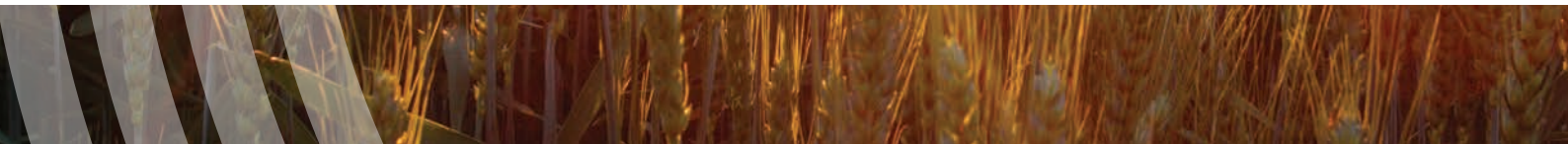
Roadmap to improved crop yields in Europe

Executive Summary

THIS PROJECT IS FUNDED BY THE **EUROPEAN UNION HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME** UNDER GRANT AGREEMENT 817690



A New Green Revolution for European Agriculture

Maintaining food security while transitioning towards more sustainable food systems, in the face of climate change, is one of the greatest challenges facing our growing global society. These drivers of change are increasingly urgent. The Covid-19 pandemic and the impact of the Russian invasion of Ukraine have dramatically demonstrated the fragilities of European and global crop and food value chains.

We will need to produce food for 9.7 billion people in a sustainable way by 2050, as well as to meet the demands of a future bioeconomy. This will require a doubling of global crop productivity, but current projections of crop yield suggest we will fall 40-70% short of demand by 2050.

Securing a European supply of high-quality food, feed, and biomass for bio-based products and energy, is a priority for Europe. A second Green Revolution in crop production is needed to meet future crop biomass demands, whilst aligning with the EC's biodiversity strategy ambition to reduce agricultural land by 10% by 2030. This represents a huge challenge to biologists, plant breeders, agricultural technologists, economists, and farmers. Unfortunately, crop breeding research and innovation is fragmented and is on a rather small scale. Common approaches to crop improvement make this sector ideal for a strategic European scale research and innovation programme. Multiple areas of technology are already at Technology Readiness Levels (TRLs) 3-5.

Innovation in Crop Science has the potential to address societal needs - but action is required now.

The timescales for crop development from basic research to commercialisation are long (see Figure 1), and regulatory restrictions for certain crop improvement technologies limit their market access. Urgent action is needed to deliver the next generation of crops in the coming decades. Future-proofing crops must be a priority, to provide a robust and sustainable supply of plant-based production in the medium and long-term.

This Roadmap has been developed in the CropBooster-P project (EC Grant Agreement 817690). This is a summary of the detailed CropBooster Strategic Research Agenda and CropBooster-P White Paper. These documents can be accessed using the QR code.

