EU CAP Network Focus Group

Production of protein crops under climate change

Mini Paper 2

Characterisation and genetic improvement of protein crops

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June 2025

Funded by the European Union

Acknowledgement

This Mini Paper was supported by the Legume Generation consortium. Legume Generation (Boosting innovation in breeding for the next generation of legume crops for Europe) is an innovation action funded by the European Union through Horizon Europe under grant agreement 101081329. Legume Generation also receives support from the governments of the United Kingdom, Switzerland and New Zealand. The contributions of Johann Vollmann, Fred Eickmeyer, Sanu Arora, Klaus Oldach, Tania Gioia, Juan Jose Ferreira, Lars-Gernot Otto, David Lloyd and Tim De Clercq are gratefully acknowledged.

If you wish to cite this Mini Paper, please refer to it as 'Annex to the final report of the EU CAP Network Focus Group 'Production of protein crops under climate change', 2025'.

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Introduction

The purpose of this paper is to characterise protein crops and to discuss the challenges and opportunities for their genetic improvement in a changing world. We hope to address all with an interest in the improvement of legume crops: farmers, agronomists, and breeders upon whom crop genetic improvement depends. This paper is a summary of a longer document which is published separately as Legume Generation Report 8.[1]

In line with the Common Agricultural Policy of the European Union, protein crops are defined here as nitrogen-fixing crops. These are all members of the legume family. The legumes of interest to farmers in Europe belong to the subfamily *Faboideae* or *Papilionoideae*, defined by the characteristic 'butterfly' shape of their flowers. 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 low temperatures, survive frost when young, and can be grown as an over-wintering crop in many European regions.

Warm-season: Warm season legumes such as soya bean and common bean do not grow or develop when temperature falls below about 6°C. They originate from the tropics and sub-tropics and are sensitive to frost at all stages.

Short-day plant: These plants require a minimum night-length to flower. These are warm-season legumes.

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

Pulse: A pulse is a grain legume that have a high carbohydrate (starch) content in the seed. Pulses can be used directly for food without processing.

Oilseed legumes: Oilseed legumes store energy for germination as oil and are rich in protein. Oilseed legumes usually require industrial processing.

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[1] Murphy-Bokern, D., Papathanasiou, F., Hast, M. and Stoddard, F., 2025. Characterisation and genetic improvement of protein crops. Legume Generation report 8. Available from www.legumegeneration.eu and www.legumehub.eu

Fine-seed legumes: Unlike the grain legumes, many legumes such as the clovers used for forage have very small, fine seed.

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

Vegetable or green legumes: Legumes that are consumed as immature (green) pods and seeds, e.g., vining pea, broad bean, snap (green) bean, and edamame.

Hypogeal germination: The seed leaves remain below ground during germination. This form allows seedlings to produce new shoots if damaged, e.g., pea

Epigeal germination: The seed leaves emerge above ground making seedlings vulnerable to damage from which they do not recover, e.g., soya bean and common bean.

An agronomic characterisation of legumes

Linked to their ability to fix nitrogen, legumes have high protein contents. The protein quality complements cereals in particular in diets. The cool-season grain legumes came 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. 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 from predators. Methods have been developed to remove or denature these toxins, or reduce them through breeding. We have chosen the ten most widely grown legume crop species 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 (Common 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 agronomic characterisation of the ten most widely-grown species is provided in Figure 1. This is supported by general characteristics summarised in Table 1.

