus on faba beans used for animal feed and grown as arable crop for combine harvesting.

Genetic and Botanical Basics of Breeding Faba Bean

Faba bean is diploid, $2n = 2x = 12$. It is closely related to the $2n = 2x = 14$ *Vicia narbonensis* or *Vicia peregrine* species. Two chromosomes in these related species were united in the evolution of *Vicia faba* to give rise to one very large faba bean chromosome (Fuchs et al., 1998). The genome of *Vicia faba* is huge and consists of about 13,000 Mbp, which is about 30 times the content of barrel medic (*Medicago truncatula*) and about 100 times the content of mouse-ear cress (*Arabidopsis thaliana*) – the latter two being known as model crops for dicot genomic research because of their small genomes. Faba bean's large genome size causes difficulty in molecular and genomics research (Ellwood et al., 2008).

In temperate regions, both spring and winter bean cultivars are grown. In the Mediterranean Basin and similar climates (e.g., parts of China, Australia, and South Africa), the crop is sown in late autumn, grows during mild winters, and matures very early in spring, thereby escaping summer drought and heat. Winter types show only a limited need of vernalization. In order to speed up breeding schemes, breeders may have recourse to two cycles per year, using greenhouse facilities or shuffling seed across both hemispheres.

Unlike grain legumes such as soybean or *Phaseolus* bean, faba bean cannot be crossed with related species. No wild progenitor species is known. Yet, a number of important features wait to be transferred from related vetches, such as tolerance to frost and drought, and resistance to fungal diseases and pests such as aphids (Link, 2006). The genetic diversity within the species is large, reflecting its wide distribution across its agro-ecological niches on all continents. It is only in the tropics that faba beans are not grown. Generally, *Vicia faba* var. *paucijuga*, *V.f.* var. *minor*, *V.f.* var. *equina* and *V.f.* var. *major* are identified as subspecies, classified mainly based on seed size (Mansfield, 2010).

Faba bean seeds are large. Thousand seed weight is approximately 200 to 500 g regarding *V.f.* var. *paucijuga* and *minor* types, 600 to 900 g regarding *V.f. equina* types, and 1,000 to more than 2,500 g regarding *V.f. major* types ("broad bean"). Thousand seed weight of typical feedstuff beans like Fuego or Sultan is 500 to 600 g. With a sowing density of at least 30 seeds per m^2, yield of one faba bean plant only allows the seeding of about one m^2 of field. Thus, faba bean has a low reproduction coefficient.

Mature grain legume seeds do not contain endosperm. Seed coat is maternal tissue with seed coat color, hilum color and tannin content being determined by maternal genotype. The embryo is inside the seed coat. Embryo traits such as cotyledon color (green vs. yellow) are determined by the embryo's genotype. Seed injuries, caused for example by combining or transporting, frequently injure the embryo. Small faba bean seeds are globular in shape but become less so with increasing size. Large broad bean (*major*) seeds are flat and therefore sensitive to mechanical impacts.

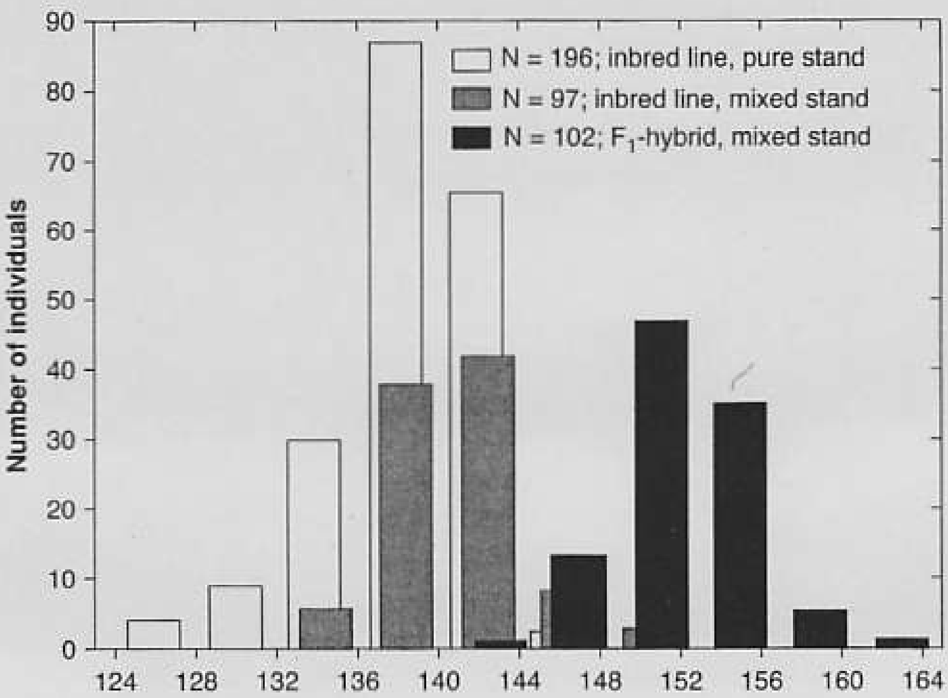

Figure 13.1 Distribution of individual plant height in a topcross-progeny plot (mixed stand) of faba bean, compared with its pure-line seed parent (pure stand). F_1-hybrid plants were identified in the mixed stand based on flower color. Data taken from Leineweber and Link (unpublished).

