Legume Generation

Boosting innovation in breeding for the next generation of legume crops for Europe

Characterisation and breeding of legume crops

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Characterisation and genetic improvement of protein crops

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Legume Generation Report 8

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Legume Generation

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Introduction

It all starts with a seed.

The purpose of this paper is to characterise protein crops and to discuss the challenges and opportunities for the genetic improvement of legumes in a changing environment. It relates to the pre-farm gate part of protein crop value chains. We hope to address in particular further public (such as the European Union) and private investors (breeders) and breeders in crop genetic improvement. This paper was prepared to support the European Union CAP Network Focus Group 'Production of protein crops under climate change'.

In line with the Common Agricultural Policy of the European Union, protein crops are defined here as nitrogen-fixing crops. In practice, these are all members of the legume family. The legume family (*Fabaceae* or *Leguminosae*) is large and diverse. The legume species of interest to farmers in Europe belong to the subfamily *Faboideae* or *Papilionoideae*, defined by the characteristic butterfly shape of their flowers. The flowers have five petals, two of which are fused to form a keel. The flower is symmetrical in only one axis.

Before going into more detail, it is useful to clarify some terms often used to characterise legumes.

Cool-season. Cool season species are well-adapted to relatively cool conditions. Like wheat, they grow at temperatures above 0°C (base temperature around 0°C), survive frost when young, and can be grown as an over-wintering crop in many European regions. They are generally sensitive to frost during and after flowering.

Warm-season. Warm season legumes such as soybean and common bean stop all growth at about or below 6°C. They are sensitive to frost.

Short-day plant. These plants require a minimum night-length to flower. Soya bean is an example. Phaseolus bean (e.g., common bean) is also considered a short-day plant.

Long-day plant. Chickpea, faba bean, pea, lupin and lentil are considered long-day plants because longer days stimulate flowering.

Pulses. Pulses are grain legumes that have a high carbohydrate (starch) content in the seed. Unlike the oilseed legumes, they can be easily used directly for food without processing. Examples are faba bean, chickpea, pea, and lentil.

Oilseed legumes. Oilseed legumes store energy for germination as oil. They are rich in both protein and oil. Oilseed legumes usually require industrial processing to separate oil from the protein-rich residue.

Fine-seed legumes. Unlike the grain legumes, many legumes such as the clovers used for forage have very small, fine seed. These are referred to as fine-seed legumes in some countries.

Grain legume. Pulses and oilseed legumes grown for their seed (grain).

Vegetable or green legumes. Pulses and oilseed legumes that are consumed as immature (green) pods and seeds. Examples are vining pea, broad bean (the vegetable form of faba bean), snap or green bean (the vegetable form of phaseolus bean), and edamame (vegetable form of soya bean).

An agricultural characterisation of widely-grown legumes

Linked to their ability to fix nitrogen, legumes have high protein contents, typically between 20 and 40% in the seed. This compares with eight to 14% in cereals. They are important sources of protein in animal and human diets, with protein qualities that complement cereals in particular. The cool-season grain legumes (chickpea, faba bean, lentil, pea and lupin) came to Europe from the Middle East with arable agriculture, followed much later by the warm-season legumes from tropical and sub-tropical regions: the common bean from the Americas and soya bean from China.

Unlike cereals, legumes are indeterminate by nature. Stems extend indefinitely and a single plant may have flowers, pods and even mature seed at the same time. Most species are self-pollinating and produce more flowers than can mature as pods. Seed size and colour are highly variable and different types of the same species address specific markets. Most self-pollinate with some outcrossing in faba bean and clover. Legumes are characterised by a wide range of anti-nutritional substances evolved to protect legume seeds from predators. Methods have been developed to remove or denature these toxins, or reduce them through breeding. Far more flowers are produced than is necessary for a high-yielding pod formation and farmers need not be alarmed by the flower abortion.

Based on the contribution of the focus group and on our knowledge of European farming and of production statistics, we have chosen the top-ten legume crop species grown in Europe. These are:

Chickpea (*Cicer arietinum*)
Clover (*Trifolium spp.*)
Faba bean (*Vicia faba*)
Lentil (*Lens culinaris*)
Lucerne (Alfalfa, *Medicago sativa*)
Lupin (*Lupinus spp.*)
Pea (*Pisum sativum*)
Phaseolus bean (*Phaseolus spp.*)
Soya bean (*Glycine max*)
Vetch (*Vicia spp*.)

Here we characterise these major legumes in five groups: the cool-season starch grain legumes (chickpea, faba bean, lentil, pea); the cool-season oil-rich legumes (lupin); the warm-season legumes (common bean, soya bean); the fine-seeded forage legumes (clover, lucerne), and the vetches.

A broad characterisation of the ten most widely-grown species is provided in Figure 1.

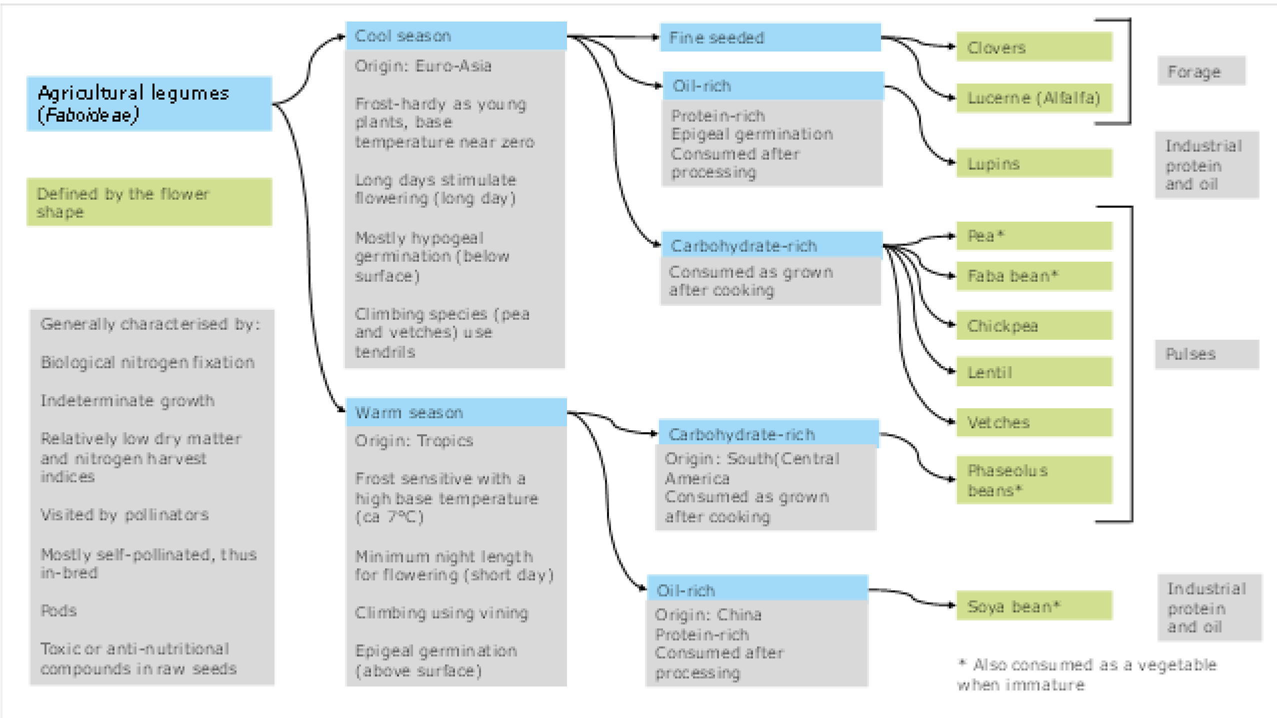

Figure 1. Agronomic characterisation of the ten most widely-grown agricultural legume species or species types grown in Europe

The cool-season starch-rich legumes

The cool-season starch-rich grain legumes have a common evolutionary source and so have similar characteristics. The seed leaves (cotyledons) remain under the soil surface (hypogeal germination) so new shoots can be produced from the seed leaf axils if the seedling is damaged. The young plants are generally tolerant of mild frosts, from -4°C in lentil to -10°C and lower in some cultivars of faba bean and pea. Autumn-sown faba bean and pea have been developed for oceanic climate regions and efforts continue to increase their frost tolerance. Nitrogen fixation depends on the infection of roots with *Rhizobium leguminosarum* in most of these species, which is found in most European soils. Several strains have been selected for optimum performance on individual species. Chickpea requires *R. ciceri*.

Starch is the main energy store and so these species are all pulses with positive characteristics for use in healthy diets. The protein concentration in the seeds is typically 20-30%. The starch is digested slowly, reducing obesity and the risk of diabetes. The oil concentration is low, around 1% of dry matter, except for chickpea which is 3-6% oil.

Pea

Pea is one of the most widely grown grain legumes in Europe and the fourth-most grown in the world. Pea is also one of the most widely grown vegetables thanks to a mutation in vegetable cultivars that increases sucrose content. The pea pod can also be used as a vegetable when young (Mangetout). Dry pea (grain pea) grown to maturity for use as food or feed is generally smooth and round. Dry pea is valued for technical food uses, e.g., for producing protein isolates (Figure 2). A range of seed sizes, shapes and colours address the needs of different markets.

Pea evolved as a tendrilled climber and its stems are weak. The mutation in modern semi-leafless cultivars turns leaves into tendrils so that the plants support themselves by clinging to each other. This ‘semi-leafless’ trait was discovered about 100 years ago and was developed into cultivars by the John Innes Institute in the United Kingdom. It remains the only significant change to crop architecture in the major legumes in the 100 years. Spring-sown cultivars generally produce one stem whereas autumn-sown cultivars usually produce 3-5 stems from the base. Increased branching would allow seeding rates to be reduced, but could lead to late flowering and maturity.

Trypsin inhibitors protect the crops from various bruchid beetles so they are valuable in crop production, but unless the feed is heat-moisture treated to denature them, they reduce feed conversion efficiency and cause stress to animals. Low trypsin inhibitor content can be bred but the use of this trait is complicated by the need for segregation in grain handling.

Figure 2. Flowering stage of the yellow pea variety Kameleon meant for protein extraction. Belgium, 2025. Photo: Mathijs Hast.

Faba bean

Faba bean (widely known as field bean) is used for food as dry mature seed and as a vegetable (broad bean). In Europe, most faba bean is currently grown for feed. Faba bean is very different to other legumes characterised by the following:

1. Good adaption to heavy clay arable soils with pH 6-8.
2. A strong deep taproot.
3. Tolerance of frost to -10°C.
4. Potential to overwinter in regions with relatively mild winters.