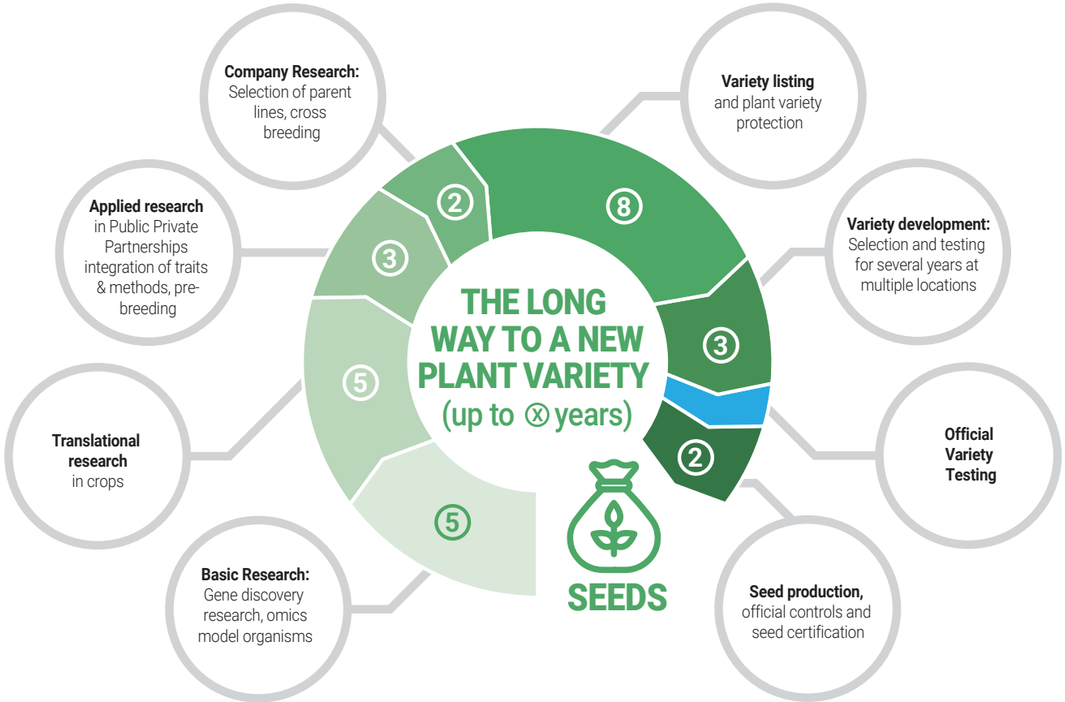


Figure 1: The innovation cycle in crop breeding indicating estimated (maximum) timescales at each stage (redrawn from Euroseeds).

Crop innovation is a critical part of the solution for climate-smart agriculture.

The EU-H2020 Coordination and Support Action "CropBooster-P" has developed a program to future-proof Europe's crops, that is aligned with societal expectations. This CropBooster Program proposes a strategic Research and Innovation Roadmap that builds on current advances in plant science and crop research. Research excellence distributed across the European Research Area will be combined with professional expertise from plant breeders, farmers and the bioeconomy value chains. The Program will deliver breakthrough translational research, and deliver **blueprints for future-proofed** crops designed to address the emerging environmental challenges to crop production, and provide more sustainable food systems and the supply of plant-based materials for the bioeconomy.

The CropBooster Program science-based "blueprints" for improved crops will address key critical challenges including:

- **More efficient use of resources and inputs in agriculture:** in the case of CropBooster the primary resources are water and nutrients (e.g. nitrogen and phosphorus).
- **Increasing crop yields to provide sufficient food for the growing global population.** The growing global population is expected to have an increased per capita food demand, estimates suggest crop production may need to increase by up to 110%.
- **Transitioning to a more sustainable bioeconomy to meet increasing demands for biobased materials and products.** New feedstock crops and bio-factories will be better designed to meet the needs of processors and end users.
- **The adaptation of crops to improve resilience to climate change:** this will affect different regions in Europe facing diverse changes in climate and weather extremes.
- **Increasing the nutritional value and other quality parameters of future crops.**
- **Improving the mitigation of greenhouse gases,** especially carbon dioxide, fixed by photosynthesis and sequestered and stored within plant biomass or below ground (carbon farming).
- **The need to preserve space for natural ecosystems:** new crop science should increase yields and sustainability without the need to expand the area of croplands.

Alignment to EU Policies

The European Commission has already declared sustainable yield improvement in agriculture a priority in view of global problems (food, energy, climate). Crop innovation will play a critical role in increasing the yield of lower input systems, such as organic farming, while reducing the need for inputs (e.g., fertiliser and pesticides) for other farming systems, in line with the Common Agricultural Policy (CAP) and Farm to Fork Strategy (May 2020).