The anthracnose-causing fungus *Ascochyta faba* is partly seed transmitted. This is true as well for the stem nematode (*Ditylenchus dipsaci*), the broad bean true mosaic virus, and the broad bean stain virus (Rohloff, 1980). Thus, actual provenience, health, and quality of seed are important topics in faba bean breeding and production (Hebblethwaite, 1983).

Faba bean, unlike most other grain legumes, is partly self- and partly cross-fertilized (mixed mating). Both self-pollen and foreign pollen are fully compatible and fertile. The degree of cross-fertilization is about 40 to 50% (see fig. 13.1), and highly variable, with variation depending on the supply of pollinators, the genotype, and the inbreeding status of the plant (Link, 1990; Palmer et al., 2009). Honey bees and solitary bees such as *Osmia rufa* and bumble bees (*Bombus terrestris* and *Bombus hortorum*) are frequent and efficient pollinators. Other insects such as flies, aphids, butterflies, and thrips do not contribute to pollination.

A typical visit of a pollinating insect to a flower causes a mechanical action and stimulation of the stigma (called a "tripping" effect; Zaleski, 1956), thus allowing pollen to germinate and fertilize the ovules. Tripping happens every time the flower is visited by a pollinator. Even if an insect carries no pollen, its visit still stimulates fertilization with self-pollen in the flower. Typically, pollinators are dusted heavily with foreign pollen (pollen from other individuals), thus inducing the germination of a mixture of self-pollen and cross-pollen. The mixed mating system of faba bean is quite different from other grain legumes (such as pea, common bean, lentil, chickpea, groundnut, and soybean), where fertilization is nearly exclusive via selfing, which is caused by anther dehiscence prior to anthesis.

When pollinators are absent, only self-fertilization occurs. European faba beans are variable but generally have a marked dependency of tripping. A low tripping requirement (autofertile genotype) is correlated with a high level of selfing. Without being tripped, seed set may vary from zero to 100%, depending on the genotype, its inbreeding status, and partly on the environmental conditions. High levels of inbreeding favor low autofertility and a high degree of cross-fertilization. Late flowers on a plant tend to need less tripping for seed set. Faba bean is one of those crops that depend on the currently threatened pollinator fauna (UNEP, 2011).

The tripping effect can be triggered and imitated manually. One holds the banner petal of a flower with two fingers of one hand and the wing petals with the other hand and opens and closes the flower two or three times, thus making the stigma, anthers, and pollen extrude past the tip of the keel. Tripping manually in pollinator-free conditions is a standard job of faba bean breeders that ensures full seed set while avoiding contamination with foreign pollen (controlled, tripping-assisted selfing; Link, 1990).

Methodological Considerations

General Considerations for Breeding Diploid, Mixed Mating Crops

Faba bean populations consist of a mixture of more or less inbred individuals. If cross-fertilization was 50% in the previous generation, then 50% of plants in the current generation are hybrid (i.e., non-inbred). If the same was true in the penultimate generation, then there would be, in addition, 25% of F_2-individuals (half-inbred) in the current generation; and so on. For heterotic traits like vigor, plant height, or yield, mixed mating causes the better performing plants to be, on average, less inbred than the weaker ones (see fig. 13.1). Heterosis for grain yield may vary from 40 to 119% (Zeid et al., 2004). The most vigorous individuals are superior mostly because of their higher level of heterozygosity and to a lesser extent because of superior genes. Unfortunately, it is the genes and not the inbreeding statuses that are transmitted to offspring. The individual differences in inbreeding status partly mask the "true" genetic value. Thus, mass-selection of superior individuals is less promising in a mixed mating crop than in a self-fertilizing or a cross-fertilizing crop (where genotypes are not different in inbreeding status).

As is obvious from the example of oilseed rape, sorghum, or cotton, conventional breeders of mixed mating crops prefer to breed hybrid cultivars. As an attractive alternative, synthetic (population) cultivars can be bred.

In the breeding of synthetic cultivars, testing pure lines used to assemble the synthetics may not be appropriate because complete homozygosity is not representative of the inbreeding status of a synthetic population. Inbred line ranking for agronomic value per se is not necessarily identical to their ranking for their "breeding value" (i.e., the "value as parental components" of a synthetic cultivar). A useful solution is to produce topcross- or polycross-progeny using the pure lines. Progeny are tested and superior lines selected based on these results, instead of testing the parental lines themselves (see fig. 13.2). These polycross-derived offspring are very similar in heterozygosity and heterogeneity to that realized in a synthetic cultivar. The progeny effectively reflect their parental lines' differences in (1) per se performance, (2) combining ability and (3) degree of cross-fertilization (Becker, 1982; Link and Ederer, 1993). By maintaining pure lines as parents, cultivars can be resynthesized at will.