5. Free-standing stems (rather than climbing, Figure 3).
6. High rates of vegetative growth and biological nitrogen fixation.
7. Very distinct pods with a large variation in pods from 3 to 10 seeds.
8. Exceptionally large variation between cultivars in seed size from 0.25 to 3.00 g.
9. A relatively high protein content from 25 to 35% (highest of all pulses).
10. High yield up to 7 t/ha, particularly in north and northwestern Europe.

The pyrimidine glycosides, vicine and convicine, that comprise about 1% of the dry weight of wild-type seeds, limit the use of faba bean. The vc-gene reduces the vicine-convicine content to levels that are considered safe. The aglycones, divicine and isouramil, are powerful oxidants that cause acute haemolytic anaemia (termed "favism") in susceptible humans and in poultry.

As in pea, autumn-sown cultivars produce several stems but spring-sown plants generally produce only one. Autumn-sown cultivars require some vernalization (weeks of chilling at 0-4°C) to flower. More flowers are produced than is required for full yield. Most cultivars produce 3-4 seeds per pod, and some produce up to 10.

Faba bean, unlike the other cool-season legumes, has a mixed breeding system, with both self- and cross-pollination. Within a mixed population, hybrid individuals are generally able to self-pollinate (‘autofertile’), while inbred individuals are reliant on bee activity for cross-pollination. The pollen and nectar attract insects, particularly bees. Depending on the cultivar, outcrossing rates range from zero to 83%. Consequently, the valuable early-generation seed crop in breeding programmes must be isolated from other sources of pollen by distance or in a cage. An excess of flowers that attract pollinators from afar is produced. It is quite normal for these excess flowers to be lost.

Figure 3. Left: flowering faba bean visited by pollinators. Right: characteristic free-standing stems of faba bean during the flowering stage. Belgium, 2025. Photo: Mathijs Hast.

Lentil

Lentil is an ancient European crop from the Mediterranean. It was used by the ancient Greeks as a versatile food and was also valued for its therapeutic qualities. Lentil is currently grown throughout the Mediterranean region but consumption in the European Union exceeds production with the deficit met by imports, particularly from Canada. It is sensitive to waterlogging and grows well from autumn sowing on well-drained soils in the Mediterranean. In continental climates, lentil is spring-sown. Frost tolerance is an important breeding goal (Figure 4).

A range of seed sizes (30 mg to 70 mg) and colours address different markets. Large-seeded cultivars tend to be later maturing. The plant is relatively short (often only 40 cm tall), and more highly branched than pea or faba bean. The later leaves end in small tendrils that tie the plant stand together. The small flowers are self-pollinating and produce pods with 1-2 seeds each. The pods hang close to the soil so seed beds must be level so that the cutter bar of combine harvesters can be set low.

Red-seeded cultivars are generally sold as decorticated split grain, so ease of dehulling (removal of the seed coat) is an important trait. Cultivars with yellow cotyledons are generally sold and consumed whole and there is no need to select for dehulling ability.

Figure 4. Lentil trial in Belgium, 2019. Photo: Els Gils.

Chickpea

Chickpea originates from the Middle East where it has been grown for at least nine thousand years. It is a key ingredient of Mediterranean and Middle Eastern cuisines and is increasingly used in other cuisines as a plant-based source of protein. As animal feed, chickpea has a low anti-nutritional content and is well suited to poultry in particular.

Chickpea production is increasing in Europe. The crop yields about 1.0 to 1.5 tonne/ha. Total EU production is about 150,000 t, dominated by Bulgaria France, Greece, Italy and Spain. This compares with an import of about 200,000 t with a value of about 1,000 € per tonne.

Chickpea is a long-day cool-season legume with a base temperature of 0°C. This means that it can overwinter in mild areas. Long summer days at high latitudes stimulate flowering. Consequently, chickpea is potentially well-adapted to northern Europe. However, chickpea finds its niche in Mediterranean growing regions in particular where it overwinters from sowing in autumn to flower and mature in spring and early summer. With a deep taproot, it makes use of winter and spring soil moisture and matures early to escape summer droughts.

Canopy development is relatively slow under cool conditions. Cultivars vary in branching habit from erect to prostate. Most commercial cultivars are erect or semi-erect to facilitate harvesting. Stems continue to grow and produce new flowers after the first pods have formed. The flowers are 100% self-pollinating. The period up to pod setting start can be prolonged under cooler conditions (below a daily average of 15°C). Pods typically contain 2 seeds and are ripe about 40 days after pollination.

Cool-season oilseed legumes – the lupins

Narrow-leafed (*Lupinus angustifolius* L.), white *(L. albus* L.) and yellow (*L. luteus* L.) lupins all originated in the Mediterranean region. Owing to their high alkaloid content, lupin seeds were traditionally thoroughly washed for up to 2 days before consumption. Low-alkaloid germplasm was developed in the 20th century, largely through mutation breeding. The development of lupins was driven particularly in Western Australia from the 1950s. Total European production of domesticated lupins was 370,000 t in 2023, with much grown in Poland. The lupins form symbiosis with a rhizobium usually called *Bradyrhizobium lupini*.

Lupin germination brings the seed leaves (cotyledons) above ground (epigeal germination) so the seedlings are easily damaged and killed. In some growing conditions, up to 5 orders of branches may be produced. For cropping purposes, however, reduced branching helps bring the crop to maturity and harvest readiness. Non-branching cultivars have been produced in narrow-leafed lupin. These shorten the growing season so that the crop can be grown up to 63°N in Finland, but biomass production and seed yields are low. Reduced- or non-branching cultivars have also been developed in both yellow and white lupin. Non-branching cultivars cover the ground poorly, so they have little ability to suppress weed growth, and they require high sowing densities. Thus, a balance is required, and it may be that reduced branching, rather than non-branching, will provide the best combination of sowing density, ground coverage, and maturity date for all but the most extreme climates.

Narrow-leafed and yellow lupins self-pollinate in the bud, but are still attractive to bees (Figure 5). White lupin self-pollinates shortly before flowering, and its outcrossing rate is higher than that of the other two. Seed size is less variable than in some of the other grain legumes.

The agricultural lupins are well-adapted to acid, sandy soils and are sensitive to waterlogging and free calcium, although there has been some success in breeding calcium-tolerant germplasm. Winter-hardy cultivars of white lupin have been developed for the oceanic regions. The oil content ranges from about 6% in narrow-leafed and yellow, 10% in white and 15% in Andean. Energy is also stored as beta-galactan deposited in the thickened cell walls of the cotyledons. Seed protein content is about 32% in narrow-leafed lupin, 35% in white lupin, 40% in Andean lupin and 45% in yellow lupin.

The main restricting factor in lupin usage is quinolizidine alkaloids that are up to 2% of the dry matter of landraces. The alkaloids are synthesised throughout the plant and transported to the seed, so the development of a lupin with sweet seeds but bitter leaves that protect it from herbivores would depend on the identification and silencing of a still unknown alkaloid transporter. In several countries including the UK and France the maximum alkaloid content in lupin seeds for food and feed use is 200 mg/kg, and most current cultivars are below that level.

Figure 5. Left: Blue lupin flowering. Right: blue lupin pod filling. Belgium 2019, photo: Els Gils.

The warm-season legumes

The warm-season legumes are of tropical and sub-tropical origin. They are different in many ways from the cool-season legumes. The wild species climb as vines rather than with tendrils. There is little frost-hardiness in most species, and the optimum growing temperature is above 24°C. Seedling leaves emerge above ground (epigeal germination) where they are susceptible to damage. As is typical of tropical and subtropical species, these are short-day species requiring a minimum period of darkness to initiate flowering. In northern Europe, these longer nights are not reached until too late after mid-summer, so selection by breeders has gradually developed insensitivity to photoperiod. A major gene conferring this trait, Ppd, is in common bean. More than one gene is required in soya bean. Clusters of flowers are borne in the leaf axils after a certain number of vegetative nodes have developed. The flowers of common bean and soya bean self-pollinate before opening. The development of determinate cultivars has been important making them uniform in maturity and suitable for mechanical harvesting. Determinate cultivars produce several branches, whereas indeterminate ones branch more rarely. The usual seeding rate is 30-50/m^2 for both species, depending on soil type, maturity group and branching pattern.

Common bean

Common beans (*Phaseolus vulgaris*) are well-known as simply 'beans' comprising the bush bean and the climbing pole bean. They are grown for both vegetable (snap bean, green bean, French bean) and dry grain uses (e.g., kidney beans, navy bean, haricot bean). Common bean is highly sensitive to frost at all growing stages, and requires warm soils for germination.

The common bean came from the Americas originating from apparently independent domestication events around 6,000 years ago in Mexico, Colombia and Bolivia. It is one of several phaseolus bean species which include the similar scarlet runner bean (*Phaseolus coccineus*). Several introductions from the New World combined with direct exchanges between European and other Mediterranean countries have resulted in large diversity in these species (Figure 6). World production of phaseolus beans was 38 million t in 2023, making them by far the most produced grain legume after soya bean.

Seed size ranges from 170 mg at least to 1,000 mg. Seed-coat colour is highly variable, and there are cultural preferences for colour and seed size in markets. Apart from specialised uses of the climbing types for forage with maize, it is a food crop and is seldom used for feed owing to its high cost and the presence of phytohaemagglutinins that require denaturing by thorough cooking at boiling temperature. Each pod contains up to 8 seeds, and the long pods often reach the soil surface so plant height and an upright growth habit have been important breeding objectives. The immature pods can be consumed as snap beans. The seed coat is very thin and is easily damaged during sowing and harvest, leading to poor germination rates.

Figure 6. Phaseolus bean field, Greece. Photo: Fokion Papathanasiou.

Soya bean

After maize, wheat and rice, soya bean is the world's most widely-grown grain crop, with 371 million tonnes harvested in 2023. Production in the European Union in that year (FAOSTAT data) was 2.86 million t (Figure 7). This compares with a net import of about 35 million tonnes of soya bean (as bean or meal). The Ukraine is a major European producer outside the EU producing 4.74 million tonnes in 2023.

Soybean is an ancient tetraploid (~8–10 MYA). Although much of the genome has diploidized, some duplicated genes remain functionally redundant, which can complicate breeding and sometimes requires targeting multiple homeologous loci.

The oil content at around 20% and the protein content at around 40% makes the seed intrinsically valuable. The oil-free meal is usually 45-50% protein. The amino acid composition of the meal is considered excellent for most feed and food purposes. Usage in food and feed is limited by two strong trypsin inhibitors that require heat treatment for denaturation.