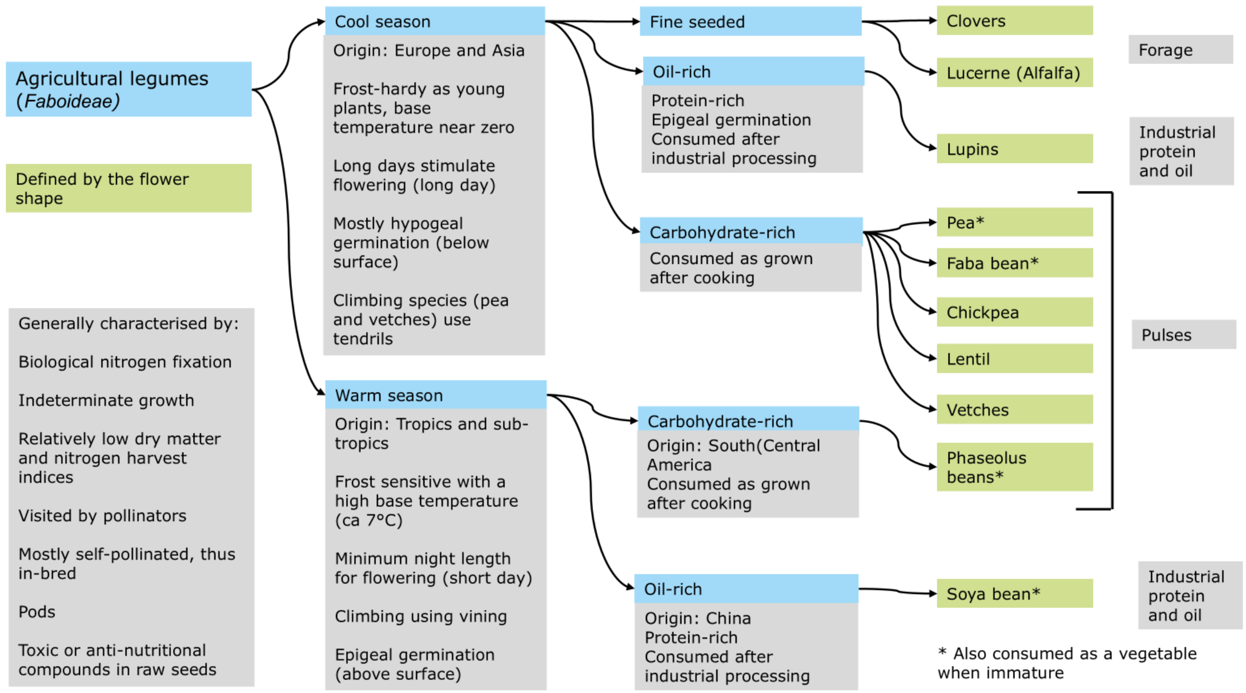

Figure 1. Agronomic characterisation of the ten most widely-grown agricultural legume species or species types grown in Europe. (Source: Donal Murphy-Bokern)

The cool-season starch-rich legumes

The cool-season starch-rich grain legumes (pea, faba bean, chick pea and lentil) have a common evolutionary background and so have similar characteristics. Hypogeal germination protects seedlings. 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. 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 dietary characteristics. The protein concentration in the seeds is typically 20-30%. The oil concentration is low, around 1% of dry matter, except for chickpea which is 3-6% oil.

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. They are characterised by a high protein content used for feed and technical food purposes. Unimproved lupins are toxic due to alkaloids. Total European production was 370,000 tonnes in 2023, with much grown in Poland. The lupins form symbiosis with *Bradyrhizobium lupini*. The seedlings are easily damaged due to epigeal germination. Up to five orders of branches may be produced. More limited branching helps bring the crop to maturity and harvest.

The warm-season legumes

The warm-season legumes (phaseolus beans and soya bean) are of tropical and sub-tropical origin. 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. Epigeal germination makes seedlings susceptible to damage. These are short-day species requiring a minimum period of darkness to initiate flowering. This constraint has been overcome by breeders to provide daylength insensitive varieties. 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.

The fine-seeded forage legumes

The forage legumes (clovers and lucerne) are referred to as fine-seeded legumes because of the very small seed. They are all perennial. The clovers are native to Europe while lucerne originates from Asia. All are extremely frost-hardy, but lucerne requires warm summers to thrive.

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 seed, forage, and cover-cropping and green manuring. 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 have decreased and is located mainly in Spain and Eastern Europe in the EU.

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. An overview of minor used legumes is given Bennett, Francis and Reid[2] and discussed here with a focus on their potential agronomic value.

