Legume Generation

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

The Legume Generation Innovation Communities

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Summary

The purpose of this report is to provide and overview of the Legume Generation innovation communities and to record some insights from their establishment.

The overall purpose of the Legume Generation innovation communities is to make the connection between research activity and the breeding process. The idea can be traced back to the observation in the Department of Food and Rural Affairs (Defra, UK) of a serious disconnect between public investment in research that depends on plant breeding for its impact. In the UK then, that disconnect had been increased by the privatisation of the world-renowned Plant Breeding Institute in Cambridge in 1987. To address this, Defra diverted some of its funds for project-based research relevant to plant breeding towards the funding of species-specific partnerships between plant breeders and the relevant research base. These were called the Defra Genetic Improvement Networks. Despite relatively modest funding, these new structures had a far-reaching impact on the relationships between research and plant breeding. This experience provided the background to the innovation community concept in Legume Generation.

Two worlds meet in an innovation community:

1. The research world focused on science disciplines, experimentation, academic publication, and the project/grant cycle.

2. The practical plant breeders focused on the breeding cycle of their species.

The key feature of the innovation communities is their species-specific character. This gives priority to the genetic improvement of the species and gives breeders the opportunity to lead the research and development processes.

The experience in Legume Generation shows that establishing real interaction and mutual support between these worlds is not straight forward. The creating and recognising the pre-competitive space in which there can be sharing of ideas and results between researchers and breeding companies. Trust within the communities is vital. An underlying factor is that the working-level breeders are as individuals sometimes not in a position to develop the more strategic aspects of these partnerships. Building for the long-term sustainability of these innovation communities requires the involvement of those in breeding businesses who work on business strategy. This is especially the case in large companies where there is separation between the day-to-day breeding work and company strategy. Similarly on the research side, developing a research organisation's position in an innovation community and this pre-competitive space has strategic implications for research organisations.

We have successfully established a common understanding of how these collaborations can exploit the precompetitive space in these crop-facing communities. Each IC has worked hard to establish their plans and conducting the experimental programme in 2024. Building and deepening the trust within these partnerships is a goal of this part of coordination going forward.

Introduction

Innovation is risky and requires an entrepreneurial spirit to drive and manage change. While the plant breeding work-cycle is annual and species focused, a breeding enterprise or programme is a long-term endeavour operating to decadal timescales. And plant breeding draws on the work of research scientists who generally operate to shorter (project) timescales and to different incentives within an academic framework. Consequently, and especially with the decline of public-sector plant breeding, harnessing public research to boost breeding is not a trivial undertaking. This is particularly so in the case of legumes where the market for research fails profoundly due to the low commercial rewards for better cultivars. The different components required for research-supported innovation operate to different incentives and timescales.

Legume Generation seeks to change how research supports legume plant breeding and to overcome the disconnections described above. It systematically combines the entrepreneurial and commercial ambition of breeders with the inventiveness of the supporting research base within breeder (innovator) facing structures (Figure 1). Six species-specific innovation communities link our research-base with our 78 breeding and pre-breeding programmes focused on soybean, pea, lupins, lentil, common bean, and clovers. A key feature is our explicit organisation according to how our target species are bred (i.e., how plant breeding works) rather than according to how research is organised in science disciplines. We hope that this new articulation between breeding and research will provide long-lasting structures, drivers, and partnerships for investing in the genetic improvement of legumes.