The strong photoperiod dependence of soybean has led to the development of numerous 'maturity groups' each with narrow (2-3° of latitude) zone of adaptation in North America. Maturity groups 000 to 2 cover most of the Europe's needs from the Baltic to the Mediterranean. Photoperiod insensitivity is essential in Europe, especially for the growing regions north of the Alps.

Although soya bean is susceptible to frost, young plants of many cultivars can survive temperatures of -3°C, especially if the exposure to frost is short (an hour rather than overnight), and the seedling or young plant has been hardened by exposure to cool temperatures (<10° for several days).

Soya bean grows on most arable soils. Several rhizobia nodulate soybean, but two species predominate, *Sinorhizobium fredii* on neutral to alkaline soils and *Bradyrhizobium japonicum* on acid or saline soils. Since these species are not widespread in Europe, it is necessary to inoculate soya beans before sowing the crop for the first time in a field.

Figure 7. Soja bean pod filling. Belgium 2024. Photo by Mathijs Hast.

The fine-seeded forage legumes

Clovers

Red clover (*Trifolium pretense*) and white clover (*T. repens*) are particularly relevant to the sustainable development of grassland-based agriculture, arable forage (esp. red clover), and for nitrogen fixation in mixed cropping. The clovers are very widely adapted with wild white clover growing freely between Finland and the Mediterranean. White clover is a natural component of European grasslands. It is valued in low-input farming systems in particular because of its ability to fix nitrogen that supports the whole sward. It tolerates grazing and provides a high-protein and palatable feed for ruminants either grazed or ensiled with grass. White clover grows well under warm conditions and tends to complement grass because its growth peaks in mid-summer (whereas grasses peak in April and May). White clover is particularly valuable in reducing reliance on synthetic nitrogen. Irish research has shown that the overall productivity of clover-supported pasture-based farming systems is 70-90% that of intensively-fertilised grassland and clover-supported dairy systems can financially out-perform intensive system when the fertiliser nitrogen to milk price ratio exceeds about 2.5.

Despite these clear advantages and even though white clover seed is added to many grass seed mixtures, pastures with a high clover content have become relatively rare. Over the last fifty years, grassland has been increasingly intensively fertilised. This has increased grass growth at the expense of clover. Clover-supported systems require more careful management to maintain the clover in the sward.

Lucerne (Alfalfa)

Lucerne (*Medicago sativa*), also known as alfalfa, is a valuable forage crop in Europe, grown for its high yield, nutritional quality, and soil-improving properties (*Figure 8*). Its biology and agronomy are well described by Julier et al.[1] It is botanically closely related to clovers. Cultivated lucerne originates from between the Middle East and central Asia. Wild populations are now present in Europe contributing to genetic diversity for breeding. Lucerne is an outcrossing species with both diploid and tetraploid cultivars. It thrives in temperate climates and is extensively cultivated across European countries, including France, Spain, Italy, Germany, and Poland. It requires warmer conditions than clover with a base temperature of about 5°C (compared to 0°C for clover) and it grows best at 20-30°C. For this reason, it is well suited to regions with relatively warm summers. It is particularly well-adapted to well-drained, calcareous soils and moderate rainfall. Its deep root system allows it to access water from deeper soil layers, making it more drought-resistant than many other forage crops. Along with the benefits that legumes bring to cropping systems, lucerne has particular advantages due to its deep rooting. Because it is perennial grown for several years in a field, it brings particularly large rotational benefits for subsequent crops. Lucerne is highly valued for its high content of protein and the high digestibility of the forage for ruminants.

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[1] Julier,m B., Gastal, F., Louarn. G., Badenhausser, I., Annicchiarico, P., Gilles, C., Le Chantelier, D, Guillemot, E., Emile, J-C. Lucerne, (alfalfa) in European Cropping Systems. . In: Murphy-Bokern, D., Stoddard, F. and Watson, C. (Eds.). Legumes in cropping systems. CABI.

The optimum management of lucerne requires care during the establishment year and management of the stand in subsequent years to balance harvesting and allowing the build-up of reserves in the root for overwintering. In some situations, it can be established from sowing after the harvest of an early maturing crop such as winter barley. Between four and eight harvests per year are made with more harvests in warmer regions.

Figure 8. Alfalfa field in Sevilla, Spain. Photo by Mathijs Hast, 2025

The vetches

The vetches are a group of legume species of the genus *Vicia* that are characterised by a climbing growth habit aided by tendrils. They are grown for a wide range of purposes: seed for feed, forage, and cover-cropping and green manuring. A major advantage is their dual-purpose crop in low input, extensive, and organic cropping systems, with value from both hay and seed. They survive frost and grow in a wide range of soils making them suitable for soil protection and erosion control. Only occasionally are vetches used for human consumption. Many vetch species are underutilised and neglected crops, although significant economic potential exists. Production and cultivated area worldwide had decreased and is within the EU located mainly in Spain and Eastern Europe.

Vetches were present in the everyday diet of hunter-gatherers between 12,000 and 9,000 years ago. Of the approximately 210 species within the genus, 34 are cultivated. The most commonly cultivated are common vetch (*Vicia sativa*) and hairy vetch (*Vicia villosa*), with regional importance of Hungarian vetch (*Vicia pannonica*), Narbonne vetch (*Vicia narbonensis*) and bitter vetch (*Vicia ervilia*).

The use for animal feed is well-established in some regions, either as a sole crop, or in a mixture with other species. Vetches are also commonly cultivated as a cover crop, with a wide range of environmental benefits.

They are a rich source of proteins (21 to 38%), fat (9 to 38%), minerals and other nutrients, while being cheaper than other alternatives. The main deficits are the lack of sulphur amino acids, methionine and cysteine, and the presence of a variety of anti-nutritional factors such as vicine, convicine, tannins, phenolic compounds, trypsin inhibitors and cyano-alanines. This limits the use in monogastric animals, but does not restrict the use ruminant diets.

Other agricultural legume species

The legume family is large and diverse and so there are other species grown locally in Europe in special circumstances. These are well-adapted to their local environment and can have interesting characteristics, while negative properties are a drawback for wider cultivation. Their genetic base is substantial and increasing knowledge of these species is opening possibilities for breeders as literature on them is scarce. An overview of minor used legumes is given Bennett, Francis and Reid.[2] This is discussed here with a focus on their potential agronomic value.

Within the *Anthyllis* genus, the kidney vetch (*Anthyllis vulneraria*) is the only cultivated species. Cultivars show tolerance to high and low pH, and poor and sandy soils. It is used as a fodder and forage crop, it may be sown as a substitute for red clover in dry, chalky pastures.

The hairy milkvetch (*Astragalus cicer*) is one of two *Astragalus* species, known to be very winter hardy and moderately drought and frost resistant. It is a valuable forage legume for pastures with grasses, and for erosion control. The other, A. *hamosus*, is one of the most widespread potential pasture legumes that is well adapted to alkaline soils.

Biserrula (*Biserrula pelecinus*) is a relatively high yielding forage legume with agronomic potential for acidic soils. Its pods are soft and papery and are therefore easily harvested using a conventional header. For those reasons, it is currently under domestication Australia.

Sulla (*Sulla coronaria*) is a perennial legume cultivated extensively in southern Italy and Spain for animal fodder and hay. Its main virtues are the tolerance to mild frosts and resistance to viruses. It is comparable in nutritional value to red clover and alfalfa.

Yellow and pink serradella (*Ornithopus compressus* and *O. sativus* respectively) are grown as forage crops and for soil improvement in some parts of Europe. The caterpillar plant (*Scorpiurus muricatus*) is grown as a minor vegetable. The crown-vetch (*Securigera varia*), used as a forage crop, has been reported to show tolerance to drought, frost, grazing, low pH, insects and poor soils while growing vigorously.

Fenugreek (*Trigonella foenum-graecum*) is widely grown for flavoring, for food, and as a forage crop. It has been reported to be tolerant of disease, drought, high pH, poor soils and salt.

Bird's-foot trefoil (*Lotus corniculatus*) is a perennial forage which, compared with alfalfa and clover, has softer stems and a higher carbohydrate content. It can tolerate cold temperatures and frosts to -6°C but is susceptible to high summer temperatures. It is

[2] Bennett, S., Francis, C., Reid, B. (2001). Minor and under-utilised legumes. In: Maxted, N., Bennett, S.J. (eds) Plant Genetic Resources of Legumes in the Mediterranean. Current Plant Science and Biotechnology in Agriculture, Springer, Dordrecht. https://doi.org/10.1007/978-94-015-9823-1_12

thought to be more resistant to pests and diseases than *Trifolium* or *Medicago* species in humid areas and is moderately salt tolerant.

Another forage legume is white sweet-clover (*Melilotus albus*). It is cultivated for forage and hay, where it is extremely drought resistant. It has been shown to tolerate disease and viruses, frost, heat, poor soil conditions, weeds and water and is salt tolerant. It cannot stand heavy grazing, but is a useful fodder and green manure crop where clovers persist poorly. Other species are tall yellow sweet-clover (*Melilotus latissimus*), sour-clover (*M. indicus*) and yellow sweet-clover (*M. officinalis*).

Common sainfoin (*Onobrychis viciifolia*) was an important forage legume in temperate regions until the 1950s, but is gaining attention again because of its potential to be used as an alternative to drugs to control nematode parasitism in the guts of small ruminants. It is considered tolerant to drought, frost, heavy grazing, moderate salt levels and poor soils. However, the yield is significantly lower than those of alfalfa and clover. Another less cultivated, but high-protein species, is sand esparcette (*O. arenaria*).

Grass pea (*Lathyrus sativus* L.) is a dual-purpose annual legume grown for its seeds for human consumption, and fodder for livestock feeding. Grass pea is one of the preferred legume seeds in low fertility soils and arid areas because of its outstanding tolerance to drought and flooding. It has low fertiliser and water requirements. It can withstand heavy rains in the early growth stages, and prolonged drought during grain filling. It is tolerant to moderate alkalinity or salinity and can be grown as a sole crop, in intercropping systems or in mixtures. Grass pea is adapted and cultivated in many areas of southern, central and eastern Europe and mostly around the Mediterranean Basin where is a staple food used in many dishes.