A standard initiation of a synthetic cultivar is to allow between (about) four and eight lines to reproduce under natural (partial allogamous) conditions, the mixture being called Syn-0 (the subsequent generations being Syn-1, Syn-2, etc.). As long as cross-fertilization is less than 100%, maximum heterosis is not achieved in Syn-1 but will be realized in later generations. For instance, with 67% self-fertilization, it will take until generation Syn-4 to realize (nearly) the maximum achievable heterosis. Only 50% of possible heterosis can be realized in this case (minimum

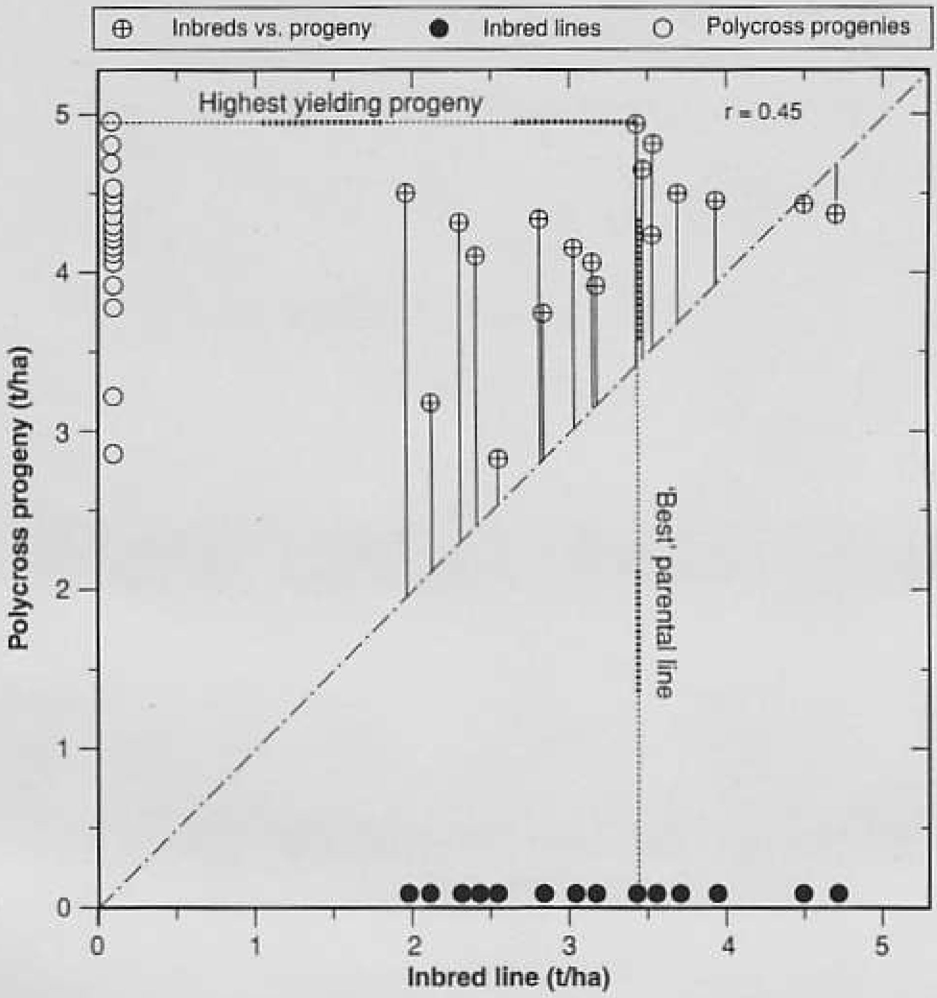

Figure 13.2 Correlation between grain yield of inbred lines and their polycross progenies. Data on y-axis reflect the inbred lines' value as parental components of synthetic cultivars. Results were taken from participatory faba bean experiments (Ghaouti, 2007).

inbreeding coefficient is F = [s/(2-s)] = 0.5). With only 33% self-fertilization, only two generations (Syn-2) are required, and the ultimate minimum inbreeding coefficient is F = [s/(2-s)] = 0.2, hence 80% of heterosis can be realized.

These considerations are based on an assumption of "constant degree of cross-fertilization" (Busbice, 1970). If there is environmental variation for outcrossing, then it is of utmost importance to allocate the highest possible degree of cross-fertilization to the last step of seed production, thus offering the lowest inbreeding and the highest share of heterosis to the farmer (in favor of high vigor, yield, and yield stability in farmers' fields; Geiger, 1982).

