Legume Generation

Position Paper 1

An agenda for public investment in legume plant breeding

Summary

The purpose of this position paper is to provide an agenda for the development of European Union Horizon support for legume breeding in Horizon Europe. It has four parts:

1. It all starts with a seed: what is plant breeding?
2. Further public investment in legume plant breeding.
3. Priority traits for publicly supported plant breeding.
4. Fostering efficient and focused 'Horizon' projects.

Plant breeding is a powerful technology. It is a cornerstone of competitive sustainable farming systems. The seeds we use today incorporate all the improvement plant breeders have made since our crop species were first domesticated, cascaded through the generations. In addition to directly benefiting farmers, the genetic progress in new improved varieties gained by a breeder in Europe is usually freely available to all competing breeders for their own further breeding. This free access to improved cultivars fosters innovation and gives most plant genetic improvement a strong public-good character. However, as is typical for public goods, there is under-investment in breeding for most crops due to biological constraints on the revenue from breeding. This is especially so for minor crops such as the grain legumes. Grain legumes in particular are easily reproduced on farms without paying royalties and their minor crop status means that the market for their seed for multiplication by agents is limited. The overall result is sub-optimal investment in legume breeding from both an agricultural and wider societal viewpoint. This market failure applies to all relevant agronomic and quality traits, including crop yield.

Grain legume crop yield has not kept pace with the yield of competing crops such as wheat and maize that European farmers excel in growing. Achieving meaningful yield progress in legumes requires long-term, high-risk investment that is unlikely to come solely from private breeding programmes under current market conditions. Against this background, relevant public funding needs to focus on supporting the connection between biological research and breeding within collaborative innovation structures led by breeders. Further relevant EU-funded work needs to focus on clear researchable scientific and innovation challenges and opportunities identified by breeders. This must recognise the pre-farm position of breeding in the value chain and avoid having funded work distracted by requirements that are not clearly relevant to boosting the breeding of keynote legume crops.

1. It all starts with a seed: what is plant breeding?

It is important to understand what legume plant breeding is. Some misunderstandings have developed about participatory breeding, organic breeding, breeding for climate change, and the position and role of legume plant breeding in legume-supported value chains. These are addressed here.

Plant breeding is the deliberate genetic improvement of plants by selecting plants with desirable traits from new gene combinations. The methodologies used depend on the reproductive biology of the crop species, but in most legume breeding new gene combinations are generated by crossing carefully selected parents.

Figure 1. Macro photograph of the reproductive organs of a soybean flower (*Glycine max*, Fabaceae) after petals had been removed. Visible are multiple pollen-bearing anthers (male component, androecium) surrounding the centrally positioned style and stigma (female component, gynoecium). The close spatial arrangement of the sexual organs is characteristic of the predominantly self-pollinating floral biology of soybean. Photo credit: BOKU University

Plant breeding is essential to modern sustainable farming. Its impact is especially powerful because genetic resources and technology are embodied in seeds which farmers readily adopt. Genetic improvements accumulate and cascade through the generations. The practical use for society of genetic resources, gene editing, GWAS, genomic selection, transcriptomics, advanced phenotyping etc., depend on plant breeders using these to deliver improved cultivars to the market for purchase by farmers. The improved cultivars benefit farmers, the wider economy, food producers, consumers, and the environment.

Legume breeding is economically precarious

Legumes are underutilised in Europe even though they provide clear and well-known benefits for farms, the environment, and our diets. They are a cornerstone of sustainable farming and food systems and essential to agroecological approaches to farming. By delivering new cultivars that farmers are more willing to grow, breeders make a key contribution to increasing legume production and use. Despite this, our work in Legume Generation shows that legume breeding in Europe is currently in a precarious state. Unlike with hybrid crops such as hybrid maize or crops that do not produce seed on farms such as sugar beet, breeders of legumes must rely on small revenue streams from sales of breeder seed to agents and the royalties on certified seed sold to farmers. While the 'breeders' privilege'[1] promotes innovation in breeding, it shortens the period during which an individual breeder can exclusively recover the costs of its own investment in new or improved traits. Farm saving of seeds without paying royalties is a significant cause of revenue loss. Consequently, breeders' revenues are small in relation to the long-term societal value created by breeding. The breeding step that links biological resources and knowledge with farming is a financially constricted step (Figure 2). Because improved varieties can be freely used by other breeders, genetic improvement has a strong public-good character. Consequently, rewards for breeders do not reflect the societal benefits of their work. Especially in the case of legumes, this market failures applies to both input and output traits, especially yield. Achieving meaningful yield progress in legumes requires long-term, high-risk investment that is unlikely to come solely from private breeding programmes under current market conditions. This provides the rationale for public investment.[2]