Lathyrus clymenum L. is an annual Mediterranean grain crop of restricted distribution, still grown today in several Aegean islands such as Thira (Santorini), Anafi and Karpathos (Figure 9). It was recently added to the European Union's products with a Protected Designation of Origin. The seeds of *Lathyrus clymenum*, from which the dish fava Santorinis is made, has a very high protein content (25%), an excellent source of dietary fibre (26%) with low fat content. *Lathyrus clymenum* L. has a creeping growth allowing resistance to strong winds and can be grown in low fertility soils and arid areas because of its outstanding tolerance to dry conditions.

Figure 9. Lathyrus clymenum in Greece. Photo: Fokion Papathanasiou.

Groundnut (*Arachis hypogaea* L.) is grown in tropical and subtropical countries worldwide, including parts of the Mediterranean region. It thrives in a range of low fertility sandy soils except in saline ones due to its low salt tolerance. Irrigation is important for high yields with drought and high-temperature stress to be the most important limiting factors. The stages of reproductive development before flowering, at flowering, and at early pod development are particularly sensitive to these constraints. The kernels of groundnut have a remarkable composition of protein (approximately 25%), oil (about 50%), antioxidants, essential minerals, and vitamins while the leaves and stems are used as animal feed. The flour is also used for animal feed after the oil is extracted.

The *Vigna* genus contains familiar food species such as the cowpea (*V. unguiculata*) and the mung bean (*V. radiata*). Most cultivation occurs outside Europe. Cowpea for example requires very few inputs and is tolerant for sandy soils and low rainfall, which makes it an important crop in the semiarid regions across Africa and Asia. Mung bean is a warm-season, frost-intolerant legume and requires short daylengths otherwise delaying flowering and podding. It has high adaptability to various soil types.

Priority traits

Here we examine the traits of interest to farmers. These provide the basis for prioritising breeding challenges and investments.

Yield – resource capture and partitioning

Even though legumes bring a range of benefits for cropping systems and society, they are not widely grown in Europe. This is because other crops, especially cereals, grow exceptionally well here due to the combination of mild winters, long summer days, and relatively even rainfall through the year, especially in north-western Europe. In these circumstances, it is not enough that legumes fix nitrogen and have high protein contents: they must compete with the cropping alternatives that farmers have. This makes increased productivity a key goal for breeding if legumes are to contribute to the sustainable development of European agri-food systems.

Intrinsic differences between species in the composition of the crop must be kept in mind when considering crop yield and productivity. Protein and oil require more photosynthetic energy than carbohydrate (starch). For this reason, the biological and economic value of crops rich in protein and oil such as soya bean is intrinsically higher than cereals. The starchy grain legumes such as faba bean produce more grain per hectare than soya bean largely because faba bean has a longer growing period and the seed is carbohydrate-rich with little oil.

Benefits for society from legumes depend on the expansion of legume cropping at scale (beyond niches), from 2-3% of the EU arable area today up to 8-10% in line with agro-ecological principles. This depends on having better cultivars that farmers recognise are profitable enough to grow due to their higher economic output (yield × price) and/or reduced production costs of the cropping system in which they are grown.

Ultimately, the yield of a crop depends on the amount of resource, especially sunlight, it captures in its life, the efficiency of turning that light into biomass, and the partitioning of the biomass into the harvested part of the crop. In the case of legumes, the host legume provides the energy for nitrogen fixing rhizobia and this must be taken into consideration when comparing the performance of legumes with that of other crops.

It can be said that much legume crop breeding is concerned with defect elimination. Concerted efforts to improve yield generation with improved resource capture have not been a priority. While we can see the results of efforts to increase yield potential over the last 50 years in wheat, maize, sugar beet and other crops, there have few improvements to basic yield generating processes in legumes. The only substantial change to legume canopy architecture has been the development of the semi-leafless trait by the John Innes Institute about sixty years ago. This trait improves light penetration, photosynthesis and standing ability.

Approaches to fundamentally improving yield potential include extending the growing season with over-wintering crops, reducing the base temperature of young plants so that they grow better under cool conditions in spring, increasing the allocation of biomass to grain (increased harvest index), and careful adjustment of maturity so that late summer light is used.

In recent years, selection of plants based on their genes rather than their performance in the field (genomic selection) has resulted in some rapid progress in breeding programmes. However, genomic selection alone is intrinsically conservative. It increases the speed, precision, and accuracy of seeking improved plants within an existing population but does not support the introduction of new traits from un-adapted sources. As we know from the development of the semi-dwarf trait in wheat, introducing new yield-related traits involves the initial introduction of low-yielding germplasm containing the target traits into the breeding pool.

Quality

The second part of the productivity equation is the per tonne value of the crop, which is determined by the quality of the crop product for different markets.

It is sometimes assumed that high prices in food markets leads to corresponding high prices for the crop. As we see with malting barley where farm prices track feed barley prices, the demand and supply to higher standards at the farm gate determines prices, not the price the end consumer pays for the end product.

Against that background it is recognised that European plant breeding programmes must give attention to quality if European-grown legume crops are to compete with imports. The range of traits is huge, from protein content in soya bean and anti-nutritional factors in faba bean through to special seed quality characteristic for niche food markets.

Breeding for quality presents a number of dilemmas. Niche quality traits do not generate the seed market volumes that can be targeted by breeders. Breeding for them relies on selection from gene pools that serve other purposes. Second, the benefits of cultivars with quality traits are easily transferred to genetic backgrounds used in competing export regions. This means the genetic gain for quality is transferable to breeding programmes supply varieties for exporting countries.

Resistance or tolerance to drought and heat

None of the widely-grown species is considered particularly tolerant of drought, flooding, heat, or salinity, although there are marginal differences between them, and considerable genetic variation within each one that can be harnessed through plant breeding. Chickpea is considered the most heat-tolerant, both chickpea and lentil are relatively drought-tolerant, and faba bean is the most waterlogging-tolerant. When stressed, most legumes in such conditions abort pods to reduce the number of developing seeds, thereby protecting the size of the remaining seed and hence seedling vigour in the next generation.

Tolerance of sub-optimal soil conditions

While all crops can benefit from general changes to root characteristics such as deeper rooting, some legumes have specific breeding requirements. These include reduced sensitivity to calcium in lupins (associated with high pH calcareous soils), and reduced sensitivity to low pH in lucerne. Phaseolus beans are notoriously poor at nodulating and nitrogen fixation.

Frost tolerance and over-wintering

The cool-season legumes are generally frost tolerant with killing temperatures ranging from -4°C in lentil to -20°C in some faba bean cultivars. As happened with wheat some decades ago, extending the growing season through autumn sowing is a strategy to increase overall crop growth and also to help crops escape summer drought through earlier maturity. This makes increased winter hardiness a strategic target yield trait. This is particularly relevant to adaption to climate change.

The clovers and lucerne are also frost tolerant and increasing tolerance serve increased persistence. Autumn dormancy is an important trait in lucerne because the earliness of dormancy is correlated with over-wintering survival and subsequent spring growth.

Chilling tolerance

The warm-season legumes (soya bean, phaseolus beans, and lucerne) grow slowly at temperatures below 15°C. The canopy expands slowly in cool weather in late spring/early summer, reducing the yield potential of the crop. The ability of the crop to grow under sub-optimal temperatures is a strategic yield trait.

Many legumes are susceptible to chilling at flowering, particularly soya bean. This chilling kills flowers and interferes with seed setting.

Disease resistance

Resistance to disease is a priority trait for the breeding.

The main pathogens of legumes are sets of closely related fungi. Each of the pulse species has a leaf, pod and stem blight of the genus *Ascochyta*: *A. fabae* on faba bean and lentil, *A. rabiei* on chickpea, and *A. pisi* together with *Mycosphaerella pinodes* and *Phoma medicaginis* var. *pinodella* on pea. These diseases are splash-dispersed and have a low optimum temperature for growth, so are most prevalent on autumn-sown crops in

Mediterranean and oceanic climates. They can last up to 3 years in the soil, so a minimum 4-year rotation is recommended.

Each species also has a rust: *Uromyces viciae-fabae* on faba bean and lentil, *U. pisi* on pea and *U. ciceris-arietini* on chickpea. The rusts grow best in warm, relatively humid weather, such as late summer in a continental climate. In other climates, they often arrive so late in the growing season that they help to desiccate the nearly mature crop. Chocolate spot disease, *Botrytis fabae*, is exclusive to and important on faba bean and some vetches. *B. cinerea* (grey mould) is occasionally found on pea, lentil and chickpea, and is sometimes considered to contribute to chocolate spot disease on faba bean. These fungi can cause catastrophic crop losses when plant surfaces remain wet for a prolonged period and temperatures are close to 20°C but are rarely problematic in other conditions. *Peronospora viciae* causes downy mildew on pea, faba bean, lentil and some vetches. Because of these diseases, and their ability to survive in the soil, it is widely recommended that grain legumes are used no more often than every fourth year in the cropping sequence.

Anthracnose, which is a breeding target for lupin in particular, is a general term for related fungal diseases affecting legumes, caused by various species of the *Colletotrichum* genus. It can significantly reduce yield and seed quality in a range of crops including soya bean, lentil, pea, chickpea, common bean and lucerne. It causes leaf spotting and thrives in warm, humid conditions, making it a common problem in temperate and tropical regions.

Aphanomyces euteiches is an oomycete that has become the major limitation to growing pea in many parts of the world, as it causes a root rot disease and persists in the soil for up to 9 years, so rotations have to be at least that long. Lentil is considered generally susceptible, but resistance exists in some accessions of faba bean and vetches.

In Europe, the main pathogens of soya bean are *Peronospora manshurica* (downy mildew) and *Pseudomonas syringae pv. glycinea* (bacterial blight) on leaves, *Diaporthe phaseolorum var. caulivora* (canker) and sclerotinia on stems, and *Macrophomina phaseolina* (charcoal rot) on roots. Resistance breeding has made progress against the bacterial diseases, but not significantly against sclerotinia (Figure 10).

Figure 10. Symptoms of soybean with white mold Sclerotinia sclerotiorum *showing white mycelium. Copyright Taifun-Tofy GbmH, Germany. Accessed via the Legume Hub under the Creative Commons 4.0 license.*

Pest resistance

The most important and widespread insect pests are aphids (*Aphis fabae*, the black bean aphid, and *Acyrthosiphon pisum*, the green pea aphid), leaf weevils (*Sitona lineatus* and other species), seed weevils or bruchids (*Bruchus pisorum* on pea, *B. rufimanus* on faba bean, and *B. lentis* on lentil), and the pea moth (*Cydia nigricana,* Table 4). The aphids are important not only because of the direct damage they do but they also transmit viruses. The adult leaf weevils reduce the leaf area of young seedlings, and their larvae do worse damage by consuming root nodules. Bruchids are the hardest to control, as the larvae develop within the seed and are protected from contact insecticides.