Within the *Anthyllis* genus, the kidney vetch (*Anthyllis vulneraria*) is the only cultivated species used for feed and forage. It is an annual with traditional medicinal properties. Cultivars show tolerance to high and low pH, and poor and sandy soils.

Biserrula (*Biserrula pelecinus*) is a relatively high yielding forage legume with agronomic potential for acidic soils. It is currently being domesticated in Australia.

Sulla (*Sulla coronaria*) is a perennial legume cultivated extensively in southern Italy and Spain for forage. 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 annuals grown as forage crops and for soil improvement in some parts of Europe.

Fenugreek (*Trigonella foenum-graecum*) is an annual widely grown in Asia for flavouring, 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 frost tolerant perennial forage but is susceptible to high summer temperatures. It is thought to be more resistant to pests and diseases than *Trifolium* or *Medicago* species in humid areas and is moderately salt tolerant.

White sweet-clover (*Melilotus albus*) is cultivated for forage where it is extremely drought resistant. 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*).

[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

Common sainfoin (*Onobrychis viciifolia*) was an important perennial forage legume in temperate regions until the 1950s. It 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.

Grass pea (*Lathyrus sativus* L.) is a dual-purpose annual legume grown for its seeds for human consumption, and fodder for livestock feeding. It has outstanding tolerance to drought and flooding and 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. (known as Spanish vetchling) is an annual Mediterranean grain crop of restricted distribution, still grown today in several Aegean islands such as Thira (Santorini), Anafi and Karpathos. It was recently added to the European Union's products with a Protected Designation of Origin. The seeds, from which the dish fava Santorinis is made, has a high protein content (25%), an excellent source of dietary fibre (26%) with low fat content.

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. Irrigation is important for high yields with drought and high-temperature stress to be the most important limiting factors. The seeds 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 *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.

It all starts with a seed. What is plant breeding?

Plant breeding is the art and science of changing plant genetic makeup to produce desired characteristics. It is a commercial activity at the very start of the agri-food chain and is the foundation of much of the technical progress on farms and in food chains. Plant breeding is particularly powerful because a great deal of knowledge and technology can be incorporated into seed which farmers easily adopt. Genetic progress accumulates and cascades freely through the generations. The practical use for society of technologies such as gene editing, GWAS, genomic selection, transcriptomics etc., depends on commercial plant breeders using these to produce improved cultivars for farmers.

Almost all breeding starts with the generation of new variation, usually through the crossing of carefully selected parents, followed by stabilisation of progeny through self-pollination for different environments. For self-pollinating stable varieties, which applies mostly to our legumes, the plants of one generation are practically genetically identical to the previous generation. Consequently, breeders are dependent on the sale of small quantities of breeder's seed and the royalties from the sale of final certified seed by agents and seed merchants. These income streams are small in inbred crops compared with the great value added by breeding over time, especially for 'minor' or underutilised crops such as legumes. There is considerable leakage of royalty revenue where farmers save seed without paying royalty. The result is a classic market failure where the private incentive to invest in genetic improvement is sub-optimal in relation to the wider societal benefits. This is especially true because under varietal rights the seed or clonal material of any new superior variety can be immediately used as a parent by competing breeders. This is a valued aspect of the varietal rights system because it disseminates genetic progress across competing commercial programmes quickly. However, it reduces the incentive for individual breeders to invest in new challenging traits. Consequently, public or collective investment in breeding is required to compensate for the private under-investment.

Legume breeding in a resource-constrained and changing world

Farmers are at the end of the breeding pipelines and act as customers selecting from the range of cultivars offered. Their changing needs are quickly detected by breeders through seed markets. Breeders' agents and seed merchants are in constant contact with both breeders and farmers matching breeders' lines with farmers' needs. At the end of the breeding pipelines, farmers themselves commonly assess new varieties using on-farm testing before deciding to grow a new variety on a fully commercial scale.