DG AGRI's "A Strategic Approach to EU Agricultural Research and Innovation" highlights the need to "*improve the characterisation, information and access to genetic resources to support their use by breeders, farmers, foresters and in value chains for food and non-food products*", and the findings of 4th Standing Committee on Agricultural Research (SCAR) foresight conference "the Sustainable Agriculture, Forestry and Fisheries in the Bioeconomy - A Challenge for Europe" stated that natural genetic resources should be exploited more effectively for the EU bioeconomy. Improved crops will contribute to the Food 2030 policy of Food and Nutrition Security to build sustainable and resilient food systems, and support work towards European action on the UN's Sustainable Development Goals (SDGs): providing steps towards ending poverty and hunger (food security, SDG2).

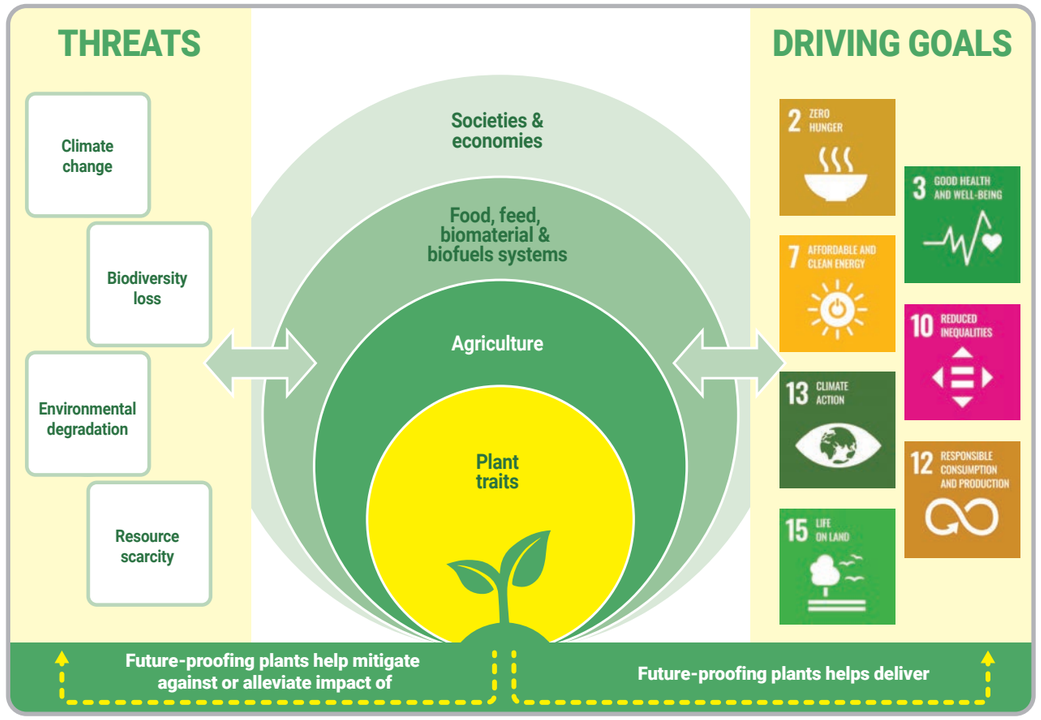


Figure 2. Plant trait innovation and refinement is a key enabling technology for future-proofing crop plants against multiple global threats and help to transform Europe to sustainable agricultural systems. This agricultural production needs to be enhanced to meet societal needs for food, biomaterials and biofuel in a sustainable manner that contributes to the COP and sustainable development goals. From Harbinson et al 2021 https://pubmed.ncbi.nlm.nih.gov/34356545/