Some alternative financing models exist in niche markets, such as direct sales of seed to organic growers, food-product certification schemes that require farmers to use certified seed, or closed-loop systems where breeding, production and processing are vertically integrated, e.g., breeding of vegetable pea for freezing. Local levies on crop outputs can provide funds for local breeding programmes. While these approaches can work in specific cases, they remain limited and do not replace the need for broader public support.

Plant breeding is a specific step that precedes farming in the value chain

The term 'participatory breeding' has led to misunderstanding. Unlike with animals, farmers do not breed crop plants. Participatory cultivar selection is widespread and not new: farmers have always been involved in assessing new cultivar options. In most legume breeding, carefully selected inbred (pure-breeding) parents are crossed using specialised skills and facilities (Figure 3). There are different ways to generate variation: simple crosses, multiple crosses, backcrosses, mutations, and gene editing.

---

[1] Under the UPOV (International Union for the Protection of New Varieties of Plants) system, the breeder's privilege is a provision that allows other breeders to use protected plant varieties for certain breeding activities without infringing on the plant breeders' rights (PBR) of the original breeder.

[2] Market failure provides economic justification for public investment in public goods. Public investment can improve outcomes where markets do not allocate sufficient resources efficiently in relation to societal benefits, in this case due to constraints on breeding revenue.