General Considerations of Breeding Faba Bean

Hybrid breeding in faba bean is not yet feasible, due to lack of a stable cytoplasmic male sterility (CMS) system and lack of any other tool to control pollination on a large scale (Link, 2006).

To breed and multiply pure lines, for line cultivars, or as components of synthetic cultivars, faba bean breeders use isolation cages that prevent access by pollinators. This allows controlled, pure selfing but requires manual tripping. In conventional breeding, the production of doubled haploid lines would be an attractive means to bypass this procedure. For this and other tissue culture techniques (callus and protoplast regeneration, and genetic transformation), *Vicia faba* is recalcitrant. While genetic transformation has been successful, it is very demanding with low efficiency; there has been very little activity in this area of research. No method of doubled haploid line production is known (Link et al., 2008; Ochatt et al., 2009). Due to the absence of such techniques, conventional and organic breeding differ less in the technologies that are available from each other in faba bean than in many other crops.

Local versus Formal Breeding, Heterogeneity and Heterosis, Intercropping, and Participatory Breeding

With the focus on organic breeding, the following interrelated items must be considered: (1) use of genotype × environment interaction, (2) deployment and exploitation of genotypic heterogeneity and of heterosis in farmers' fields, (3) breeding for intercropping, (4) farmers' participation in the breeding process.

In organic farming, genotype × location interactions are, on average, larger than in conventional agriculture; the purpose of agrochemical inputs in conventional agriculture is largely the mitigation of and compensation for environmental stress. Large genotype × location interaction favors regional or local breeding rather than breeding for geographically wide adaptation. Cultivars are selected to be specifically adapted to the agro-ecological features of their regions. In the local breeding approach, genotype × location interactions are transformed from a nuisance to a heritable part of variation (Ghaouti and Link, 2009). Nevertheless, cultivars have to be well buffered against variability for factors such as weed competition and fungal infection, because part of this variability is not specific to regions but, rather, is associated with specific years.

Important questions are whether (1) the entire breeding process has to be organic; (2) conventional (formal) breeding is fine enough as long as the resulting genotypes are tested in organic conditions; or (3) the ultimate results from conventional breeding are good enough for organic farmers (Desclaux et al., 2008; Sperling et al., 2001). These questions cannot be solved in general but need to be addressed on a crop by crop basis (Schmidt, 2009). From a series of faba bean trials in organic farms, Ghaouti and Link (2009) found that the locally realized gain from selection based on a formal breeding approach was 75.5% of that gain, which resulted from testing and selecting locally, underlining the superiority of local (and regional) breeding (see table 13.1 and see Chapters 2 and 6 of this book).

As with many crops, increasing genotypic heterogeneity and heterosis of faba bean cultivars increases yield stability (Link et al., 1996; Stelling et al., 1994). Both factors seem to be of similar importance in faba bean. The stabilizing impact of heterogeneity is mainly a statistical phenomenon. First, each individual existing within a heterogeneous cultivar shows its own type of interaction with environmental features; thus, the cultivar's interaction is near to the mean of its individuals'

Table 13.1 Ratio of responses to selection for faba bean grain yield: Response realized locally and based on formal breeding results versus response realized locally and based on local results; data are from a series of participatory, organic trials (Ghaouti and Link, 2009)

Expected heritability from testing at an organic location (Local)	$h^2_{(Org.)} = 0.803$
Expected heritability from multi-location testing (Formal)	$h^2_{(Form.)} = 0.765$
Genetic correlation coefficient (Local vs. Formal)	$r_{G(Org.; Form.)} = 0.773$
Expected ratio of responses	Ratio = 0.755

interactions, and variances of means are smaller than variances of single values. The stabilizing impact of heterosis reflects the finding that under stress, heterosis tends to be larger (Abdelmula et al., 1999). Thus, the higher the expected level of stress and the expected level of genotype × environment interaction, the more strongly increased levels of heterosis and more heterogeneous cultivars are favored. Assuming that stress is a more frequent feature of organic farming, more parental lines ($6 < n$) should be used to construct an organic synthetic cultivar compared to a conventional synthetic cultivar (Link and Ederer, 1993). The same reasoning applies if faba bean cultivars are specifically bred to show improved frost or drought stress tolerance. However, some traits such as days to maturity should be homogenous. In support of this approach to cultivar development, regulations of cultivar release (distinct-uniform-stable or DUS) should be relaxed (see Chapter 8). Alternatively, farmers could experiment with cultivar blends.

The reasoning given above leads as well to the topic of intercropping. Positive experience has been observed from intercropping winter wheat with winter faba beans (Hof-Kautz et al., 2008), and spring oats with spring beans is a well-known mixture (Köpke and Nemecek, 2010). Testing faba bean in a mixture with a cereal would not only allow us to breed cultivars that are better adapted to this situation, but would also favor genotypes with high symbiotic performance (Hof and Rauber, 2003). The intercrop niche is small and there is no one specific breeding for it.