The CropBooster Strategic Research Agenda has identified multiple routes forward, building on a rich science base. New crop varieties need to be developed with improved yields and higher Resource Use Efficiency (RUE). This will reduce reliance on synthetic fertilisers whose production is energy intensive and depletes natural resources. Lowering inputs will contribute to delivering the European Green Deal's (December 2019) aims to reduce GHG emissions to 55 % of 1990 levels by 2030 and reaching climate-neutrality by 2050. In addition, developing crops with better root architectures, and able to sequester carbon, will help both resilience and carbon farming approaches to contribute to the EU Soil Strategy for 2030. This is directly aligned to the climate change commitments of the Paris (COP 21) and Glasgow (COP 26) Agreements. Reduced use of fertiliser will mitigate eutrophication problems and contribute to the EU Biodiversity Strategy 2030 and Europe's Zero Pollution Action Plan (May 2021). The CropBooster programme will demand a multidisciplinary approach combining life and social sciences and economics. New tools and sensors will be developed to meet crop monitoring needs: by improving in-field sensors and remote monitoring, the digitisation of agriculture will be directly supported. Research infrastructure and field-based Living Labs will be expanded or created, to provide demonstration sites and testbeds across Europe. The future proofed crops will be designed to align with emerging agroecology approaches in addition to organic and conventional farming.

Key ambitions:

- The CropBooster tools and knowledge base are designed to select target genes in a more accurate and efficient way by reducing the carry-over of non-target DNA during the breeding process.
- CropBooster's improved phenotyping capacity and tools will improve and speed up screening. This should drive down crop development times that are currently estimated to be at least 7-15 years with Molecular Assisted Selection (Euroseeds and CropLife figures, see also Figure 1).
- The Program will deepen the crop science knowledge base and accelerate the development of new future-proofed (climate smart) varieties in the coming years by advancing TRLs in the primary traits to testing under relevant production systems in partnership with industry.
- The Program will deliver the blueprints for improved crops including pre-breeding materials in collaboration with the seed & plant breeding sector for use in breeding programmes.

Highlights of "The CropBooster Program"

CropBooster will steer and accelerate crop breeding, primarily by exploiting natural variation in key traits to boost important crops to deliver improved yields in the field. A multidisciplinary approach will combine state of the art 'omics and systems biology approaches with expertise in phenotyping and engineering, metabolic modelling, plant physiology and biochemistry, and plant breeding. This will deliver tools for accelerated plant breeding and deeper knowledge of target traits to optimise crop design strategies. Citizen engagement, environmental and socioeconomic analysis will be led by social scientists and agricultural economists.

To future-proof our agri-food system the CropBooster Program will collaborate with farmers, agronomists, breeders and other agri-food value-chain actors to ensure that outputs are suitable for end-use. An open consortium of partners from across EU Member States and Associated States will deliver two strategic phases:

Phase 1 (10 years):

Early work will focus on research needed to address knowledge gaps, but also to develop partnerships with industry for collaborations and to ensure the transfer of basic research and pre-breeding materials to breeding programmes for the most advanced traits. This should ensure some “Early Wins”. A strong cooperation will also be built with European programs focussing on plant pests and diseases, ensuring that relevant outcomes of such programs will feed into Phase 2, together with the main outcomes of the CropBooster Program.

Phase 2 (6+ years):

A second dedicated translational science phase will build on established partnerships with the plant breeding sector to translate the results of the core Phase 1 program into new elite breeding material. Open Science and Open Innovation cultures will allow a circulation of knowledge and ideas whilst protecting intellectual property rights and commercial interests of industry. Field testing will include diverse farming practices and assess the suitability of new crop cultivars for diverse agricultural systems (e.g., agroecology, conventional and organic) across a range of geographic and climatic zones. This should ensure that trade-offs between environmental, social and economic sustainability, are assessed in real world “living lab” settings.

Figure 3. Plant breeding pathway for crop improvement.

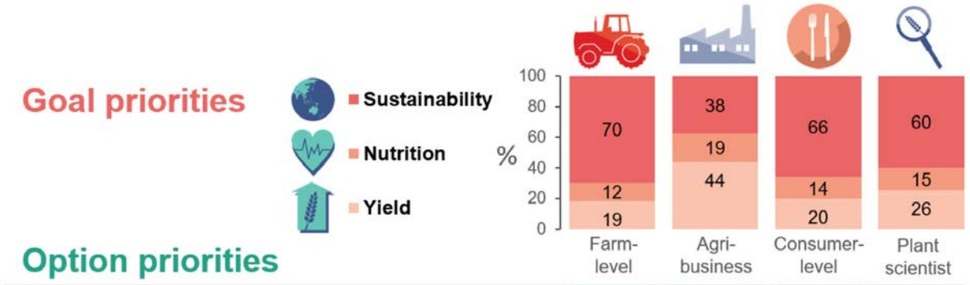
The research across both Phases will be conducted with the highest standards of ethics and integrity. Citizen engagement will be maintained throughout the programme CropBooster will embed Responsible Research & Innovation (RRI) into the activities.