The same aphids and leaf weevils attack lupins as *Fabeae* legumes, along with two European specialist *Sitona* species, *S. gressorius* and *S. griseus.* Alkaloid content appeared not to affect leaf weevils, but alkaloid composition affected aphid infestation, indicating that there is potential for combining low overall alkaloid content and aphid resistance.

Broomrapes (*Orobanchaceae*) are flowering plants that parasitize the roots of many crops and are particularly damaging in Mediterranean climates. *Orobanche crenata* is the most common one attacking pea, faba bean, lentil and vetches, but most germplasm of chickpea is resistant to it.

Breeding for environmental change

Most plant breeding and selection seeks to produce and select the best varieties for different environments using existing genetic resources and by generating new variation through crossing. The resulting selected germplasm is multiplied and tested in the different target environments. Climate change as a form of environmental change does not affect breeding specifically in the way many might expect. While climate science tells us that man-made climate change is rapid with respect to historical timescales, it is slow in relation to breeding time scales. The breeding and selection cycle can keep up. Furthermore, many breeding programmes already breed for adaptation in future climates for given environments through the range of environments they already target and select for.

A key question for plant breeding is how climate change is perceived by and affects our target legume species. The climate change challenge to annual crop plants cannot be predicted with certainty. Even the direction of change in temperature in Europe is not certain because there may be cooling due to a slowing of the North Atlantic Drift. Winters and summers might get drier or wetter, crops may become more susceptible to chilling as they develop earlier in spring after mild winters. Consequently, we cannot direct breeding for climate change adaptation with certainty or precision. However, we can identify a number of crop characteristics that are relevant to climate change adaptation and have these introduced into breeding programmes (Table 1). These include:

1. Crop progress to maturity (earliness of harvest).

Crops mature faster in a warmed climate. Earlier maturity accelerated by warming reduces yield simply by reducing the time that the crop canopy is absorbing sunlight. In many situations, breeding for later maturity would be a rational response to warming. But there may also be a demand for early maturity to escape drought or to facilitate double cropping in a warmed world. The progress to maturity is partly determined by the timing of the commencement of flowering. The genetic basis of this in soya bean is well understood and already exploited.

2. Insensitivity to long days.

Warming will allow the production of soya bean move further north to areas with longer days in summer. This increases the need for daylength neutral cultivars. This is already being bred for and the genetic control of daylength neutrality is well understood.

3. Winter-hardiness for autumn sowing to extend the growing period.

For cool season grain legumes, milder winters will extend the opportunity for more winter cropping. This will be particularly relevant where farmers want to have crops mature before summer droughts and heat. The required frost tolerance is already a well-developed trait in most cool season legumes for all but the most severe climates

4. Early vigour and growth under cool conditions in spring.

Except in the warmest frost-free places, autumn sowing is not an option for the warm-season legumes (e.g., soya bean, common bean). Climate change may allow earlier sowing of later maturing varieties, but the performance of these might be affected by slow growth in the longer pre-summer period. Young plant vigour under cool conditions may become a useful trait.

5. Tolerance of summer chilling.

Advanced warm-season legumes (esp. soya bean) are susceptible to chilling, especially around flowering. Climate warming accelerates crop development resulting in crops that are well advanced in late spring when they are vulnerable to chilling. Therefore, paradoxically, tolerance of chilling may be useful under climate warming.

6. Tolerance and survival of heat stress.

We can see already that climate change is causing extremely hot weather in summer. Plant breeding might approach this in different ways, including early maturity to escape heat.

Tolerance is a complex breeding outcome that depends on several traits such as the presence of heat shock proteins, improved transpiration efficiency, improved rooting to access water.

7. Tolerance of drought and water-logging

While the effect of climate change on the distribution of rainfall through the year is unclear, it is widely accepted that climate change will increase the intensity and frequencies of drought affecting crops. Drought tolerance is an extremely complex characteristic depending on a range of plant-level traits ranging from rapid early growth and development to escape drought, the conservation of water in the canopy, through to rooting depth. In the changing climates in some regions such as the Nordic and Baltic, the extended droughts are punctuated by heavy rainfall, with the soil changing directly from water-limiting to oxygen-limiting.

Breeding challenges and opportunities

Ever since the first farmers collected seeds from wild plants, plants have been selected to improve farming. For most arable crops, parent plants are chosen, crossed, and the progeny selected for adaptation in different environments and for different market uses. Breeders' improvements cascade through the generations. The seed contains genetic progress made by generations of farmers and breeders since the species was domesticated. Under Plant Breeders' Rights in Europe, all registered cultivars can be freely used as parents and so the benefits of the work of breeders are freely available to other breeders. Plant breeding is therefore a very powerful and open technology. Farm adoption is simple: through seed, farmers benefit from all the supporting public and private investment in research and technology. Plant breeding provides the foundation for all other agronomic improvements and typically accounts for about half of the technical progress made in developing cropping systems (*Figure 11*).

Despite the importance of breeding, the breeding of in-bred grain species and many population-based species is economically precarious. The value captured by the breeders is low compared to the total value added by breeding to the food value chain (Figure 12). Breeders rely on the revenue from the sale of seed to the seed trade for multiplication and on the royalties from farmers growing their cultivars. All registered cultivars except hybrid cultivars can be propagated by farmers, sometimes without paying royalties. The free use of newly registered cultivars in other breeding programmes makes improved elite germplasm in registered cultivars a public good (i.e., a good that is freely available and non-rival in consumption). The overall result is the revenue streams for breeders are not strong enough to support levels of investment commensurate with the total societal benefit.

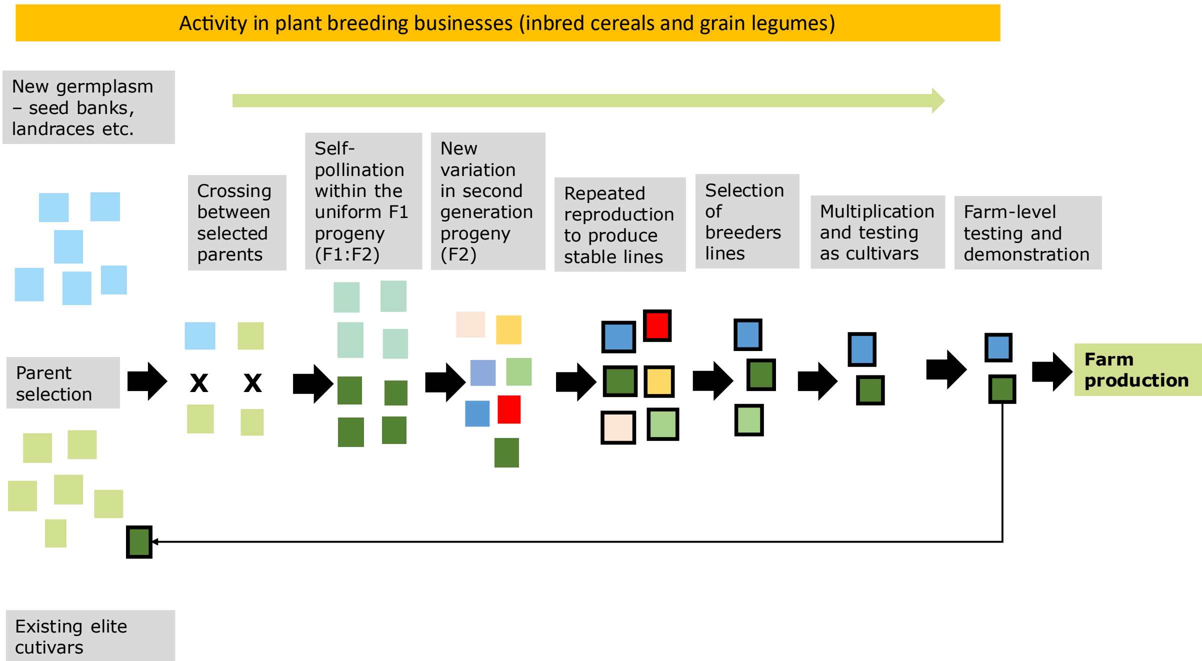

Figure 11. The basic activities in a breeding programme for in-bred and population legume species. Most grain legume species are inbred and their breeding follows this scheme. Typically, the breeding process starts with the selection of true-breeding inbred parents which are crossed. The first-generation progeny are uniform hybrids that are not true breeding. Genetic variation is revealed in the next generation. From that point, repeated self-pollination combined with selection of individual plants in each successive generation results in true-breeding stabile lines after about 10 generations. These can be multiplied up to produce enough seed for cultivar testing. Once a cultivar is granted plant breeders rights, it can be freely used as a parent for crossing in all other breeding programmes. Variations to this include the creation and selection of populations of similar but not identical plants (clover and lucerne) and the breeding of cultivars from single landrace plants using single seed descent.

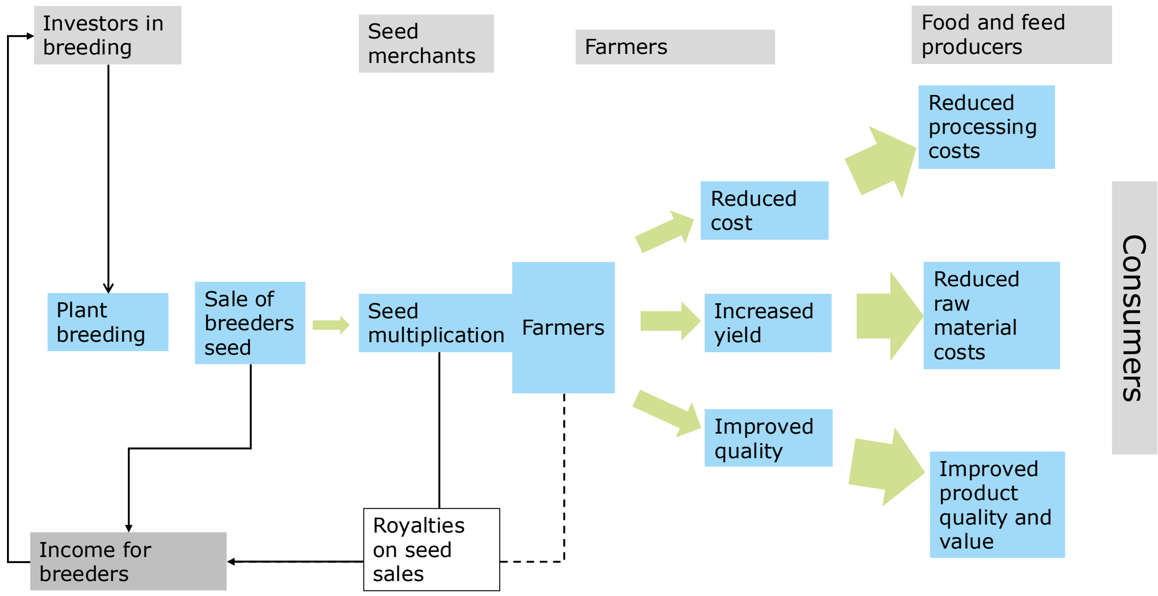

Figure 12. The generation and distribution of value from the breeding of in-bred grain legumes in the food value chain. The value captured by the breeders is low compared to the total value added by breeding to the food value chain.