In the UK, where faba bean was never abandoned and knowledge of its production, marketing, and use is actively pursued, participatory breeding is attractive. In Germany fewer farmers have experience with the crop. Ghaouti et al. (2008) reported that organic farmers in Germany favored bean types that best fit their local needs, such as tall types in dry and weedy locations, and short types in sites with fewer weeds and greater lodging risk. Paradoxically, farmers appreciated neat, homogenous inbred lines in spite of their lower grain yield, compared to shaggy, heterogeneous polycross-progenies (see fig. 13.1). This was in contradiction to the praise of heterogeneity and diversity that is commonly espoused by the organic community. We must be aware that faba bean is in peril of becoming too minor of a crop, and it may be necessary to allow for a mutual learning phase before embarking on participatory breeding (see Chapter 6).

Traits To Be Improved in Faba Bean Breeding

General

Faba bean seed production has a unique set of production problems. The production of pre-basic seed for synthetics (like Syn-1, Syn-2) and line cultivars should be conducted in environments with as little infestation of *Ascochyta*, *Sitona* beetles and aphids, as possible to keep seed free from fungi and viruses. When producing certified seed of synthetics, pollinator activity must be maximized and combine harvesting and conditioning of seed must be carefully and gently done to keep seed intact and clean and the embryo vigorous.

Traits ranked from most important to least important for spring bean improvement are: (1) grain yield and yield stability, (2) resistance to lodging, (3) *Botrytis*, *Ascochyta*, and downy mildew resistance, and (4) in specific locations resistance to rust and the soil-borne *Fusarium*-complex. Traits that are adequate and need (at least) to be kept at the current levels are: tolerance to viruses, non-shattering, synchronous maturity of pods and straw, date of maturity directly after combine harvest of winter wheat, thousand seed weight between 400 and 600 g, and round seed shape.

Resistance to drought is important; there is limited genetic variation for this trait, and the genetic correlation for grain yield under drought and under non-stressed conditions is high (Link et al., 1999). Resistance breeding is most promising in the case of *Ascochyta faba* (anthracnose) and *Uromyces fabae* (rust), since major genes exist (Link, 2006). Yet, even in these promising cases, breeding activities are very limited.

Additional traits for winter beans are winter hardiness and resistance to fungal attack in early spring. There is some ongoing work on frost resistance and winter-hardiness, and with the advent of climate change, winter faba beans will probably extend their adaptation beyond the UK to more continental climates such as Germany (Arbaoui et al., 2008; Roth and Link, 2010).

For Organic Conditions

Following Schmidtke (2010), the main constraints to a successful organic faba bean production include weeds, aphids, and *Sitona* beetles and larvae. Breeding for insect resistance is not very promising because no marked genetic differences seem to exist within the primary gene pool. Thus other areas of research have to contribute to a solution. However, faba bean does possess favorable genetic variation for weed suppression. Based on a two-year experiment at Göttingen, Ghaouti (2007) reported on the impact of genotypic differences, heterosis, and heterogeneity on grain yield of spring beans with and without *Camelina sativa* (serving as artificial "weed"). *Camelina* caused, on average, 25% yield reduction of the bean. Bean yield was highly correlated with and without *Camelina* ($r = 0.84^{**}$; see fig. 13.3). Nevertheless, genotypes were significantly different for yield reduction. The most important factor was inbreeding status. Without weed stress, blends of hybrids yielded 35% higher than pure lines, and even 95% higher with stress. Hybrids lost 6% of their yield and inbred