Developing suitable solutions to a diverse set of food security and environmental challenges is a daunting task. The required increases in crop productivity must be accomplished while balancing the three pillars of sustainably (social, economic and environmental). Future-proofed climate-ready crops will require increased resilience to maintain productivity in the face of the negative effects of climate change especially increased frequencies of extreme temperature, drought, or salinity and other extreme events. Importantly, future-proof crops will also need to assist mitigation of the effects of climate change by enhancing below-ground carbon sequestration and contributing to improved soil health, resistance to erosion and fertility.

A sustainable increase in crop production cannot rely on further expansion of the agricultural area. The goal will be to increase resilience of crops resulting in better yield stability, and to increase overall crop yield. However, in many countries, further increases of crop yields are currently constrained because of restrictions on inputs, and land for further agriculture is limited. There are additional pressures due to limitations on the use of water, pesticides, fertilisers, and new efforts to promote agroecology and organic farming practices. Together, these pressures increase the urgency to boost plant breeding efforts as proposed in the CropBooster Program.

Stakeholder-Led Priority Setting

Exploiting advanced crop breeding and biotechnology to improve our crop varieties is a critical area for innovation to address the challenges outlined. To ensure a balanced program that is well aligned to the needs of society in a changing climate, a range of stakeholder engagement activities have been undertaken to help codesign the program alongside the experts from Europe's plant science knowledge base. Based on this broad approach the Strategic Research Agenda enlists research priorities to address these targets for improvement, forming the basis for the future Program.



Option priorities

		Farm-level	Agri-business	Consumer-level	Plant scientist
Sustainability	Improving plant water use	92	96	97	97
	Improving heat stress tolerance	90	73	94	74
	Improving nitrogen uptake and use	85	85	92	85
	Improving phosphorus uptake and use	79	85	80	85
	Improving salt stress tolerance	58	54	68	54
Yield	Improving photosynthesis	79	69	62	70
	Improving digestibility of biomass	50	38	46	39
	Use and movement of nutrients within the plant	53	65	57	66
	Altering growing season of plants	55	65	54	66
	Increasing the size of harvestable parts	41	38	42	39
Nutrition	Improving protein content and quality	64	73	69	74
	Increasing vitamin and mineral content	55	65	72	66
	Increasing antioxidant content	58	50	57	51
	Decreasing negative and toxic compounds	51	54	69	54
	Producing healthy omega-3 fatty acids in oilseeds	53	50	60	51

*Figure 4. The percentage of respondents from each stakeholder group selecting a given CropBooster option as 'important' or 'very important' is indicated in green, with darker green shading indicating a higher proportion of respondents expressing a preference for a given option. *Farm-level: farmers, farmer representatives, NGOs and policy makers working on agri-environmental issues; consumer-level: consumer experts and consumers (survey only); agribusiness: plant breeders, seed companies, supply chain experts, wider agribusiness stakeholders (survey only); plant scientists (survey only).*

Crop Booster-P adopted a Co-Designed approach: Desk-studies, foresight work, rapid evidence reviews, and a dedicated stakeholder-led approach explored the social, environmental, and economic impacts that the different options to improve crop varieties may achieve. Experts from the farm-level, through to crop breeding value-chain businesses, and citizens as consumers, were consulted to help prioritise the most important goals of new crop breeding and the traits needed for future-proofing new crops (Figure 4). The impacts of adopting different breeding methods were also considered. These findings were then implemented into the plant trait selection process and Roadmap development.