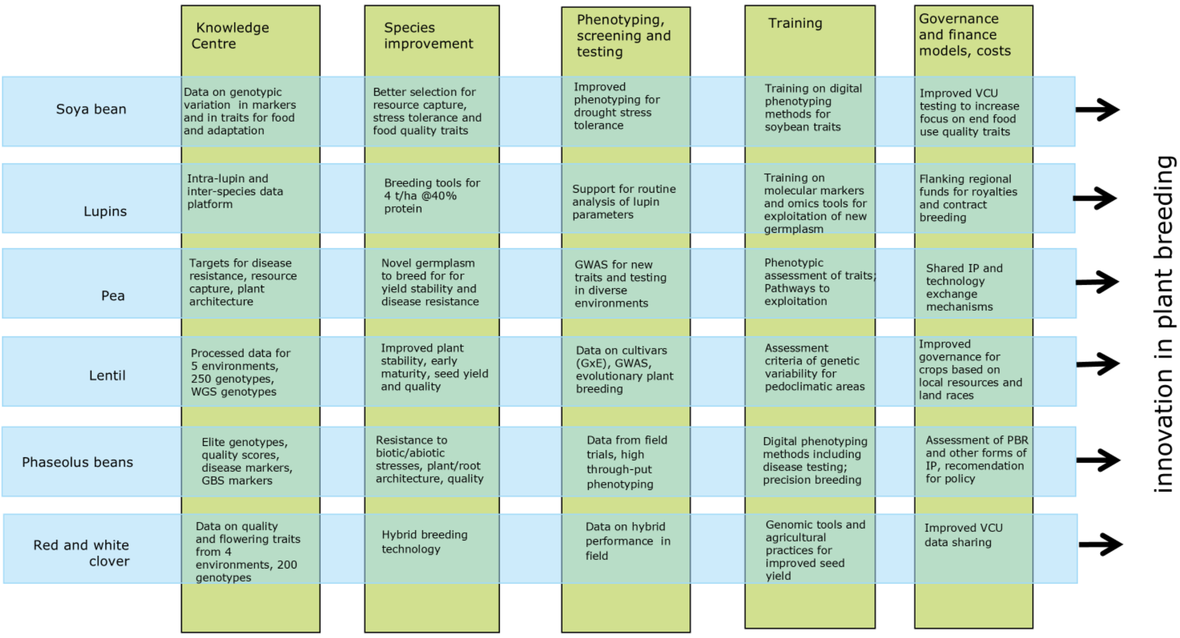

Figure 1. The project is led by innovation communities, each focused on the breeding of a single species or species type. Each is supported by a knowledge centre for breeding, shared tools and approaches for genetic improvement, shared phenotyping: screening, demonstration and testing of cultivars; training, and investigations into governance and finance models. Examples of results are shown in the intersections between the innovation communities and the supporting research-based WPs.

Legume crops remain underutilised in Europe because farmers exploit the comparative advantage of cereal crops, particularly under temperate conditions and the high latitudes that characterise many European farming environments. To address this, competitive yields based on effective resource capture (light, water, and nutrients) from good adaptation to environments are key. Improved quality traits for sustainable healthy diets add further value.

Each of our species-facing innovation communities (*Figure 2*) are supported by insights into resource capture, ideotype concepts, and beneficial traits; a catalogue of legume species, cultivars, and breeding methods; the production and validation of novel resources; demonstration and testing of germplasm; training; and by the European [Legume Hub](). Drawing on governance and financial case studies, the ICs' long-term sustainability will be supported by business plans. The project will support innovation up to the point where newly-bred germplasm and cultivars are proven on farm.

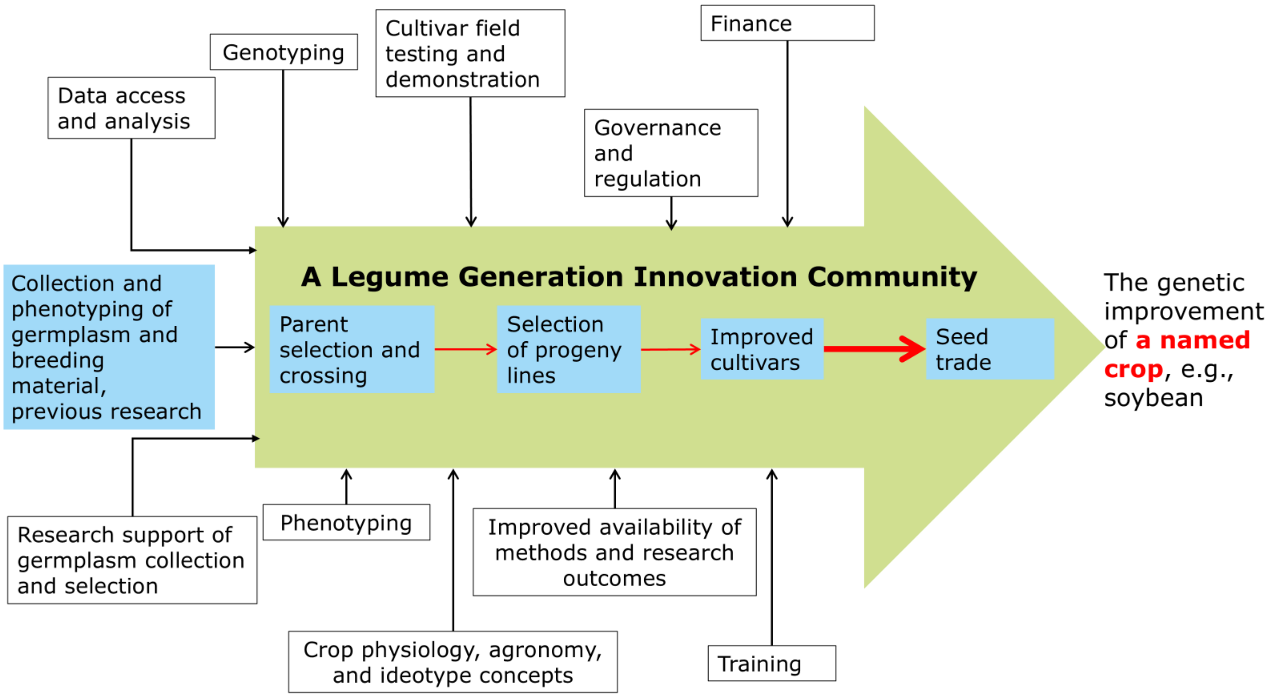

Figure 2. Each species-specific innovation community focuses research and science support services on boosting the breeding of a species or species type.