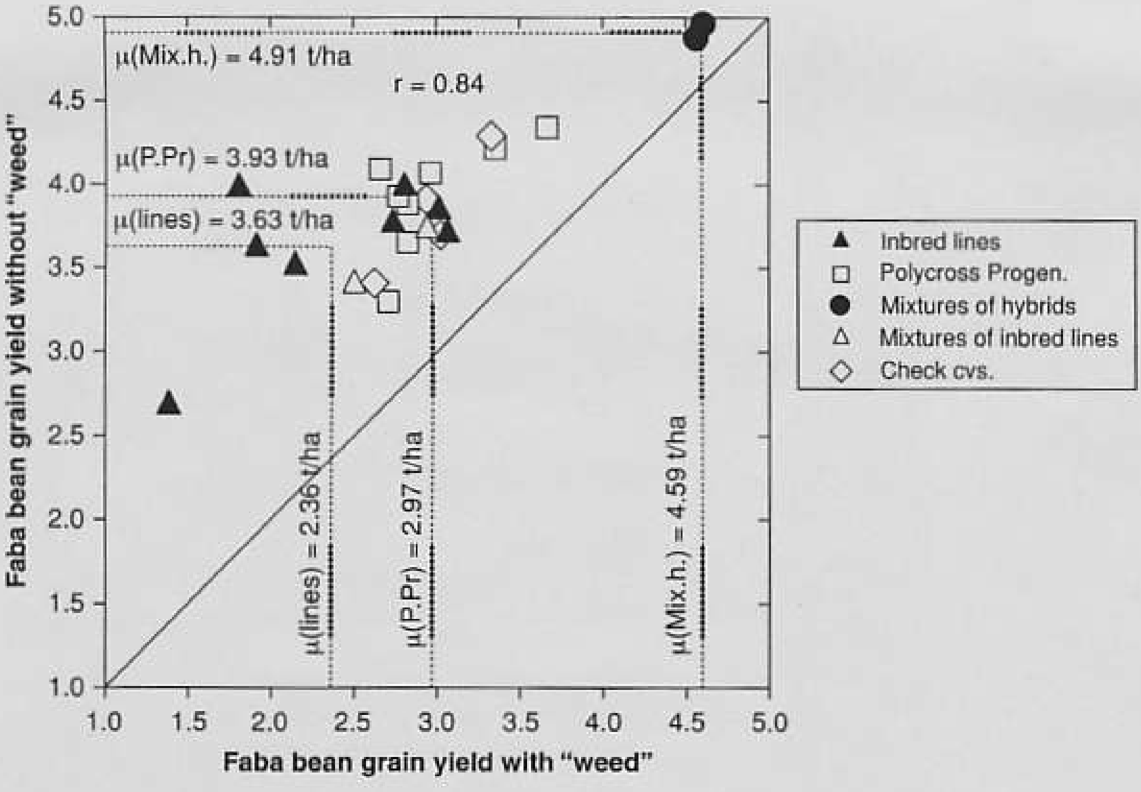

Figure 13.3 Correlation of grain yield with and without artificial weed competition (*Camelina sativa*) for different faba bean genotypes (based on data from Ghaouti, 2007).

lines lost 35% of their yield due to the *Camelina* competition. Yield of *Camelina* was positively correlated with yield loss of the beans ($r = 0.55^*$): Competing with hybrid bean mixtures, *Camelina* yield was 0.29 t ha^{-1}, whereas in inbred bean lines it yielded on average 0.59 t ha^{-1}. Plant height had no major influence on weed tolerance as long as genotypes were of the same inbreeding status.

Tolerance to late sowing (spring beans) may be of specific importance to organic agriculture, because it offers time to mechanically control weed before sowing. This trait is connected to drought and heat tolerance and to the speed of juvenile growth. Prospects of genetic progress in the near future are uncertain.

High quality seed has high (>30%) protein, relatively high methionine content, and low burden of anti-nutritive compounds. Quality is especially important if beans are used on-farm as animal feed. Protein content could be improved, but it is a low priority because buyers are not willing to pay a premium for high protein beans. Genetic variation for methionine content is low, and prospects for improvement are poor unless new genetic variation is discovered, e.g., following mutagenesis (Schumacher et al., 2009). Tannins and vicine are anti-nutritive compounds for pigs and chickens, respectively (Crépon et al., 2010). Hence, zero tannin cultivars like Tangenta and low vicine cultivars like Divine and Mélodie are especially attractive. Since these are monogenic traits, breeding is easy and straight-forward. In the case of zero tannin, caution is advised because seed coat tannins mimic fungicide seed dressings, controlling soil-borne fungi during germination and emergence. Based on past experience, harvesting seed under favorable and dry conditions, employing a cautious transport and proper storage will avoid moldy seed in store, and this is often more important for feed quality than genetic differences of seed quality.

Maximum efficiency of symbioses (to feed the rotation with air-derived nitrogen) is a further specific topic. Current cultivars are able to adequately fix high amounts (>100 kg N per ha, even in high-N soils; Köpke and Nemecek, 2010). Yet, there is currently not much applied research on the interaction between environment, *Rhizobium*, and faba bean (Roskothen, 1989).

Open Questions, Need for Action

In France, faba bean average yield in 2008 was 5.18 t ha^{-1}, compared to 4.46 t ha^{-1} of dry pea. Hence, aiming at a premium market (export to Egypt), conventional farmers are able to produce quite high faba bean yields with current cultivars.

Yet, there are unsolved problems for breeding and growing faba bean as a feed component, especially under organic conditions: (1) susceptibility of the bean to aphids (mainly *Aphis fabae*) and to the *Sitona* leaf weevil, and (2) difficulties in production of high quality seed without chemical insecticides and fungicides. Very likely, breeding alone will not be able to overcome these obstacles for the short term.

Furthermore, with no interspecific crosses available, more care must be devoted to the available intraspecific genetic variation. Hence, more gene bank accession must be phenotyped for agronomic traits, and in certain regions new collections must be acquired, e.g., in the Hindu Kush area and in parts of China (Maharajan et al., 1990).