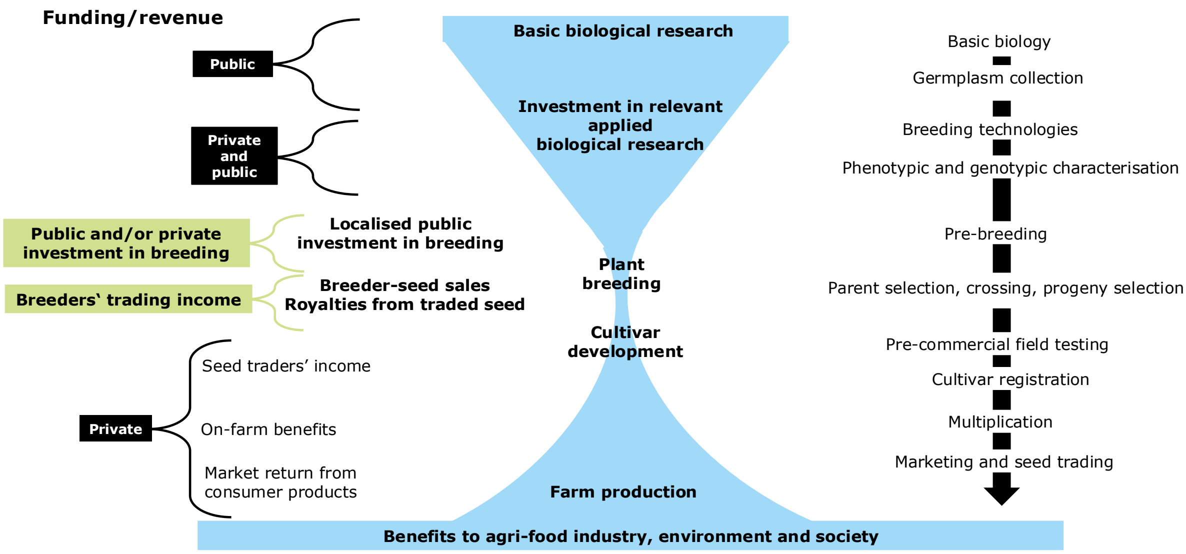

Figure 2. A schematic illustrating levels of funding or revenue generation in the plant breeding innovation chain. The shape represents the revenue or funding potential at each stage from relatively basic research at the top to farm deployment and agri-food impacts at the bottom. The constriction between public funding for basic research and the large economic returns in farming and the food industry represents the constrained resourcing of plant breeding. The outcome is insecure resourcing of the essential plant breeding compared with the investments made in basic research and the benefits of plant breeding for farmers and wider society further down the value chain. This constriction applies particularly to in-bred minor crop species such the legumes. Copyright: Donal Murphy-Bokern

The first generation (F1) offspring plants are genetically uniform hybrids of the parents. They self-pollinate and genetic variation appears in the second generation (F2). Breeders develop a range of stable lines through repeated self-pollination ('selfing') of plants selected from this variation, often using single-seed descent accelerated by speed breeding. The most promising lines are progressively multiplied and tested from single rows to small plots and then at field scale. This testing ('phenotyping') takes place in different environments and farming systems so that a breeding programme can serve different markets, including organic farming. Breeders sell small batches of 'breeder' seed of finished cultivars to traders. The traders multiply this under the supervision of authorities to produce certified seed for farmers, who may also legally multiply this seed under some national regulations (Figure 3).

Breeding for different and changing environments

The generation of variation through crossing and early selection are often centralised, while selection for adaptation to different field environments is a decentralised local activity. Organic farming, low-input farming, and other practices such as intercropping provide additional environmental variation for the selection of parents and progeny within wider programmes. Consequently, some scientists cogently argue that there is no such thing as 'organic breeding'. Similarly, breeding for climate change is a response to the increasing range of environments. The breeding cycle can keep up with climate change. This ability of plant breeding to self-adjust to environmental change is further supported by many programmes that are already breeding for adaptation through the range of environments they already select for.