Soybean

Building on the BOKU/DS-led European Soya Improvement Network, our Soybean Innovation Community (IC, Figure 3) is addressing these risks by connecting European researchers with European breeders through the EU-funded Legume Generation project, creating a permanent framework for pre-competitive, breeder-led research on crop genetic improvement. While soya yields in Europe are in line with the global average, European cereal yields significantly exceed global levels. This favours cereal production and leads to the well-known protein deficit. To correct this imbalance and strengthen the competitiveness of soybean cultivation in Europe, targeted public investment in soybean breeding is essential. Our strategic goal is to coordinate breeding activities to optimise both the yield and quality of soybean. This should make the soybean more competitive in European cultivation systems in the long term.

To achieve our goal, the data collected by breeders and institutes is analysed comprehensively together. Our members benefit from joint genotyping and special phenotyping trials, which provide valuable information about the breeding material. To this end, we carry out multi-year field trials with modern breeding lines at various locations.

Figure 3. Johann Vollmann leading a meeting of the Soybean Innovation Community in Tulln (BOKU) in September 2024

Strategic goals up to the end of the project in 2028

We will focus on technological development until 2028. The collaboration between members of the soybean IC with either partners within the Legume Generation consortium or with other members of the wider IC (i.e., BELIS consortium members, other stakeholders in the feed and food industry) will continue. This will mainly include work carried out in the pre-competitive space 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. Thus, further collaboration between small and medium size European soybean breeding companies will be necessary to maintain efficiency of breeding programmes and competitiveness against multinational/large players. The IC can be kept alive through the development of follow-up projects on technology delivery (technology packages), through joint ventures (something like Saaten Union in Germany, but coordinated across Europe, perhaps by Euroseeds or other platforms), or through specialised service providers (something like the Hiphen service company already in place).

Strategic goals up to 2033 (five years after the project ends)
Looking beyond 2028, we aim to focus on developing soybean as a crop in Europe. The acreage of European (EU) soybean production will continue to grow. European soybean breeders will further expand their breeding programmes to maintain their position in the seed market with superior cultivars which are adapted to drought or specific northern-latitude growing conditions. As the consumption of animal-based protein products decreases further, plant breeders will increasingly deal with food grade soybean developments. This includes very high protein soybeans, specialty cultivars, advanced product quality analysis, and a more intensive collaboration/dialogue with food industry (through joint research projects, research platforms etc., similar examples can be seen in cereals with bread-making, brewing companies…). 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) among members of the soybean IC to acquire a critical capacity to implement the technology.

Lupins

The species of the genus *Lupinus* that are grown in Europe are generally well-adapted to dry and acid soils. The high protein content and oil provide market opportunities. But we need progress in yield and yield stability from better resource capture. Legume Generation provides a breeder-led framework and long-lasting partnership to integrate research resources to improve lupin.

For narrow-leafed lupin, we are developing several important agronomic traits such as calcareous soil tolerance and increased pod formation from long-term introgression and pyramiding using bitter genebank accessions. Some material has already reached good levels of grain yield and protein content for food- and technical-protein processing. First crosses have been done and we have conducted genetic analyses and inheritance studies of several traits on first segregating F2-populations at JKI. Several lines were field tested in 2024.

For white lupin, genebank accessions and single seed decent lines from the INCREASE project together with some bitter accessions from the Vavilov Institute, St. Petersburg, are being multiplied and evaluated for yield, anthracnose resistance/tolerance and alkaloid level in field and laboratory tests. This forms a new breeding programme in ESKUSA.

For Andean lupin, we start also with genebank accessions that are well-developed and can be multiplied quickly in Europe. We are conducting field evaluation of a selected set of accessions to learn which agronomical trait combinations suit Europe.

IHU and ABER perform field trials with different emphases (diseases, soil quality, Figure 4) while partners IPK and SRU are testing for heat and drought stress. BOKU is searching for resistances and tolerances against soil-borne fungal diseases. IPG, UPM and JKI contribute phenotyping, genotyping, molecular markers, and analyses of quality.

All this is done within the long-term framework of ESKUSA's breeding programme. A key for the success of the LUPIC will be cooperation across the different species. We need to develop a trans-species point of view in our activities to join our forces, grow together and to solve problems in common. Because ESKUSA is a breeding company, we identified our most important breeding goals from farmers' needs and transfer these into cultivar-development. We are open to share our approaches with other breeders and scientists.