'Participatory breeding' is sometimes discussed as a way to better address farmers' needs. With true participatory plant breeding (PPB), farmers are directly involved from the early stages of crossing and selection. As described above, market processes transmit signals from farmers and processors back to breeders influencing breeders' choice of parents and selection. This in principle makes all breeding participatory. There may be special examples of growers and processors having more direct influence over the breeding process, especially for food markets. Examples include soya bean crossing and selection to meet specific needs of tofu makers, crossing and selection of vegetable legumes (e.g., vining pea) to meet specific processing needs etc. Sometimes, the reproduction of composite crosses (i.e., very diverse evolving mixtures of plants derived from multiple crosses) is considered participatory breeding. However, these farmers are reproducing seed, not breeding it.

Landraces deserve special mention. A crop landrace is a traditional variety that has developed over time through adaptation to its natural and cultural environment, including climate, soil, pests, and farming practices, usually without formal plant breeding. They are often genetically diverse, locally adapted to where they have been grown over generations and reproduced by farmers over centuries. Landraces are preserved in seed banks and in-situ by farmers who grow them year after year.

All plant breeding is about generating variation and selecting from that variation for adaptation to different environments and farming systems. The generation of variation and early selection is often centralised, while selection for adaptation to different field environments is a local activity. In this context, organic farming and other practices such as intercropping just add more environments to the selection process. Similarly, breeding for climate change is just a response to the increasing range of environments change might bring.

Difficulties in accessing genetic resources, varieties and seeds are sometimes discussed. Our understanding is that genetic resources in seedbanks are well documented and accessible to breeders. The seed trade is also effective in supplying farmers. What may be missing is information to ease farmers' and seed traders' access to varieties and landraces across Europe, especially for the niche legumes. This could be addressed by expanding existing knowledge platforms such as the Legume Hub which is Europe's knowledge platform for legumes.

Priority traits

Increasing the 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 to 8-10% in line with 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.

Yield – resource capture and partitioning

Ultimately, the yield of a crop depends on the amount of resource, especially sunlight, it captures in its life through a healthy canopy, the efficiency of turning that light into biomass, and the partitioning of the biomass into the harvested part of the crop. In 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 complemented by selection for yield. Concerted efforts to improve resource capture have not been a priority, compared with other arable crops. 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 (harvest index), and careful adjustment of maturity so that late summer light is used.

In recent years, selection of plants based on genome-wide markers rather than solely on field performance, an approach known as genomic selection, has led to rapid progress in plant breeding programmes. However, genomic selection is intrinsically conservative: it improves the precision and accuracy of identifying superior individuals within existing breeding populations but is less effective at incorporating novel traits from genetically diverse or un-adapted sources.

Quality

The second part of the productivity equation is the per unit value of the crop determined by the quality for different markets. The range of quality traits is huge, from protein content in soya bean and anti-nutritional factors in faba bean through to special seed quality characteristics for niche food markets. Breeding for quality generally relies on selection from progeny already bred for other purposes. The benefits of cultivars with improved quality traits are easily transferred to genetic backgrounds used in competing export regions. This means that, in contrast to breeding for environmental adaptation, the genetic gain for quality is easily transferred to competing exporting countries.

Resistance or tolerance to drought and heat

Table 2 summarises stress factors for the ten leading legume species. None of the widely-grown legumes 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 abort pods to reduce the number of developing seeds, thereby protecting the size of the remaining seed. Overall, root-related traits provide the foundation of tolerance to drought, flooding, and indirectly heat.

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 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

Specific biotic stress factors are set out in Table 3. Resistance to disease is a priority trait for breeding. 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 are splash-dispersed and have a low optimum temperature for growth, so are most prevalent on autumn-sown crops. They can last up to three years in the soil, so a minimum four-year rotation is recommended.

Each species also has a rust caused by species of the genus *Uromyces*. The rusts grow best in warm, relatively humid weather, such as late summer in a continental climate. In other climates, they often arrive late helping 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 caused by species of the *Colletotrichum* genus. It can significantly reduce yield and seed quality in 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 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 nine 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.