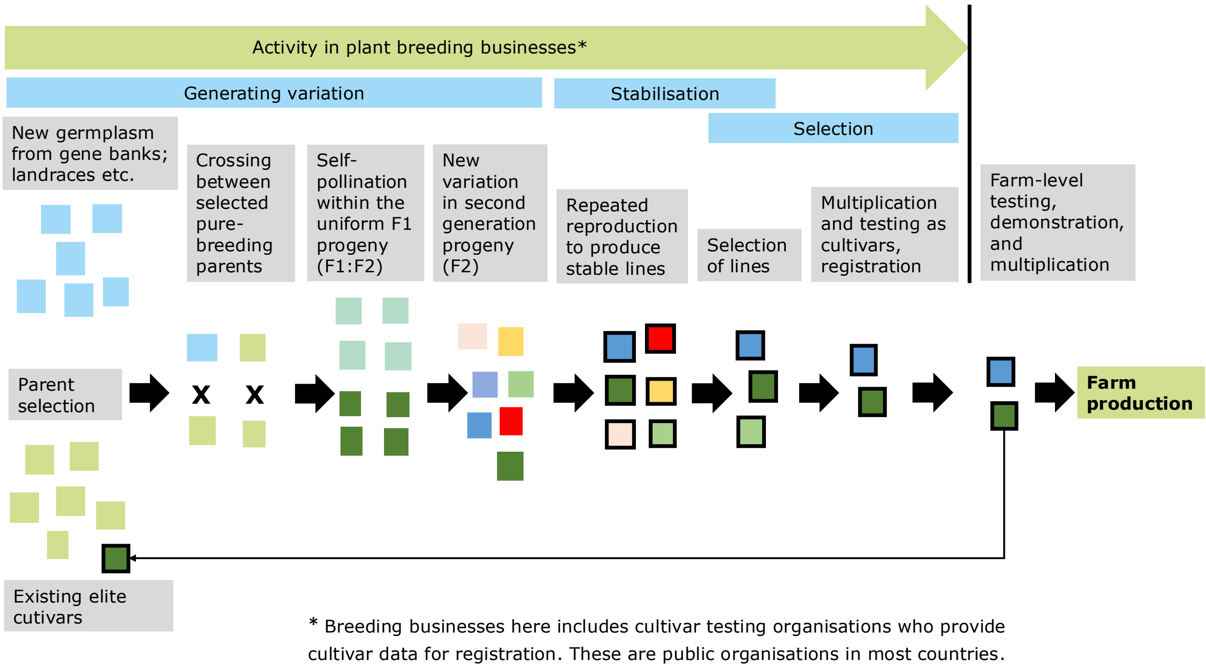

Figure 3. The basic steps in the breeding of inbred (true-breeding) and self-pollinating legume crops. The process begins with the selection of parents carrying desired genes and ends with the multiplication and testing of new cultivars. New genomic techniques, such as gene editing, expand the range of trait variation available for plant breeding.

2. Further public investment in legume plant breeding

In planning further public investment, the key primary decision is about fostering real meaningful interaction between biological research and practical breeding through innovation communities. For too long, biological research that depends on breeding to deliver impact has been disconnected from breeding. We advocate that investment to boost breeding is best organised according to how breeders work. This complements existing academic discipline-based structures. Breeders generally work in species-specific structures. Adopting a species-specific structure helps put breeders in the lead and focuses the work on boosting the breeding of named key legume crops. Once such a collaborative structure has access to germplasm, tools, etc., the secondary question concerns the traits that can be effectively addressed by these collaborations. It is important that each collaboration is always focused on practical and time-bound outcomes. To identify targets to focus on, it helps to outline a theory of change.

Expansion of legume production in Europe will reduce nitrogen fertiliser use, agricultural greenhouse gas emissions, and reduce reliance on imported plant protein improving European food autonomy. European-grown grain legumes provide raw materials for diverse food products for sustainable healthy diets. However, all these benefits of expansion depend on one critical decision point: the decisions that each individual farmer makes in allocating land to the different crop options they have. Consequently, increasing the competitiveness of legume crop options in each farming situation is key to change.

Against this background, our theory of change is as follows: All the agricultural outcomes 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 agroecological principles. This depends on better cultivars that farmers recognise are profitable enough to grow[3] due to their higher economic output (yield × price) and/or reduced farm production costs. Consequently, yield and product quality (price) are strategic breeding priorities. Commercial breeders are the essential agents of change and so it is important to explicitly support breeders' ways of working. They bring a deep understanding of the opportunities for innovation and the expectations of growers and their markets.

The link between academic research and breeding needs strengthening

The key message here is that further investment in supporting legume plant breeding should focus on supporting the breeding step directly via species-specific collaborations between breeders and the supporting science base. Such investment directly addresses the constriction illustrated in Figure 2 in a way tailored to each species.

Until around 1990, biological research and practical plant breeding were closely and strategically linked, particularly in publicly-owned programmes. For example, the Plant Breeding Institute (PBI) in Cambridge greatly increased wheat yields and quality in the United Kingdom and beyond. Public institutions generally focus their efforts, pre-breeding, and generating knowledge and materials to accelerate breeding programmes (public or private). They also perform an important task of maintaining plant genetic resources. However, the privatisation of public breeding programmes in recent decades has weakened links between public research and breeding. Relevant public biological research has become increasingly focused on scientific disciplines and academic outputs within short-term projects. More strategic bilateral alliances were to be short-lived.[4]

Species-specific innovation communities for new ways of collaboration

Legume Generation recognises this growing disconnect and directs funding into breeder-oriented species-specific innovation communities. These investments create new ways of working between breeders and researchers with potentially profound long-term impact.

The goal of Legume Generation is two-fold: to directly boost the breeding of agriculturally important legume species, and to build innovation frameworks for sustained public and private investment in these species. To achieve this, we have combined genetic, agronomic, economic and research strategy perspectives focused on the improvement of soybean, lupins, pea, lentil, phaseolus beans, and clovers within corresponding species-specific Legume Generation innovation communities.