Figure 4. Sowing lupin trials in Greece.

Strategic goals up to the end of the project in 2028

The strategic ambition for the Lupin IC is the development of narrow-leafed and white lupin lines that create interest in the seed trading companies. We expect to have lines with high protein content available by the year 2028, however these lines will still be bitter. That means they will not have access to the large feed market. We will have a breeding programme to transfer valuable agronomic traits from our bitter germplasm into sweet cultivars. However sweet cultivar candidates with improved traits cannot be ready by 2028.

We will follow a way to use the bitter accessions in a special food-protein extraction process via membrane filtration in close relationship with the Lupino AG. However, this company is the only one that is able to produce food-grade protein from bitter lupins and the process is still in development to become economically feasible. Another way that we follow is to produce films and glues from lupin protein for technical purposes. We are just at the point to raise first interest in the industry (paper and packaging) to use lupin protein for technical purposes.

We think that until 2028 we will not be independent from public funding. National, local or other funding sources will still be needed to get our initiated cooperation running as continuous as possible. However, we should be able to raise some funds from the industry to support our lupin IC network.

Strategic goals up to 2033 (five years after the project ends)
By the year 2033 we expect to have tools to edit the transport mechanism of alkaloids from the leaf epidermis to the developing seed. This would immediately lead to access of our genetic resources and our breeding programme in bitter lupins to the broad feed-market. ESKUSA expects to generate income from royalties for first varieties. With these royalties the applied breeding programme has to be re-financed. We will support our research partners as far as possible from incoming royalties. However, there will be limitations. As an IC, we will keep ongoing discussions with seed merchants and the food industry to invest in breeding and breeding research. The developed lupin germplasm should offer better income to farmers and hence generate additional lupin cropping areas. Increase of lupin cropping area is the basis for financing breeding and research activities around lupins. Our goal ”40/40” is set and will help to generate lupin cropping area.

Pea

The Legume Generation Pea Innovation Community has researchers and breeders in five countries. Challenges to the crop pea are defined and tackled by researchers and practical breeders in a tightly linked collaborative European network.

Our strategic goal is to create and maintain a lasting collaborative Europe-wide network beyond existing national ones (e.g., the PCGIN in the UK) for much-needed pre-competitive engagement in pre-breeding. Using this collaborative network, we will identify pea accessions and genotypes that harbour valuable characteristics such as disease resistances and climate resilience that are not available in modern cultivars. Improved genetics will broaden pea utility across different environments. Our foundation is a set of 250 wild *Pisum* accessions, landraces and elite cultivars that we assess in replicated trials in the UK (JIC), Germany (KWS) and Spain (SERIDA, Figure 5). Yield and disease data will be collected. An additional screening for adaptation to drought will occur at the phenomics facility at IBERS.

The available whole genome sequences of these lines at JIC will provide fast access to the genetic components underlying these traits. Increasing yield and resilience to biotic and abiotic stresses will boost the utilisation of new germplasm from now and in the future to generate novel pea varieties as a lasting source of home-grown plant-based protein. We are committed to understand the genetic basis of important agronomic traits and develop these findings into tools (e.g., molecular markers, improved screening methods) that are fit to practicable breeding. The network will serve the translation of research findings into improved cultivars coping with current and future challenges in peas as a feed and food crop.

Figure 5. A pea field trial conducted at SERIDA in Spain in 2024.

Strategic goals up to the end of the project in 2028

By 2028, we must see that the pea innovation community is more than a research project lasting five years. It will be a long-lasting interaction with early mutual benefits. This means that breeders will have started using outputs of the PIC already during the lifetime of the project (e.g., molecular tools, phenotyping protocols). The interaction must be more than a data generation exercise ending in scientific papers uncoupled from a translation into the practical world. Equally, researchers need to have the certainty that a lasting relationship in the world of peas has been established with which it is worth staying in this field thanks to the continuous interest and support from industry with the common formulation of relevant topics including also addressing more fundamental questions beyond this project.

Strategic goals up to 2033 (five years after the project ends)
By 2033, we need to have made a measurable progress in pea breeding programmes, which is most visible by having new pea genetics in form of varieties or at least lines registered in official trials. For example, pea breeding lines and varieties will carry new genetics/new characteristics from the material we are assessing in this PIC. We must have traits in breeding germplasm that we cannot find in the current, rather related breeding genetics used in Europe. Specific problems such as individual diseases or the stagnating yield must be solved or at least significantly be improved by then.

Pea researchers involved here must still be working successfully (publishing, being funded) on peas and other researchers with post-graduate students, the scientists of tomorrow, will have joined due to the greater and lasting attention peas have. More genomic resources, like in cereals, will have been developed and other industries will be directly engaged, e.g., food companies, together with breeding companies. An unbroken momentum in pea innovation can lead to the welcome investigation of new legume species for their suitability in Europe.