In Germany, farmers are not allowed to use farm-saved seed if it is a synthetic or hybrid cultivar. For such cultivars, there is not even an option to pay the so-called "fee for farm-saved seed." In case of synthetic cultivars, this makes no sense, because a core feature of a synthetic (population) cultivar is that (unlike a hybrid) its grain yield is adequate to be used as seed without genetic yield penalty (see Chapter 8 of this book for more on this issue).

References

Abdelmula, A.A., W. Link, E. von Kittlitz, and D. Stelling. 1999. Heterosis and inheritance of drought tolerance in faba bean (*Vicia faba* L.). *Plant Breeding* 118:485–490.

AEP Grain Legumes Portal. Accessed September 6, 2010. http://www.grainlegumes.com.

AMI. 2011. Accessed March 21, 2011. http://www.ami-informiert.de.

Arbaoui, M., C. Balko, and W. Link. 2008. Study of faba bean (*Vicia faba* L.) winter hardiness and development of screening methods. *Field Crops Research* 106:60–67.

Backhaus, G.F. 2009. Anbau und Züchtung von Leguminosen in Deutschland – Sachstand und Perspektiven. Fachgespräch im Julius Kühn-Institut. April 21–22, 2009, Braunschweig. *Journal für Kulturpflanzen* 61:301–364.

Becker, H.C. 1982. Züchtung synthetischer Sorten. II. Leistungsvorhersage und Selektion der Eltern. *Vorträge für Pflanzenzüchtung* 1:23–40.

Busbice, T.H. 1970. Predicting yield of synthetic varieties. *Crop Science* 10:265–269.

Crépon, K., P. Marget, C. Peyronnet, B. Carrouée, P. Arese, and G. Duc. 2010. Nutritional value of faba bean (*Vicia faba* L.) seeds for feed and food (review). *Field Crops Research* 115:329–339.

Desclaux, D., J.M. Nolot, Y. Chiffoleau, E. Gozé, and C. Leclerc. 2008. Changes in the concept of genotype × environment interactions to fit agriculture diversification and decentralized participatory plant breeding: Pluridisciplinary point of view. *Euphytica* 163:533–546.

Ellwood, S.R., H.T.T. Phan, M. Jordan, A.M. Torres, C.M. Avila, S. Cruz-Izquierdo, and R.P. Oliver. 2008. Construction of a comparative genetic map in faba bean (*Vicia faba* L.); conservation of genome structure with *Lens culinaris*. *BMC Genomics* 9:380.

Eurostat. 2011. Accessed March 21, 2011. http://www.eds-destatis.de.

FAOSTAT. 2010. Accessed September 6, 2010. http://faostat.fao.org.

Fuchs, J., Strehl, S., Brandes, A., Schweizer, D., and Schubert, I. 1998. Molecular-cytogenetic characterization of the *Vicia faba* genome – heterochromatin differentiation, replication patterns and sequence localization. *Chromosome Research* 6:219–230.

Geiger, H.H. 1982. Züchtung synthetischer Sorten III. Einfluss der Vermehrungsgeneration und des Selbstungsanteils. *Vorträge für Pflanzenzüchtung* 1:41–72.

Ghaouti, L. 2007. Comparison of pure line cultivars with synthetic cultivars in local breeding of faba bean (*Vicia faba* l.) for organic farming. PhD thesis, University of Göttingen.

Ghaouti, L., W. Vogt-Kaute, and W. Link. 2008: Development of locally-adapted faba bean cultivars for organic conditions in Germany through a participatory breeding approach. *Euphytica* 162:257–268.

Ghaouti, L., and W. Link. 2009. Local vs. formal breeding and inbred line vs. synthetic cultivar for organic farming: Case of *Vicia faba* L. *Field Crops Research* 110:167–172.

Hancock, J., R. Weller, and H. McCalman. 2005. 100% Organic Livestock Feeds in UK – preparing for 2005. Report for Organic Centre Wales, March 2003. Accessed September 6, 2010. http://orgprints.org.

Hebblethwaited, P.D. (ed). 1983. The faba bean. A basis for improvement. London: Butterworths.

Hof, C., and R. Rauber. 2003. Anbau von Gemengen im ökologischen Landbau. Booklet in German language. Accessed March 17, http://www.uni-goettingen.de/en/44360.html.

Hof-Kautz, C., K. Schmidtke, and R. Rauber. 2008. Backweizen im Gemenge. *Lebendige Erde* 59:14–15.

Köpke, U., and T. Nemecek. 2010. Ecological services of faba bean. *Field Crops Research* 2010:217–233.

Link, W. 1990. Autofertility and rate of cross-fertilization: Crucial characters for breeding synthetic varieties in faba beans (*Vicia faba* L.). *Theoretical and Applied Genetics* 79:713-717.