Breeders seek ways to strengthen their control of the fruits of their work so that revenue can be increased. Some species are difficult for farmers to propagate, for example clovers, providing some protections against illegal propagation. The most important way is to develop hybrid cultivars, which are the F1 progeny of crosses between specific parents, using male sterility. Hybrid maize is a prominent example of how hybrid breeding supports more intensive investment because the grain produced is not true breeding and cannot be used for a next generation crop. With the exception of some developments with male sterility in clover, this option is generally not available to legumes and so legume breeding relies heavily on a combination of public and private investment.

Chickpea

Increased use of legumes for food in Europe combined with the large number of landraces provides an opportunity for chickpea breeders. There are also large genetic resources available worldwide (ICRISAT and ICARDA) with different traits. Climate warming has increased extremes of rainfall and temperature and also has led to the emergence of new diseases and pests and incidence of known ones. The development of chickpea varieties exploiting possible tolerance to abiotic stresses like soil moisture stress, terminal drought, cold, frost and high temperature stress and salinity/alkalinity etc. is of paramount importance. The exploitation of host plant resistance to minimize losses from new or existing diseases and pests should be another challenge for any breeding programme as is the increase in the tolerance to different herbicides to avoid crop losses due to weeds. There is urgent need to restructure existing bushy/semi-spreading plant types of chickpeas to enhance photosynthesis and input use efficiency, and make varieties amenable to intercropping, mechanical harvesting and ease in intercultural operations. Adaptation to low input conditions and organic systems should be a challenge together with an increase in symbiosis and nitrogen use efficiency. Phosphorous (P) use efficiency is also gaining importance as we are facing a decline in the availability of phosphorus. All these require an integrated breeding approach involving conventional, new molecular approaches and rapid phenotyping-based selections to ensure rapid genetic and productivity gains for chickpea.

Clovers

White and red clover are native to Europe and grow in the wild. The cultivated forms are relatively under-developed and their breeding has relied heavily on selecting from the wild. Genetic gains for key traits such as forage/seed yield and persistency have lagged behind that of the forage grasses with which they are grown. While this means that commercial cultivars are relatively unimproved, it also means that varieties are particularly amenable to improvement through hybridisation with wild populations. There is great diversity of agronomic relevance held in European clover collections. Modern genomic breeding strategies are largely underdeveloped. There are opportunities to improve the efficiency of breeding.

One relevant approach is to use genome-wide association analysis that combines observations of the performance of clover accessions in a range of environments with data from genome sequencing. This will provide a panel of markers that can be used for parent selection targeting different environments. However, this is complex compared with cereals and most grain legumes because outcrossing in clover means that varieties are populations rather than pure-breeding lines. The commercial performance of clover depends on a complex array of traits, particularly where clover is grazed. Assessments will include harvest yield, clover content, persistency both in yield plots and under hard defoliation (simulated grazing), leaf size, stolon density and number, crude protein and WSC . This will facilitate the selection of lines with greater persistence and tolerance to cold and drought conditions seen in parts of Europe, without impacting on yield and/or quality. Information on disease susceptibility will also be scored.

Since the forage yield comprises leaves and stems, there is a trade-off between the production of seed by the plant and forage yield. There is also a trade-off between forage or grazing yield and persistence of clover in the sward. Consequently, some further opportunities lie in reproduction-related traits: increasing hybridisation and increasing seed yield. Breeding for self-incompatibility will increase the crossing (hybridisation). This raises questions about uniformity for cultivar registration.

Faba bean

The challenge is to combine improvements in how crops generate yield with increased resistances or tolerances of environmental stresses, diseases and pests. Drawing on crop physiology, we need to improve crop architecture to improve the capture and use of light by the canopy. Increased light capture can also be achieved using winter-hardiness to extend the growing season through autumn sowing. An increased and stabilizing harvest index allows these increases in biomass to increase grain yield. We also need to find and use resistances to stresses, including to insect pests such as seed weevils that will become more common with warming in traditional faba bean areas of the northern Europe. These have to be packaged within crops that match the climate so the crop flowers after danger of frost is over and matures before autumn rains (north of the Mediterranean zone) or summer drought (Mediterranean zone). We have to think outside of the box: where do we find variation that will lead to higher yield within a given growing season? Is there a variation for rapid early growth or high leaf surface per gram leaf biomass that would allow rapid ground coverage?

Faba bean genetic resources are already well known and exploited so opportunities arise from the application of new technologies. Consequently, access to new breeding technologies such as gene editing is particularly relevant to faba bean. These can be applied to the complex yield-related traits and to quality traits that will facilitate increased use of plant-based protein in sustainable healthy diets.

While major genes with large effect are easy to track in a breeding programme, minor genes with small effects have to be combined and tracked together. Doing this by direct observation of growing plants (phenotyping) is laborious, so other tools are sought. This is where genomic selection is desirable, because the breeder can use markers distributed through the genome to identify those individuals that carry the known minor genes for the desired trait.

Seed size needs to be kept within certain ranges. Broad beans (>1,000 mg/seed) have low multiplication rates and high seeding costs, so are only for premium food markets. Tick beans (<500 mg/seed) are wanted at high latitudes because they are more easily dried and also because of the lower seeding costs. In the middle range, horse beans are all-purpose generalists, and most autumn-sown faba bean is in this size category.

Major genes are known for resistance to the cold-weather pathogenic fungus *Ascochyta fabae* and the root parasites known as broomrapes. Minor genes with small effect are known for the other main pathogenic fungi, namely the botrytis species that cause chocolate spot disease, and *Uromyces viciae-fabae* that causes rust. Other minor genes contribute to frost tolerance, over-wintering ability, leaf responses to drought, and rootzone acidity tolerance. We assume that root architecture and root responses to soil water deficit are conferred by several minor genes because they are in other species. With climate change, heat waves are expected to be more common, so sources of heat tolerance should be sought.

Quality factors are important for crop end use. Vicine and convicine, the most important anti-nutritional factors, are reduced 90 – 95% by a single recessive gene that is easily tracked with a DNA marker. There are two recessive genes, zt1 and zt2, each of which prevents the deposition of condensed tannins in the seed coat, as desired for some feed uses. The developing food sector does not yet know what it needs for improving the quality of novel foods, so we can’t integrate those into faba breeding yet. It is expected that we will want different legumin (large): vicilin (small) storage-protein ratios, larger for tofu-type gels, smaller for dairy analogues, who knows what for textured vegetable protein. Reduced seed lipoxygenase levels would prevent the development of certain off-flavours in wet processing. Higher protein content is always wanted for the feed market, but changing amino acid composition is not worth the effort when feed supplements are cheap and human diets are diverse.

Lentil

The current lentil cultivars have a narrow genetic base. The use of varieties adapted in Mediterranean countries but also the large gene pool of accessions from global gene banks is a great opportunity for European breeders and breeding companies. Establishing suitable, fast and effective screening techniques is a major challenge for any breeding programme for tolerance to frost, and flooding but also to disease and pest resistance. A great challenge is to breed for varieties with shorter growing season and increased tolerance to pod and seed shedding. Similarly, improving suitability for over-wintering provides a foundation for increased yield and may result in earlier maturity escaping heat and drought stress.

The interest of the organic sector in the cultivation of inbred lines derived from landraces provides further opportunities. The genetic diversity in land races is expected to provide crop resilience and yield stability from local participatory breeding schemes. Breeding for intercropping may be challenging for lentil breeders which need to identify traits that could maintain a high production when intercropped. Improved nitrogen fixation and nitrogen use efficiency are also a great challenge for breeding. The conventional methods of lentil breeding are characterized by long timelines and many years of intensive effort are usually required to achieve near-homozygosity in advanced lines. The integration of new speed-breeding tools, advanced molecular approaches, and rapid phenotyping are essential to achieve genotypes with resilience to the increased abiotic and biotic stresses due to climate change.

Lucerne

Lucerne is well represented in European and global gene banks providing the foundation of on-going breeding efforts. The genetics and consequently the approaches to breeding are complex. Lucerne is out-breeding and consequently cultivars are populations derived from four to 200 parents, each parent being a single plant and genotype. Despite the complexity, lucerne breeding in Europe remains dynamic, integrating advanced genetic tools while maintaining sustainability and adaptation to diverse growing conditions. Breeding in France is focused on yield, breeding in Italy and Spain, and winter-hardiness in continental regions. The approaches include the use of hybrid breeding to generate synthetic varieties, market assisted selection of parents, and gene-editing and transgenic approaches. Lucerne is the only legume covered here for which there are genetically modified varieties (outside Europe). Tolerance of glyphosate is the main GM trait used in the USA.

Forage yield and quality remain key goals for breeding. Higher yield is reached through a range of ways, including better adaption to the local environments. Stem length and resistance to lodging are important traits. However, this is negatively correlated with intake by small ruminants.

Improved resistance to diseases is a major goal with genetic progress being made for verticillium wilt and anthracnose. Other targets include stem nematode, resistance to aphids, and to sclerotinia.

In Europe, both private companies and academic institutions are actively involved in the breeding of lucerne.

Lupins

Lupin breeding is limited in Europe with small programmes in Poland, Germany and France. There are also breeding programmes in Belorussia and Russia. Much depends on pre-breeding in research organisations such as the Julius Kuhn Institute in Germany and the Institute of Plant Genetics in Poland. ESKUSA GmbH is pioneering breeding research on the private sector side.

The gene pools for the three cultivated **sweet** lupin species *L. angustifolius, L. albus* and *L. luteus* are narrow. Serious breeding progress for yield is no longer to be expected within these pools. The focus on low alkaloid (sweet) types means that the genetic base is narrow in all species. The variation in the high alkaloid (bitter) types remains largely untapped. A fundamental challenge and opportunity lies in the expansion of the genetic base using bitter varieties. Lupins have a wide range of plant architectures and have the potential for over-wintering thus offering the opportunity to use ideotype concepts to improve resource capture.