Lentil

Lentil (*Lens culinaris* Medik.*)* is traditional to European farming and cuisine. It has great potential in sustainable healthy diets. European consumption is increasing but much of the lentil used in the EU is imported, for example from Canada. Lentil is a short- and cool-season legume and so it can occupy niches in cropping systems. Production is based on spring sowing in northern and central Europe, and autumn sowing in the south.

Our goal is to establish and use an entrepreneurial innovation chain between biologists, agronomists and breeders to boost the breeding of lentil for Europe. We have already conducted a network of experiments in 2023-2024 to phenotype lentil germplasm. Autumn-sown trials were conducted in Greece (IHU, two sites, Figure 6) and Italy (UNIBAS). Spring-sown trial were conducted in France (LIDEA) and Germany (two sites (IPK and KEY)).

The EU's lentil market of about 300,000 t is growing with demand for heathy sustainable diets. This provides a business opportunity for us. We have two approaches:

1) the selection and improvement of traditional landraces connected with specific regions. These can be used for Protected Geographical Indication (PDO) and Protected Geographical Indication (PGI) products; and

2) boosting the wider production using higher-yielding cultivars that have improved seed size and quality, different colours, and better adaptation agro-ecosystems, especially in water-stressed regions.

We will use tools from the SRU for the evaluation of the physiological adaptation of the germplasm combined with the experience in molecular genetics from UNIVPM.

Figure 6. Variation in flowering date measured in the phenotyping of lentil at the IHU in Greece.

Our germplasm includes 180 accessions from the IPK that are tested at 4 sites in Greece, France and Germany, and partly at a fifth site in Italy. We are also testing a further 220 accessions, including landraces and improved lines, mainly originated from ICARDA in Greece (IHU) and 200 lines mainly originating from previous project (UNIBAS, Italy) and (KEY, Germany). Standard measurement protocols are being used. The follow-on work will include the further development of single seed descent lines, and the identification of genotypes that make an efficient use of resources across environments.

Our further activities to boost breeding will be based on the results of Year 1 and 2, and on information from previous projects. The performance of single plant selections will provide a basis of promising breeding lines to be evaluated and used in the Lentil IC. Experience of UNIVPM genomic prediction models for target traits will also contribute to estimate a good combination ability of lines with desirable phenotypic characteristics. The final aim is to produce lines with good productive and quality characteristics to be evaluated in farming practice.

Strategic goals up to the end of the project in 2028
Our goal is to gain from market opportunities in lentils and ensure sustainability of the Lentil Innovation Community (IC), we can take several strategic steps in connection to:

1. **Produce high-yield cultivars:** The availability of high-yielding cultivars of lentils will directly support the expansion in lentil production in Europe. Farmers benefit from the

reduction in production cost per unit due to higher yield per unit land area. This makes lentil more competitive for land on farms.

2. **Serve the organic market:** Lentil is particularly relevant to the organic food market. Our goal is to stimulate and serve this market with suitable cultivars. KEY is member of The European Consortium for Organic Plant Breeding (ECO-PB) and willing to share results, accessions with other breeders in the organic sector.

3. **Produce high-protein lentils:** The availability of high-protein cultivars elevates lentils to the status of a superfood in the plant-based food markets. Health-conscious consumers, vegetarians, and the food-processing industry are looking for protein-rich plant-based foods and plant protein alternatives.

4. **Exploit opportunities in the food sector:** Building relationships with food processors to create lentil protein flour, lentil snacks, or meat substitutes. This will open new market opportunities and increase the demand for lentils.

5. **Partnerships:** We need to encourage partnerships between public and private actors to share costs and benefits of breeding. Some members of the Lentil IC are already members of the EVA network (ECPGR). The use of our lentils in the market needs to resource experimental activities, knowledge transfer from the universities, access to a pool of well-educated students following market needs.

6. **Infrastructure**: Maintain a network of field trials for lentil crops, using the facilities of the public and private sector for seed testing.

7. **Knowledge Sharing:** Sustain the Lentil IC platform of shared knowledge, including research findings, cultivation practices, and market trends. Develop digital platforms for remote collaboration and data sharing through the Legume Generation project (or/and the Legume Hub).

Strategic goals up to 2033 (five years after the project ends)
The Lentil IC could be an "ecosystem" that stabilises lentil improvement by linking with the related market for the lentil crop (release of new varieties-seed companies-lentil producers (lentil)-consumers or industry uses). The good collaboration between private – public sector will enhance the ability of the "system" to identify "early-warnings"/"signals" from the market (in connection with the availability of the products, prices or even problem related to crop growth). This will enable us to harness the support of the public sector better so the new challenges and new needs are identified and addressed.