Research Priorities and Action Points:

Yield

Increasing yield and yield stability is currently the primary goal for many crop breeding programmes and will continue to be a priority for the plant breeding sector and the growers who must sustain production in a changing climate.

Given the challenges of a changing climate, yield stability to sustain production, rather than just the further improvement in yields, will be included in the research efforts.

Action Points for Yield

- **Advance mechanistic understanding of the key factors contributing to or limiting yield and use that knowledge for "Breeding-by-Function".**
- **Yield stability. Farmers need crops to at least maintain yields in a changing climate.**
- **Set up common and shared pools of genetic material of current crops and their wild ancestors and use that material for constructing common and shared segregating populations for allowing an easy introduction of major QTLs. Expand the availability of current resources.**
- **Exploit underutilised crops with promising traits, particularly neglected traits related to resistance to stresses or quality that have not been exploited when breeding for higher yields.**
- **Set up shared experimental stations and Living Labs equipped with state-of-the-art tools for phenotyping the relevant traits and allow field testing of improved crops.**

Nutritional Quality

Healthy diets are a key goal of the EU's Green Deal which adds challenges to crop breeding programmes. Improvements in crops must include maintaining and ideally improving the nutritional quality of plant-based foods.

Action Points for Nutritional Quality

- **Increase protein, nutrient, yield, and quality per area of agricultural land used.**
- **Focus on how global climate change impacts the micronutrient and vitamin content of plant-based foods.**
- **Understand the mechanistic interrelationship between yield and resource-use efficiency, and content and composition of essential nutrients in crops, then transfer this know-how to plant breeding and agricultural practices.**

Sustainability

The sustainability of agriculture is a high priority. Ecosystem services should be amplified, including carbon sequestration and nitrogen fixation and the alignment with sustainable farming practices.

At the same time, the strong interconnections between the individual traits and their impact on yield potential and yield stability will be elaborated. This leads to the following action points for future research.

Action Points for Sustainability

- **Exploitation of natural diversity in the adaptation of plants to varying resource availability (water, macro- and micro-nutrients), and abiotic/biotic stresses; in this context the exploitation of genetic variability existing and accessible in gene bank collections should be supported and strengthened.**
- **Further development of tools for precision phenotyping, especially under conditions of practical agricultural plant production, also allowing the analysis of root development and function. and including the synthesis of metabolites of importance for ecosystem services, food quality and plant protection.**
- **Investigating the impact of soil parameters on plant performance, with a focus on understanding functional processes regulating the interaction of plants with their soil environment.**
- **Test/development of agricultural practices for using crops for carbon sequestration and identifying features of plants that need to be optimized to improve the efficiency of such processes.**

CropBooster Program Recommendations: Key Target Traits to address the priority action points.

The following traits have been selected for their potential to drive future improvements in plant yield, and have the potential to support the shift towards future-proofed crops. The next step will be to refine the Research Agenda to allocate resources and timescales to take CropBooster forwards, to successfully improve the following traits.

Resource use efficiency and resilience to stress

- Traits that improve resource use efficiency and resilience to stress eg. Water Use Efficiency, temperature stress, and stomatal traits.
- Canopy and root architecture traits, improving resistance to stresses including drought stress, Nitrogen Use Efficiency, and the plant's biochemical capacity to use the nutrients.
- Sub-traits involving secondary metabolites induced as protective compounds after the onset of abiotic or biotic stress conditions, or in response to priming to stress conditions.

Energy Use Efficiency - Photosynthesis

- The process driving plant productivity and a major tool that can control and mitigate climate change. There are multiple promising traits to address including important enzyme pathways (e.g. Calvin Benson Cycle, photorespiration), chlorophyll tuning and adapting to changing light.

Architecture at canopy and root system level

- Important for plant structure affecting limitations of productivity, for example light interception in spatially and temporally dynamic (fluctuating) environments, or the take up of water and nutrients.