Our consortium shows that legume breeding is advanced species-specifically by several international companies alongside smaller, region-specific breeders, all supported by various interactions with public research organisations. This fragmented structure and the important role of public support underlines our second goal: to create innovation frameworks to sustain long-term public and private investment. Our species-specific approach helps identify opportunities for pre-competitive collaboration tailored to each species within each innovation community. Effective internal governance ensures genetic resources, data, and know-how move quickly and legally between partners while protecting commercial assets and keeping selection aligned with European farmers' needs. Partners exchange seed and lines under material transfer agreements to accelerate trials while preserving traceability. Our innovation communities also align on data governance:

---

[3]Murphy-Bokern, D. (2022). Developing legume-supported cropping systems in Europe: Have we overlooked something? Annals of Applied Biology, 1–4. https://doi.org/10.1111/aab.12764

[4] John Innes Centre Loses Research Partnership with Syngenta | CABI News

harmonised trait descriptors, multi-site/multi-year trial designs, and an Open Science policy that shares data and insights internally as early as possible. This is followed by academic publication that protects all partners' intellectual property. These balance open science with protection of competitive positions.

3. Priority traits for publicly supported plant breeding

Efficient resource capture and high yield is the foundation of competitiveness

It is not enough that legumes are attractive because they fix nitrogen, diversify cropping, and have high protein contents: they must compete with the cropping alternatives that farmers have and excel in growing. This makes increased productivity a key goal for breeding if legumes are to contribute to the sustainable development of European agri-food systems.

Assessing yield: legume grains and forages are resource dense

Grain legumes are often characterised as low yielding crops. This can be misleading. Intrinsic differences between species in the composition of the crop must be kept in mind when assessing crop productivity. Protein and oil synthesis requires more photosynthetic energy than carbohydrate (starch). For this reason, crops rich in protein and oil such as soybean have an intrinsically higher biological value (per tonne) than cereals. Ultimately, the yield of a crop depends on the amount of resource, especially sunlight it captures, the efficiency of turning that light into biomass, and the partitioning of the biomass into the harvested part of the crop. Legume plants also provide the energy for nitrogen fixation and this must be taken into consideration.

Compared with cereals, breeding for yield has not been a priority

It can be said that much legume crop breeding is concerned with defect elimination. Concerted efforts to improve yield generation processes with improved resource capture and harvest indices involve long-term research and high risk that private breeding programmes cannot address. While we can see the results of efforts to improve fundamental yield-related processes over the last 50 years in wheat, maize, sugar beet and other crops, there have been few corresponding improvements in legumes. The only substantial change to legume canopy architecture has been the development of the semi-leafless trait in pea by the John Innes Institute about sixty years ago. This trait improves light penetration, photosynthesis and standing ability. Approaches to improving resource capture 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 the timing of maturity so that late summer light contributes to yield. As we know from the development of the semi-dwarf trait in wheat and the semi-leafless trait in pea, introducing such new yield-related traits sometimes involves first introducing of low-yielding germplasm containing the target traits into the breeding pool. Repeated crossing ('back-crossing') combines the target novel trait with existing elite genetic backgrounds (Figure 4).

Figure 4. Crossing of two pea lines in a greenhouse by manual exposure of the anthers of one flower and application to the stigma of another closed flower. Photo copyright: Alba Pacheco-Moreno (JIC)

Increasing the value of the crop: crop quality

The second part of the competitiveness equation is the per tonne value of the crop, which is determined by the quality of the crop product in relation to market requirements. Serving high quality markets, especially food markets, provides some protection from external competition in commodity markets. European plant breeding programmes must give attention to quality if European-grown legume crops are to compete with imports. The range of traits is large, from protein content in soybean and anti-nutritional factors in faba bean through to special seed quality characteristics in pulses for niche food markets.

Breeding for quality presents a number of dilemmas. Niche quality traits alone do not drive the seed market volumes that are needed to finance breeding. Breeding for them generally relies on selection from existing gene pools that mostly serve other purposes. Unlike adaption traits for yield, the genetic gain for quality is relatively easily transferred to breeding programmes in competing exporting countries.