Phaseolus beans

Phaseolus beans (or common beans, *Phaseolus vulgaris* L. and *P. coccineus* (scarlet runner bean)) are the second most important cultivated legume type in the world, grown as bush beans or pole bean for their green pods and for dry seeds (37 million ha, FAOStat 2022). In Europe, phaseolus beans are traditional food crops with 191,068 ha grown in 2022 for grain and 124,865 ha grown for the green, vegetable consumption. Almost all cropping is for food quality with 18 dry bean production chains protected by Protected Geographical Indication (PGI) and Protected Designation of Origin (PDO). Despite our substantial research base, the wider growing market for beans used in sustainable healthy diets will be met by more imports unless the European crop is revived. This revival is the goal of our Legume Generation Phaseolus Bean Innovation Community (BIC): a group of breeders and research scientist from both commercial and academic organisations, spread over six countries (Figure 7, Figure 8). Our community has already grown beyond the project partnership and now includes Van Waveren Seeds and Pharmaplant GmbH.

Figure 7. Field trial of bush beans at the IPK Gatersleben (Germany) in 2024 for phenotyping and seed propagation.

The BIC will boost breeding by exploiting genetic resources and providing novel tools and strategies for a practical improvement. We systematically draw on existing European research resources with leading innovative breeders to produce new cultivars with new combinations of traits. To achieve this, and supported by the results of on-going and past projects (BEAN_ADAPT, INCREASE, BRESOV, NEXT_BEAN, PARDOM, TOOLBEAN), the objectives are to:

(i) collect information about genetic resources from related projects;
(ii) screen panels of bean breeding lines and genetic resources, including common bean and scarlet runner bean accessions, to identify sources of resistance to biotic/abiotic stress, variation in plant/root architecture and in seed quality;
(iii) develop and provide new resources and new tools such as breeding populations (multi-parental), inter-specific lines, and validated user-friendly genetic markers for our breeders for genomic assisted breeding; and
(iv) develop new bean genotypes and cultivars, suitable as either breeding and pre-breeding material, through recombination and pyramiding using cutting-edge methods, such as precision breeding, high-throughput phenotyping and high throughput genotyping complementing classical phenotypic selection.

We have already designed two bean diversity panels that brings together a wide diversity useful for breeders. Also, the first crosses were carried out for the development of a multi-parental population. Moreover, one generation of single seed descent (SSD) lines was developed for an interspecific population derived from the cross *P. vulgaris* × *P. coccineus*. Precision breeding is being used for the introgression of potyvirus resistance in local cultivars.

Strategic goals up to the end of the project in 2028
By 2028, the results of the work will have been disseminated directly to our business partners, i.e., breeders of the innovation community for exploitation. Public dissemination, i.e., to scientific partners, will still be fully active to support the breeders, as also scientific publication of various research results will still be pending. To deepen specific research needs, the innovation community will be providing a platform for further projects (bilateral to few partners involved) in applied but also potentially basic research, addressing also local market demands. The innovation community should latest by 2028 have defined further strategic research needs in phaseolus bean for Europe and market niches, which could be exploited. If present, research could lead to project(s) encompassing the whole IC. If investment is available, we envisage increased work on dry bean (esp. the bush type) to improve the global competitiveness of European dry bean cultivation. Frequent interaction between the whole community will be established to keep the platform alive.

Strategic goals up to 2033 (five years after the project ends)
Over time, personnel change and so the IC needs to be based on the partner organisations moving beyond a collection of bilateral arrangements. Further projects and cooperation will be taking place to boost phaseolus bean breeding and cultivation in Europe. The core activity will remain the transferring knowledge to the breeders but preserving it within the bean innovation community. Efforts must be made to keep the interaction within the whole community alive. Legume conferences and workshops could offer one way to do this.

Figure 8. Phaseolus bean field trial at SERIDA (Spain) in 2024.

Clovers

The Clover Innovation Community is spread over three continents and five countries. As a group of breeders and scientists from both commercial and academic organisations, we have come together with the goal of improving the breeding of both red and white clover.

Red and white clover provide highly nutrition and digestible forage, particularly for ruminants. Our strategic goal is to create a lasting framework for much-needed pre-competitive investment in pre-breeding. Using this framework, we will identify accessions and genotypes that may harbour valuable characters such as persistence and disease tolerance that are not available in modern cultivars of white clover. This may broaden its utility across different environments. 200 accessions of wild populations and elite cultivars are being assessed in replicated trials in the UK (Germinal and IBERS) and in Germany (LfL) in contrasting environments. Yield and quality data will be collected. Whole genome sequencing, to be carried out at the Earlham Institute (UK), will be on populations of 100 genotypes of each accession. We will use a GWAS approach to understand mechanisms underlying yield and persistency.