Quality traits

- Traits include the protein value of food given the necessity to replace animal proteins.
- The amount and quality of secondary metabolites with beneficial dietary properties e.g. strong antioxidant properties, vitamins and micronutrients, preserving cellular integrity and contributing to fight inflammatory responses.

Biomass traits

- Increasing yields and quality of specific molecules of industrial importance e.g. bio-renewables.
- Improving the recycling capacity for agricultural and food wastes by adjusting plant qualities.

Primary Target Crop Species

Together with stakeholders from the breeding sector, an initial short list of target crops for future research has been proposed (Figure 5). The intention of making this selection was to develop a broad-based toolkit for trait improvement using diverse crop "models". Additional crops may be added, for example Blue Economy crops including seaweeds and microalgae.

C3 cereals	Wheat Barley
C4 cereals	Maize Sorghum
Root Crops including	Sugar Beet Potato
Horticultural Crops	Tomato, Lettuce, Brassica, Onion, Apple
Silvicultural crops	Poplar
Oilseed Crops	Sunflower Oilseed Rape
Nitrogen fixers	Pea, Bean, Soybean, Lupin, Clover, Vetch, Alfalfa

Figure 5. An overview of the short-listed crop types.

Communicating and engaging with Society

Citizen engagement activities have been developed including strategies to share complex scientific information effectively with the general public, and social actors. The future crop improvement program needs the support of society at large. Strategic decisions will need to be made about the use of landscapes, business models for farming, prices of food and acceptance of novel technologies to combine the advantages of the available approaches in crop improvement and management. In order to ensure that decisions are made with broad societal support, Citizen Engagement activities will confirm that the likely consequences of available options for crop improvement meet societal expectations.

Call to Action: CropBooster – A Partnership for Future-Proofed Crops

A European Partnership on Future-Proofed Crops within the Horizon Europe programme would provide an excellent platform to reduce current fragmentation in plant sciences and breeding, and would coordinate contributions from private and public partners to deliver the "blueprints" for improved crop plants. The proposed Partnership should align efforts from the EU, associated states and interested third countries to accelerate the translation of the knowledge base within the European Research Area and direct new research to address specific knowledge gaps. The proposed approach has the potential to transform how plant science delivers innovations that meet the growing need for better and more resilient crops. CropBooster fills an important strategic gap in the current Partnership strategy for food, bioeconomy, natural resources, agriculture, and environment. A review of current initiatives and the proposed new Partnerships highlights that crop plants are fundamental to this area. There is also an urgent need to develop improved crops to support the transition to more sustainable food systems, while facing the challenges of a changing climate, contributing to the growing bioeconomy, and the food and resource needs of a growing population. Our proposed Partnership "Future Proofed Crops" is designed to work in close cooperation with these initiatives and the Soil Health Mission (see Figure 6), to complement activities and develop synergies. Crop science advances have been significant in recent years, and translation of this knowledge and resource base into new future-proofed crops offers powerful potential solutions, to help address the priority issues raised around soil quality, agricultural production systems and food waste. Further developments will be closely coordinated with the leadership teams of the other Partnerships to avoid duplication in efforts, build synergies and ensure joint working on Living Labs to be multidisciplinary.