Pest resistance

Specific pests are set out in Table 4. 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*). The aphids are important because of the direct damage and because they 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 because 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 aphids, indicating that there is potential for combining low 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 climate change

Although man-made climate change is rapid in relation to geological timescales, the breeding cycle can keep up. This ability to self-adjust to environmental change is further supported by many breeding programmes that already breed for relevant adaptation through the range of environments they already select for. 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 might be 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. These include:

Root strength and depth: Regardless of the direction of climate change in any particular place, it is reasonable to assume that root-related traits will become more important. They form the foundation of resilience under stress. These include traits for dry soils and for waterlogging. 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 quickly from water-limiting to oxygen-limiting.

Crop progress to maturity (earliness of harvest): Earlier maturity driven by higher temperatures lowers yield potential by shortening the life of the canopy. Consequently, breeding for later maturity would be a rational response to warming. But there may also be a demand for earlier maturity to escape drought or to facilitate double cropping in a warmed world. The progress to maturity is partly determined by the timing of flowering. The genetic basis of this is well understood and already exploited, e.g., in soya bean.

Insensitivity to long days: Warming will allow the production of soya bean further north in 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.

Winter-hardiness for autumn sowing to extend the growing period: For cool season grain legumes, milder winters will make more winter-cropping possible. 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 frosts.

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. Plant vigour under cool conditions may become a useful trait.

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. Tolerance of chilling may be useful under climate change.

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

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 and feed	Feed
Grain yield (t/ha)***	-	1.1	-	2.7	1.1	1.6	2.4	2.4	2.9	1.1
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	++	+	+++	+++	+	+-	+++	+	+++	+
Number of EU registered varieties	889	NC	997*	666	NC	248	2915	2920	1656	297
Anti-nutritional factors	-	--	-	--	--	---	--	--	---	--

+++ highly positive response, 0 neutral response, --- highly negative response
*White and red clover. ** Common vetch, Hairy vetch, and Hungarian vetch. NC: varieties are listed in national catalogues
*** Average EU yields over ten years from 2014 to 2023, except for chick pea, lentil, and phaseolus beans where the average is for years 2014 to 2017 (FAOSTAT)

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. Specific biotic stress factors for the ten leading agricultural legume species or species types grown in Europe

Biotic stress and infection 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.
Fungal/bacterial*	**Air**	Leaf spot	Ascochyta blight Rust disease Stem rot Downy mildew		Ascochyta blight Rust Chocolate spot Downy mildew	Ascochyta blight Rust Downy mildew	Anthracnose Diaporthe Stem rot	Ascochyta blight Rust Stem rot Downy mildew	Anthracnose Rust White mold	Canker White mold Downy mildew Leaf spot	Rust disease Downy mildew
	Soil	Sclerotinia rot Wilt	Wilt	Sclerotinia rot Wilt	Sclerotinia rot	Wilt	Sclerotinia rot Wilt	Aphanomyces root rot	Wilt Bacterial brown spot* Common blight* Halo blight*	Charcoal rot Bacterial brown spot*	Sclerotinia rot Wilt
	Seeds		Ascochyta blight		Ascochyta blight Rust disease	Ascochyta blight				Phomopsis/ diaporthe	
Viral	**Air and seeds**	Alfalfa mosaic Alfamovirus-AMV			Faba bean necrotic yellows virus (FBNYV) Bean Yellow mosaic virus (BYMV)	Pea seedborne mosaic virus (PSBMV)		Pea seedborne mosaic virus (PSBMV)	Clover yellow vein virus (CYVV) Bean common mosaic virus (BCMV) Bean yellow mosaic virus (BYMV) Cucumber mosaic virus (CMV)	Soya bean mosaic potyvirus (SMV)	

Table 4. Specific pests for the ten leading agricultural legume species or species types grown in Europe. Some pest damage occurs on selected plant parts, but is of minor significance.

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 Deer, boars, birds Leaf-miner flies	Stem nematode Snails	Stem nematode Pea leaf weevil	Pea leaf weevil Gall midges Pea moth	Bean seed fly Leaf weevils Deer, rabbits and hares, 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

Funded by the European Union