We also have two further specific technical objectives: to improve the seed yield in red clover, and to develop hybrid seed production in both species.

Increasing seed yield, especially in red clover, will boost innovation from new germplasm and the use of red clover on farms. We are assessing two approaches to improving seed yield. Boron applications, carried out at the ABI in Bulgaria and Germinal/IBERS (UK), will test effects on pollen tube growth, seed production and viability. Foliage, of poor seed yielding varieties, will be sprayed with 0.75mg/l of boron, in both field and glasshouse experiments (Figure 9).

Figure 9. Erecting a security net around a ABI field test of clover at Negovan in Bulgaria.

Our other approach to improving seed yield is to utilize the already characterised S-allele markers.[1] S-allele frequencies, in the same poor seed yielding varieties, will be analysed to understand the impact on their seed yield. The S-allele technique will also be utilized to improve intra-population hybrid seed. We will use the facilities at USDA (USA) and IBERS to perform this work.

We are also committed to the elucidation of the S-alleles in white clover. This work is being carried out at AgResearch (NZ), and Aarhus University (DK). We envisage that by the end of the project we will have markers linked to allelic variants of the S-locus and will be able to trial these on different white clover populations.

Strategic goals up to the end of the project in 2028

The strategic ambition of the Clover Innovation Community for the end of the project in 2028 is to have robust molecular markers for white clover to allow clover breeders to target variation for herbage yield and abiotic and biotic stress tolerance that can be incorporated into white clover breeding programmes in an efficient manner as well as having relevant germplasm that can be used to access this variation. Furthermore, we aim to have

[1] Riday, H., and Krohn, A. L. 2010. Genetic map-based location of the red clover (*Trifolium pratense*) gametophytic self-incompatibility locus. TAG: 121(4):761-7, doi: 10.1007/s00122-010-1345-0

information on self-incompatibility alleles that will allow both white and red clover breeders to maximise successful hybridisation events in seed production. This will allow for better seed yield and seed yield stability, factors that currently limit the successful commercial exploitation of new clover varieties. An experimental semi-hybrid red clover line will have also been produced to test the potential of this methodology to harness heterosis above and beyond current breeding methodologies that utilise synthetic variety production from half sib families.

Strategic goals up to 2033 (five years after the project ends)
The Clover Innovation Community's strategic vision for five years after the end of the project in 2033 is that the work carried out in Legume Generation is built upon with information on other traits. The genotyped white clover diversity panel will be maintained and used in future projects to expand its use for clover breeders in accessing novel variation. It is hoped that the self-incompatibility work will improve seed yield in new commercial varieties, allowing for faster adoption of improved material and reduced reliance on outclassed cultivars. If the semi-hybrid methodology does indeed lead to improved hybrid vigour in cultivars the hope is that this methodology will be adopted widely amongst breeders.

Conclusions

The innovation community concept can be traced back to efforts twenty years ago by the Department of Environment, Food and Rural Affairs in the UK to renew and reorientate the connections between research and plant breeding. The result was the Defra Wheat Genetic Improvement Network and the Defra Pulse Crop Genetic Improvement Network. These still operate today. Responding to the disconnections caused by the privatisation of Plant Breeding Institute two decades earlier, they had a profound impact on the relationships between research and breeding then both at the operational and strategic levels.

Now, within Legume Generation twenty years later, the understanding of the innovation community concept varied widely across the consortium at the outset. Working across Europe, each innovation community is different and each requires its own plan to boost breeding. The tendency to treat an EU grant as just another time-bound project overlooks the strategic and long-term potential of reorienting the research and innovation onto species, led by breeders. This must change. Our ambition is that each innovation community offers an integrating platform for innovation that benefits breeders, researchers and the public investors in plant breeding. This addresses a number of serious obstacles to the smooth interaction between research and breeding, particularly from the short-term and fragmented nature of project-based funding.

The practical priority before and after the project started was to establish the experimental programmes. Parallel to this, it was necessary to establish a plan to boost breeding for each IC that would extend beyond the life of the project. This required IC leaders and associates extending their work beyond experimentation to consideration of strategic matters such as the optimal arrangements between partners, the management of IP, understanding the commercial aspects of the breeding in each IC, and governance matters.