The Legume Generation consortium has identified the following breeding priorities for the three main lupin species:

Narrow leafed lupin: Grain yield, winter hardiness, herbicide resistance, protein content, alkaloids, diseases, alkaline soil tolerance, growth types, anthracnose, seed shattering, protein content, alkaloids, mutant collections, alkaloid biosynthesis and distribution.

White lupin: Grain yield, winter hardiness, anthracnose, alkaloids, soil tolerance, earliness, diseases, seed size.

Andean lupin: grain yield, earliness.

The lupin species have an extraordinary deep growing taproot, which helps them to grow on poor, sandy soils with limited water. Lupin species can play a major role in grain legume production as climate change progresses. But new approaches to preparing and selecting varieties is required for the expected environmental conditions. Without impressive grain yield increase there will be no further acceptance by the farmers and hence, no additional cropping area for lupins. There are two large levers that we can turn to significantly increase grain yield and yield stability in the lupin crops:

1. Extending the growing season by developing varieties for autumn sowing. Frost tolerant autumn-sown crops are well-grown and well-rooted after winter able to withstand drought in spring and summer. Early spring growth provides the foundation of a higher yield in crops that can better withstand or escape intense summer drought and heat.

2. Make use of the genetically broad gene pool of bitter lupins, by i) introgression of traits from bitter accessions into sweet lupin varieties and preferably by ii) gene editing of the alkaloid transport mechanism. We have the variation that we need in the genetic resources to improve new cultivars. However short-term thinking of return on invest keeps the applied breeding programmes from use of bitter types in the breeding nurseries.

The alkaloid-rich, bitter lupin varieties are not usable for the large animal feed market; however, their protein can be used technically in films, plastics and adhesives. To develop the above-mentioned agronomic characteristics for the feed market, these have to be introgressed by crossing into sweet lupins. Alternatively, genome editing could make the bitter gene pool of the lupin species directly available if the transport mechanism of the alkaloids from the leaf into the seed can be edited. This means the development of a bitter lupin with sweet seeds. However, this alone does not make the narrow-leaved lupin any better and not more reliable in terms of grain yield. To exploit the grain yield potential, it is necessary to select further trait complexes with resource capture potential. We intend to select **winter-forms** of the lupin species. These could - sown in the fall - escape the pre-summer drought and use a longer vegetation period to build up yields. The trait complex 'winter hardiness' has then to be associated with late ripening, long, sturdy plants and firmness. Late ripening and long plants are, however, contrary to the previous pre-breeding and breeding objectives for lupins, which have been selected for 'short' and 'early maturity' for many decades. A new thinking about breeding goals is needed in this context.

Additionally, a safe herbicide strategy is urgently needed for conventional lupin cropping. We are searching for a non-gmo-herbicide resistance based on a mutation to cause resistance against sulfonylurea-herbicides. If we want to make the lupins independent from the soil type, we have to select for alkaline soil tolerance. We have single genotypes with this character, but we have to put a lot of effort in developing varieties with this character.

New cultivation methods and new breeding objectives should all be considered under the heading of "**resource capture**". This term includes photosynthesis days, stand space optimisation, root efficiency and, of course, climate resilience.

There is a lot of excellent basic research in lupins on specific traits and with state of the art molecular and analytical tools. However, there is a missing link between the basic research and applied cultivar development for release of varieties. We need to strengthen pre-breeding approaches (genetic analysis of observed characteristics; methods for reliable trait identification; suitable quality analysis, etc.) as a connecting bridge and we need a courageous, bold breeding programme based on the available plant material including genetic resources. This requires an (international) division of labour and close cooperation between breeders and scientists in the pre-competitive area even between breeding companies. The cooperation should be based on the individual legume species, as is already being pursued in the case of the current Legume Generation project. The impetus in this project comes from the applied breeding, which in turn takes the necessary breeding objectives from the conditions of agricultural practice. The agricultural expectations on lupin varieties are competitive and enough income of legume cropping in comparison to cereals and other crops. ESKUSA has set itself the goal to develop varieties of narrow-leaved lupin with 4 t/ha reliable grain yield and 40% protein content (our "40/40" approach).

Pea

Pea is probably the most intensively researched legume species in Europe where there are substantial resources in gene banks (e.g., the John Innes Centre in the UK). These germplasm resources encompass a diverse range including wild accessions, old landraces, both local old and modern cultivars and advanced breeding lines collected from different parts of the world. Other organisations such as SERIDA in Spain maintain a collection of old cultivars from southern Spain.

Pea breeding efforts must address diverse challenges, which include improving agronomic traits and seed quality to enhance resistance against biotic and abiotic stresses. It is important that efforts to boost the breeding of pea draw on integrating advanced genomic, phenomic and breeding tools to support a range of breeding strategies tailored to specific pea types. This balance between underpinning support and specific targeting ensure sustainable innovations that meet market demands and future agricultural challenges. Strategic breeding objectives include:

1. to develop high-yielding cultivars with better adaptability to diverse environments as the crop is highly sensitive to fluctuations in climatic conditions during its growth cycle and various environmental stressors can affect its yield and quality;
2. to develop tolerance against drought and heat stress, particularly during the reproductive phase;
3. to improve resistance against key pathogens adapting the crop due to shifting climate conditions and scarcity of effective chemicals and the lack of well-characterized genetic resources to control these pathogens; and
4. to identify frost tolerant peas that can be sown in autumn and to extend the vegetation period to better cope with dry conditions in spring.

Breeding for disease resistance
Vining peas that are harvested as fresh product are most affected by diseases of pods and leaves (mildews and viruses), dry peas are particularly by the root rot phenomenon, several viruses and blight. The challenge for breeding is:

- cultivated pea varieties often have a narrow genetic base and with this only a limited number of resistance genes that can be used for resistance breeding;
- many observed pea diseases are complex and their cause is not well understood or clearly identifiable, which makes targeted selection of resistant material very difficult in breeding;
- a bridge between plant pathology and pea breeding is required; and
- there is limited availability of robust molecular markers that can be used to select for existing resistance traits.

Breeding for yield and resilience
Pea cultivation (both vining and dry peas) is sensitive to fluctuations during its growth cycle, and changing weather patterns can lead to various environmental stressors that ultimately affect yield and quality. Challenges include the increasing occurrence of spring drought and heat stress, particularly during the reproductive phase and pod filling stage. We identified key traits essential for prioritising the breeding of climate-adapted and resilient pea cultivars. Special attention was given to traits related to heat and drought stress, along with yield.

The development of genomic resources and tools for pea has lagged behind other crops due to its bigger genome size (4.2 Gb) and mainly lack of investment. Due to falling cost of sequencing and availability of high-performance computing infrastructure, genomic tools can be utilized for GWAS studies and for the development of a marker-assisted breeding platform which would be of great value to breeders.

Phaseolus beans

Europe has a long tradition of bean breeding, particularly snap beans, by seed companies (e.g., Vilmorin at the beginning of the 19^{th} century). As a result of this work, a wide variety of snap bean genotypes are found in the market demonstrating diversity in colours and pod shapes. Currently, companies focus on improving resistance to diseases (anthracnose, common mosaic virus, rust, powdery mildew), pests (aphids and weevil), drought tolerance, pod quality traits (colour, shape), adaptation to processing, adaptation to mechanisation, and performance. Efforts to improve dry beans and phenotypes covered by PGI have been minor since they are very specific phenotypes produced in limited areas. However, these crops also are affected by biotic and abiotic stresses.

As a species, the common bean is really four crops: push and pole bean with both grown as either snap (green, vegetable) or grain bean. There are substantial pre-breeding and breeding activities in institutes in Germany, Italy and Spain. There is also active private breeding progammes with Lidea Seeds, KWS, Van Waveren, and Saatzucht Gleisdorf.

Soya bean

While soya yields in Europe are in line with the world average, it remains a relatively minor crop because many European farmers are exceptionally good at growing cereals due to a combination of cereal breeding, climate and high latitudes giving long summer days. We need to strengthen the competitiveness of soya bean cultivation by increasing yield in target areas and by increasing crop value through higher quality, especially for food markets (seed protein content, food processing characteristics). Crop expansion would take place in particular in central and southeastern Europe. Regardless of its use, the crop development and architecture must be well adapted to these conditions, especially the high latitude (i.e. long day-length). Increasing growth (biomass) and the proportion of biomass in grain (harvest index) increases yield potential.

European breeders have built up collections of high-performing lines. A priority is to use recently developed technical approaches such as genomic selection to accelerate accurate selection for target environments and markets. This involves multi-environment field experiments and innovative phenotyping and genomic tools to test for specific plant growth, stress tolerance, and grain quality traits during the selection of parents and superior varietal candidates. Breeding resources are available for genotyping for adaptation (earliness genes (E-genes)), drought (QTL), food safety (cadmium uptake, allergen content) and aroma/flavour traits (sucrose content, jasmine aroma) to support marker-assisted selection. Genetic diversity scans using SNP arrays or comparable services can be used to support marker development as part of a genomic toolbox of breeder markers. As the genetic base of European soya beans is narrow, genetic diversity assays will also assist in the future introgression and exploitation of additional germplasm. This has already been done in the European Soybean Improvement Network (ESIN, including the Haberlandt soya bean project (China-Europe)). Insights from EU-funded work ECOBREED and EUCLEG will also help us widen the genetic base.

Even though European soya bean breeders include large international commercial breeding companies such as Lidea and RAGT, the breeding effort is small-scale compared with countries with large soya bean areas. Much has been done by small breeding programmes (both private and public) focused on relatively local markets. In these circumstances pre-competitive collaboration between companies and public research-based pre-breeding will optimise the use of available genetic resources and technologies such as state-of-the-art genotyping, digital/high-throughput phenotyping, or AI-assisted analysis of data for selection. As all these technologies will continue to develop rapidly, the level of complexity of methods and procedures will increase accordingly, so that they cannot be handled efficiently on the level of individual/small companies, reinforcing the need for collaboration to maintain efficiency of breeding programmes and competitiveness against multinational/large players.

In addition, new genomic technologies (NGT such as CRISPR-Cas9) will mature, and interesting applications relevant for specific traits in soybean will be incorporated in breeding materials. This again requires collaborative approaches (on technology level, on legal level, in marketing NGT-derived cultivars) to acquire a critical capacity to implement the technology.