Link, W., and W. Ederer. 1993. The concept of varietal ability for partially allogamous crops. *Plant Breeding* 110:1–8.

Link, W., W. Ederer, and E. von Kittlitz. 1994. Zuchtmethodische Entwicklungen: Nutzung von Heterosis bei Ackerbohnen. *Vorträge für Pflanzenzüchtg*. 30:201–230.

Link, W., B. Schill, and E. von Kittlitz. 1996. Breeding for wide adaptation in faba bean. *Euphytica* 92:185–190.

Link, W., A.A. Abdelmula, E. von Kittlitz, S. Bruns, H. Riemer, and D. Stelling. 1999. Genotypic variation for drought tolerance in *Vicia faba*. *Plant Breeding* 118:477–483.

Link, W. 2006. Methods and objectives in faba bean breeding. International Workshop on faba bean breeding and agronomy. pp. 35–40. October 25–27, Córdoba, Junta de Andalucia, Spain.

Link, W., M. Hanafy, N. Malenica, H-J. Jacobsen, and S. Jelenić. 2008. Broad bean. *In*: Kole C., and T.C. Hall (eds). Compendium of transgenic crop plants: Transgenic legume grains and forages. pp. 71–88. Oxford: Blackwell Publishing.

Maharajan, P.L., B. Bhadra, P. Roy, R.P. Yadav, and Z. Ronsu. 1990. Environmental diversity and its influence on farming systems in the Hindu Kush-Himalayas. *In*: International workshop on Mountain Agricultural and Crop Genetic Resources. February 1987, Kathmandu, Nepal. New Delhi: IDRC and ICIMOD, Rajbandhu Industrial Co.

Mansfeld's Word Database of Agricultural and Horticultural Crops. Accessed September 6, 2010. http://mansfeld.ipk-gatersleben.de.

Ochatt, S., C. Pech, T. Grewal, C. Conreux, M. Lulsdorf, and L. Jacas. 2009. Abiotic stress enhances androgenesis from isolated microspores of some legume species (*Fabaceae*). *Journal of Plant Physiology* 166:1314–1328.

Palmer R.G., P. Perez, E. Ortiz-Perez, F. Maalouf, M.J. Suso. 2009. The role of crop-pollinator relationships in breeding for pollinator-friendly legumes: From a breeding perspective. *Euphytica* 170:35–52.

Raupp, J. 2010. Leguminosenschrote als Düngemittel. Ist die Nährstoff – und Humusversorgung damit gesichert? *Lebendige Erde* 4:16–17.

Rohloff, H. 1980. Die Bedeutung der Viruskrankheiten bei der Ackerbohne (*Vicia faba* L.). für die Resistenzzüchtung. Mitt. aus der *Biol. Bundesanstalt für Land – und Forstwirtschaft* 197:31–38.

Roskothen, P. 1989. Genetic effects on host × strain interaction in the symbiosis of *Vicia faba* and *Rhizobium leguminosarum*. *Plant Breeding* 102:122–132.

Roth, F. 2010. Evaluierung von Winterackerbohnen als Zwischenfrucht für eine ökologische Biogas-Produktion. PhD thesis, University of Göttingen.

Roth, F., and W. Link. 2010. Selektion auf Frosttoleranz von Winterackerbohnen (*Vicia faba* L.): Methodenoptimierung und Ergebnisse. 60. *In*: Tagung der Vereinigung der Pflanzenzüchter und Saatgutkaufleute Österreichs. pp. 31–37.

Schmidt, W. 2009. Fünf Jahre Öko-Mais-Züchtung. Erfahrungen und Perspektiven. Accessed September 6, 2010. http://www.kws.de.

Schmidtke, K. 2010. Masterplan Körnerleguminosen – vom Anbaufrust zur Anbaulust. Alnatura Bauerntag, March 17, 2010. Accessed September 6, 2010. http://www.bodenfruchtbarkeit.org/167.

Schumacher, H., H.M. Paulsen, and A.E. Gau. 2009. Phenotypical indicators for the selection of methionine enriched local legumes in plant breeding. *Landbauforschung – vTI Agriculture and Forestry Research* 59:339–344.

Sperling, L., J.A. Ashby, M.E. Smith, E. Weltzien, and S. McGuire. 2001. A framework for analyzing participatory plant breeding approaches and results. *Euphytica* 122:439–450.

Stelling, D., E. Ebmeyer, and W. Ly. 1994. Effects of heterozygosity and heterogeneity. *Plant Breeding* 112:30–39.

UNEP. 2011. Gobal honey bee disorders and other threats to insect pollinators. Accessed March 22, 2011. http://www.unep.org.

Zaleski, A. 1956. Tripping, crossing and selfing in lucerne strains. *Nature* 177:334–335.

Zeid, M., C-C. Schön, and W. Link. 2004. Hybrid performance and AFLP-based genetic similarity in faba bean. *Euphytica* 139:207–216.