Guided by this work, each innovation community produced a plan to boost the breeding of its respective crops. The Legume Generation Reports 1 - 6 that set out these six plans are available from www.legumegeneration.eu and www.legumehub.eu as follows:

Vollmann, J., Hahn, V., Murphy-Bokern, D. and Škrabišová, M., 2024. The plan for boosting the breeding of soybean. Legume Generation Report 1. Available from www.legumegeneration.eu and www.legumehub.eu. DOI: https://doi.org/10.5281/zenodo.17243541

Eickmeyer, F., Flüß, H., Susek, K. and Murphy-Bokern, D., 2025. Plan for boosting the breeding of lupin. Legume Generation Report 2. Available from www.legumegeneration.eu and www.legumehub.eu. DOI: https://doi.org/10.5281/zenodo.17249160

Arora, S., Oldach, K., Gervais, L., Ferreira, JJ., Niewinska, M., Ostergaard, L., and Murphy-Bokern, D. 2024. The plan for boosting the breeding of pea. Legume Generation Report 3. Available from www.legumegeneration.eu and www.legumehub.eu. DOI: https://doi.org/10.5281/zenodo.17249772

Ninou, E., Mylonas, I., Murphy-Bokern, D., Hennenkaemper, U., Lohwasser, U., Jeanson, P. Gioia, T., Papa, R., 2025. Plan for boosting the breeding of lentil. Legume Generation Report 4. Available from www.legumegeneration.eu and www.legumehub.eu. DOI: https://doi.org/10.5281/zenodo.17287728

Ferreira, J.J., Gioia, T., Otto, L.-G. and Murphy-Bokern, D. 2024. The plan for boosting the breeding of phaseolus beans. Legume Generation Report 5. Available from www.legumegeneration.eu and www.legumehub.eu. DOI: https://doi.org/10.5281/zenodo.17250917

Jones, C.; Anderson, S. U.; de Vega, J.; Griffiths, A.; Hartmann, S.; Howarth, C.; Iantcheva, A.; Lloyd, D.; and Riday, H. 2024. The plan for boosting the breeding of clovers. Legume Generation Report 6. Available from www.legumegeneration.eu and www.legumehub.eu. DOI: https://doi.org/10.5281/zenodo.17257789

Two worlds meet in an innovation community (*Figure 10*):

1. The research world focused on science disciplines, experimentation, academic publication, and the project/grant cycle.

2. The practical plant breeders focused on the breeding cycle of their species.

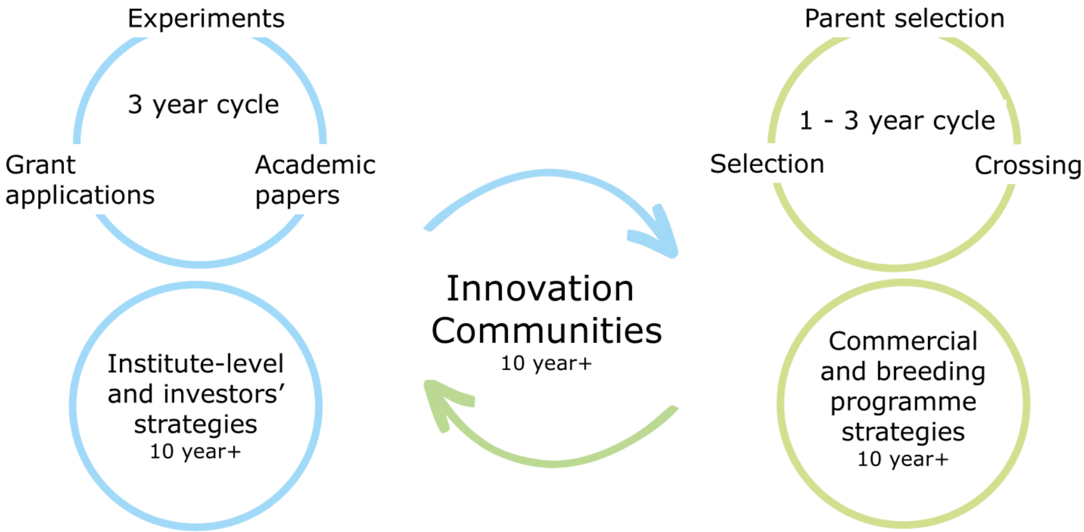

Figure 10. Legume Generation innovation communities: ecosystems where the research (left) and breeding (right) worlds meet.

The experience in Legume Generation shows that establishing real interaction and mutual support between these worlds is not straight forward. The key is creating and recognising the pre-competitive space in which ideas and results can be shared between researchers and breeding companies. An underlying factor is that the working-level breeders are as individuals sometimes not always in a position to develop the more strategic aspects of these partnerships. Building for the long-term sustainability requires the involvement of those in breeding businesses who work on business strategy. This is especially the case in large companies where there is separation between the day-to-day breeding work and company strategy. Similarly on the research side, developing a research organisation's position within an innovation community has strategic implications for research organisations.

We have successfully established a common understanding of how these collaborations can exploit the precompetitive space in these crop-facing communities. Each IC has worked hard to establish their plans and conduct the experimental programme in 2024. Building and deepening the trust within these partnerships is a goal of the project going forward.