Tolerance and resistance to stresses

Yield potential is rarely fully realised due to a wide range of environmental and biological stresses: heat and cold stress, drought, saturated soils, weeds, diseases, and pests. Increasing crop performance under real farming conditions requires breeding for resilience to these stresses alongside breeding for high yield potential.

Resistance or tolerance to drought, heat, flooding or salinity
None of the widely-grown grain legume 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 grain legume, both chickpea and lentil are relatively drought-tolerant, and faba bean is the most waterlogging-tolerant.

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.

Frost tolerance and over-wintering

The cool-season legumes (Figure 5) 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 yield target trait for the cool-season species. 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.

Figure 5. Over-wintering lupin in a field trial in Germany, 2024. Photo copyright: Fred Eickmeyer

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 and pest resistance

Resistance to biotic stresses is a priority. Trends in crop yields over the last 30 years, for example pea, show that just fungal diseases alone can be decisive in farmers cropping decisions. The challenges presented in a special Legume Generation report for this purpose.[5] Increasing resistance and tolerance to disease and pests is an essential complement to effort to increase yield potential and improve adaptation to different environments.

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 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 in 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. These include:

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 (Figure 6).

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.

Winter-hardiness for autumn sowing to extend the growing period
For cool season grain legumes, milder winters will increase opportunities 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.

[5] 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. DOI: https://doi.org/10.5281/zenodo.17988915

Figure 6. Different maturity groups (0000 - I) in a Legume Generation soybean field trial in Tulln, lower Austria in 2024. Photo credits: BOKU University

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.

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.

Tolerance and survival of heat stress

We can already see 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.

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.

4. Fostering efficient and focused 'Horizon' projects

The following comments are made as input into the design of any further framework programme investments to support legume (or protein) crop breeding. They relate to Cluster 6 (Food, Bioeconomy, Natural Resources, Agriculture and Environment) in the draft Work Programme 2026-2027 for Food, Bioeconomy, Natural Resources, Agriculture and Environment – referred to here as the Work Programme.

The key message here is that public investment in plant breeding research and innovation must take a long-term perspective focused on key system constraints. While such investment is broad and long-term in its impact, the projects themselves need to be well-focused on the constrictions in the breeding value chain illustrated in Figure 2.

The Work Programme reflects an increasing emphasis on 'horizontal requirements' in call topics to address the challenge of making projects more relevant, particularly to farming. Not only has the number of these requirements increased, the definition of some has become more complex. For example, the specific conditions for multi-actor projects described on pages 17 to 19 of the Cluster 6 of the draft Work Programme 2026-2027. These come in addition to general conditions and project implementation expectations set out on pages 12 to 16. Social and behavioural sciences are regarded as key to farm-level innovation ("changing farmer behaviour"). These horizontal requirements risk reducing focus on the core scientific challenges and the technologies (and the underlying sciences) even though it is technologies that have driven change in farming over the last century.

The most important message here is that every additional requirement or condition added to a call topic reduces project focus. It diverts resources away from the core research and innovation challenges. These complex topics have also resulted in the growth of a project management industry which also draws on project resources. Ironically, these requirements risk making projects so complex that they can only be led by large state-owned research organisations and universities thereby ultimately reducing the influence of farmers and other innovators, such as plant breeders.

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. It also receives support from the governments of the United Kingdom, Switzerland and New Zealand. The Legume Generation consortium comprises 34 partners in 15 countries.

This position paper is provided by the Legume Generation consortium. Its preparation was led by Donal Murphy-Bokern (Germany). Please cite this position paper as follows:

Legume Generation, 2026. An agenda for public investment in legume plant breeding. Legume Generation Position Paper 1. Available from www.legumegeneration.eu and www.legumehub.eu. DOI: https://doi.org/10.5281/zenodo.19563945

Legume Generation (Boosting innovation in breeding for the next generation of legume crops for Europe) has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No.101081329. It also receives support from the governments of the United Kingdom, Switzerland and New Zealand.