Vetches

Breeding targets for vetches are species-dependent. Of all the vetch species, common vetch received the most attention from breeders. However, a common focus for breeding vetches can be suggested.

The high levels of anti-nutritional factors prevent the use in monogastric animal diets. Data from gene banks show that there is a significant amount of variation in these plant metabolites, permitting selection to lower the amount in current varieties. As vetches are now mostly mixed with other feed sources, a higher percentage of the feed could consist of vetches without adverse effects.

Species where a high grain yield is the main purpose (e.g., bitter vetch and Narbon vetch), require non shattering pods, an upward growth habit, soft seeds and a high harvest index. Improving seed size, plant height and lodging resistance are therefore important traits. These traits also improve the ease of mechanical harvest.

Some varieties of vetches already demonstrate a high degree of tolerance to the main grain legume diseases like *Ascochyta* blight, *Botrytis* blight, downy and powdery mildew. The same is true regarding damage from parasitism by *Orobanche* spp. and damage from nematodes. Breeding thus offers a considerable potential for relatively low damage from pests and diseases, by combining the traits already present in current varieties. The currently cultivated species require far more breeding than is allocated to them, in order to unlock the genetic potential present in gene databanks.

Outlook for farm practice

All cultivated crops are already and will increasingly face the effects of climate change. Legumes are no exception to this, although some species and varieties have traits that may limit certain impacts. Farmers can adopt measures mitigating the effects on all crops on the farm, some more specific than others for the cultivation of legumes.

Starting with the soil, which can be seen as a farmers most important capital. To care for soil is to care for future cropping cycles. A healthy soil structure with sufficient organic matter will for example positively impact the water holding capacity during periods of drought and simultaneously prevent soils erosion during periods of heavy rainfall. The nutrients within the soil have to be within certain ranges for optimal plant growth to avoid further stress and ensure maximal nutrient availability.

Varieties with a shorter or longer time to maturation can escape critical periods of heat, drought or waterlogging. Stress factors during flowering and pod setting are often particularly detrimental to the yield and quality (Table 2 and Table 3). Other useful traits are resistance to newly introduced pests and diseases, as breeding programmes will over time automatically adjust to them. Regional trial data to highlight the differences between the available genotypes are providing essential information enabling farmers to make informed decisions.

Variations in management practices are not difficult to implement, but require an in-depth knowledge of the crop's phenology. By for example modifying the planting time, depth or density, farmers can anticipate for the shifting seasonal patterns. New integrated weed, pest and disease management techniques will be needed to deal with the unwanted emerging threats. Using technology and data to respond pre-emptively to the weather forecast and adjusting adequately will gain importance with increasing weather variability and extremes.

The region where warm-season legumes can be grown will expand northwards to areas where cultivation was previously impossible. Particularly for soya bean, the breeding programmes for those regions will give attention to producing varieties insensitive to longer days. Through independent regional trial data farmers can be informed on the photoperiodic requirements of different varieties under their local circumstances.

Nodulation with nitrogen-fixating bacteria is exclusive to legumes (Figure 13). Research has shown that heatwaves negatively impact biological nitrogen fixation while a rise in atmospheric CO_2 concentrations have a positive effect on the nodule activity and biomass. Therefore, successful nodulation will become increasingly important for farmers cultivating legumes in areas where certain legume species have never been cultivated before. If the soil microbiome does not naturally contain the necessary bacteria or their activity is too low, seed inoculation with commercial inoculum can be a risk insurance to ensure good inoculation.

Figure 13. Successful inoculation results in a substantial amount of nodules of soya bean. Copyright Josef Wasner (via Legume Hub) under the Creative Commons 4.0 license.

Table 1. General characteristics of the ten leading agricultural legume species or species types grown in Europe

	Alfalfa ***Medicago sativa***	**Chickpea** ***Cicer arietinum***	**Clovers** ***Trifolium spp.***	**Faba bean** ***Vicia faba***	**Lentil** ***Lens culinaris***	**Lupins** ***Lupinus spp.***	**Pea** ***Pisum sativum***	**Phaseolus beans** ***Phaseolus spp.***	**Soya bean** ***Glycine max***	**Vetches** ***Vicia spp.***
Crop type	Forage	Grain	Forage	Grain, vegetable	Grain	Grain	Grain, vegetable	Grain, vegetable	Grain, vegetable	Forage
Major use	Feed	Food	Feed	Food and feed	Food	Food and feed	Food	Feed	Food	Feed
N-fixation potential	+++	+	+++	++	+	+/++	++	+	++	+
Response to inoculation	+	+	0	+	+	++	+	+	+++	0
Response to temperature (season type)	Cool	Cool	Cool	Cool	Cool	Cool	Cool	Warm	Warm	Cool
Length of growing season	+++	-	+++	+++	--	+/++	-	++	+	+/++
Benefit of pollination	++	+/0	+++	++/0	+/0	+	+/0	+	0	++
Genetic resources	+++	+	+++	+++	+	+	++	+++	++/+++	++
Access to seed	++	+	+++	+++	+	+-	+++	+	+++	+
Anti-nutritional factors	-	--	-	--	--	---	--	--	---	--

+++ highly positive response, 0 neutral response, --- highly negative response

Table 2. General stress factors for the ten leading agricultural legume species or species types grown in Europe

Stress factor		**Alfalfa** *Medicago sativa*	**Chickpea** *Cicer arietinum*	**Clovers** *Trifolium spp.*	**Faba bean** *Vicia faba*	**Lentil** *Lens culinaris*	**Lupins** *Lupinus spp.*	**Pea** *Pisum sativum*	**Phaseolus beans** *Phaseolus spp.*	**Soya bean** *Glycine max*	**Vetches** *Vicia spp.*
Abiotic	**Resilience to soil conditions**	++	++	+++	+++	+++	++/--	+	+	++	++
	Tolerance to frost	+++	-	+++	+++	+	+/-	+	---	--	-
	Tolerance to chilling in the growing season	+++	--	+++	+++	++	+	++	---	--	-
	Heat	++	++	++	---	+++	+	--/---	---	+++	---
	Drought	++	+++	+	---	+++	+	---	--/---	---	--
	Excess water	--	---	+	-	---	-	---	---	--/-	--
Biotic	**Root**	--	-	0	0	-	-	---	-	-	--
	Stem	--	---	--	--	---	--	--	-	---	-
	Canopy	-	---	-	---	---	--	--	---	--	-
	Seed or forage	-	-	0	--	--	--	0	--	0	-

0 not susceptible, - mildly susceptible damage expected, -- susceptible, --- very susceptible

Table 3. Some specific biotic stress factors for the ten leading agricultural legume species or species types grown in Europe

<table>
<tr><th colspan="2">Biotic stress and infection factor</th><th>Alfalfa

Medicago sativa</th><th>Chickpea

Cicer arietinum</th><th>Clovers

Trifolium spp.</th><th>Faba bean

Vicia faba</th><th>Lentil

Lens culinaris</th><th>Lupins

Lupinus spp.</th><th>Pea

Pisum sativum</th><th>Phaseolus beans

Phaseolus spp.</th><th>Soya bean

Glycine max</th><th>Vetches

Vicia spp.</th></tr>
<tr><td rowspan="3">**Fungal/Bacterial***</td><td>**Air**</td><td>Leaf spot</td><td>Ascochyta blight
Rust disease
Stem rot
Downy mildew</td><td></td><td>Ascochyta blight
Rust
Chocolate spot
Downy mildew</td><td>Ascochyta blight
Rust
Downy mildew</td><td>Anthracnose
Diaporthe
Stem rot</td><td>Ascochyta blight
Rust
Stem rot
Downy mildew</td><td>Anthracnose
Rust
White mold</td><td>Canker
White mold
Downy mildew
Leaf spot</td><td>Rust disease
Downy mildew</td></tr>
<tr><td>**Soil**</td><td>Sclerotinia rot
Wilt</td><td>Wilt</td><td>Sclerotinia rot
Wilt</td><td>Sclerotinia rot</td><td>Wilt</td><td>Sclerotinia rot
Wilt</td><td>Aphanomyces root rot</td><td>Wilt
Bacterial brown spot*
Common blight*
Halo blight*</td><td>Charcoal rot
Bacterial brown spot*</td><td>Sclerotinia rot
Wilt</td></tr>
<tr><td>**Seeds**</td><td></td><td>Ascochyta blight</td><td></td><td>Ascochyta blight

Rust disease</td><td>Ascochyta blight</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>**Viral**</td><td>**Air and seeds**</td><td>Alfalfa mosaic Alfamovirus-AMV</td><td></td><td></td><td>Faba bean necrotic yellows virus (FBNYV)
Bean Yellow mosaic virus (BYMV)</td><td>Pea seedborne mosaic virus (PSBMV)</td><td></td><td>Pea seedborne mosaic virus (PSBMV)</td><td>Clover yellow vein virus (CYVV)
Bean common mosaic virus (BCMV)
Bean yellow mosaic virus (BYMV)
Cucumber mosaic virus (CMV)</td><td>Soya bean mosaic potyvirus (SMV)</td><td></td></tr>
</table>

Table 4. Some specific pests for the ten leading agricultural legume species or species types grown in Europe.

Infection route	Alfalfa ***Medicago sativa***	Chickpea ***Cicer arietinum***	Clovers ***Trifolium spp.***	Faba bean ***Vicia faba***	Lentil ***Lens culinaris***	Lupins ***Lupinus spp.***	Pea ***Pisum sativum***	Phaseolus beans ***Phaseolus spp.***	Soya bean ***Glycine max***	Vetches ***Vicia spp.***
Root	Root nematodes		Root nematodes Click beetles			Click beetles Leatherjackets	Root nematodes		Click beetles	
Canopy	Stem nematode Pea leaf weevil Alfalfa weevil Pea weevil	Cotton bollworm Leaf-miner flies Birds	Stem nematode Snails	Stem nematode Pea leaf weevil	Pea leaf weevil Gall midges Pea moth	Bean seed fly Leaf weevils Birds Thrips Snails	Pea leaf weevil Pea moth Cabbage moth	Bean seed fly Aphids Spider mite Thrips Snails	Bean seed fly Birds Mites Cotton bollworm Snails	Pea moth Leaf-miner flies
Carrier				Black bean aphid Green pea aphid	Green pea aphid	Green peach aphid Lupin aphid	Green pea aphid	Black bean aphid Green pea aphid		Green pea aphid
Seed		Seed beetle		Broad bean weevil	Lentil weevil Pulse pod borer moth		Pea weevil	Seed beetle	Pulse pod borer moth	Seed weevil