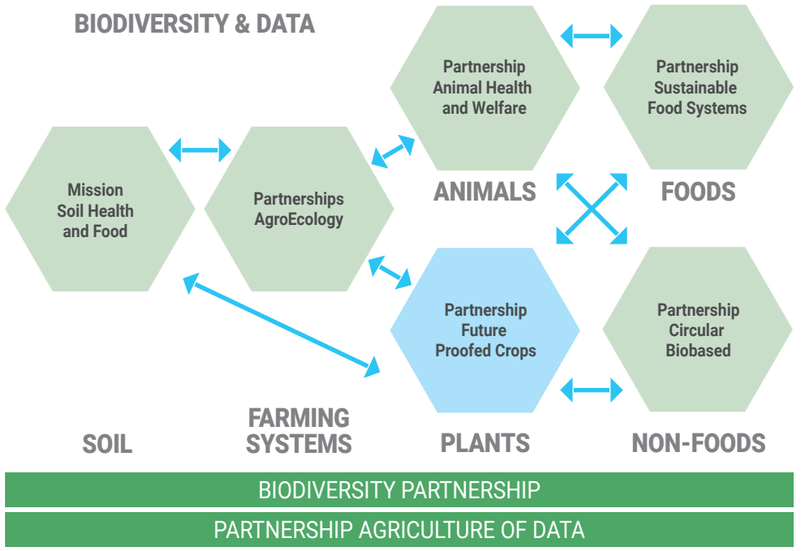


Figure 6. Strategic Positioning of the Partnership for Future-Proofed Crops within the food, bioeconomy, natural resources, agriculture and environment sector.

Governance

An initial Partnership Governance structure and core consortium is proposed. This will be refined as discussions on the proposed CropBooster programme and Partnership advance. Stakeholders will be represented and strongly encouraged to engage with the strategy development and implementation to ensure the needs of the value chain are prioritised.

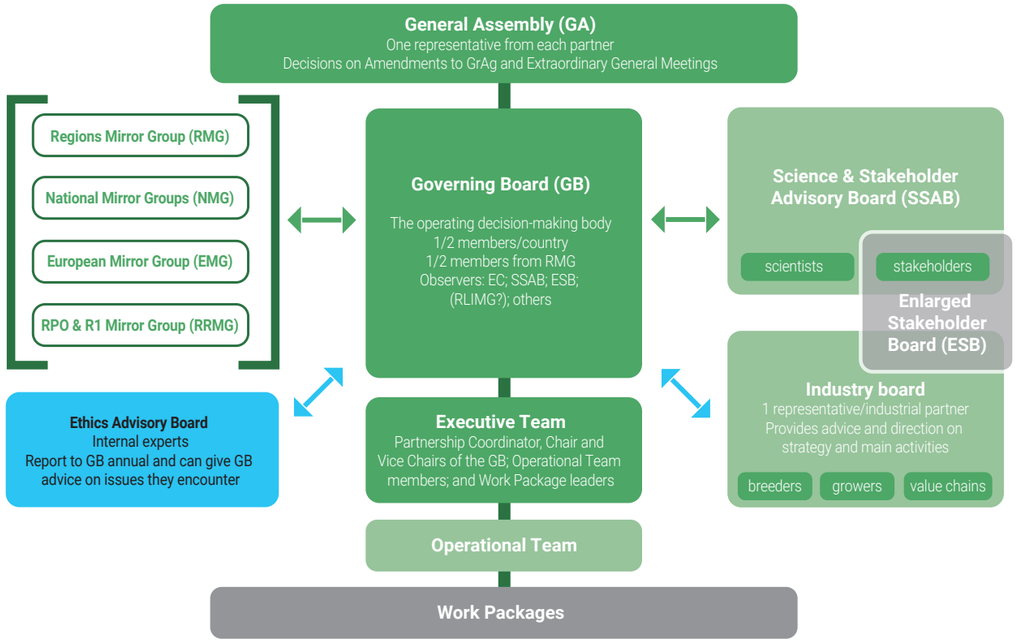


Figure 7. A proposed governance structure showing the multiple levels of stakeholder engagement.

The CropBooster Program will deliver the first Europe-wide Crop Development Programme to coordinate Research and Innovation initiatives. This will be stakeholder-led to co-develop breeding strategies with broad societal support for urgently needed “future-proofed” crop varieties.

The CropBooster-P coordinator has established an open consultation process to progress the “Future Proofed Plants” programme. Stakeholder engagement work with the Crop Breeding value chain is on-going. We invite interested parties to contribute. For further information please contact:

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The CropBooster Program was developed in the CropBooster-P project (EC Grant Agreement 817690) with additional contributions from academic and industry experts, the agricultural value chain, citizens and societal actors. This is a summary of the detailed CropBooster-P Strategic Research Agenda (Deliverable 5.6) and the White Paper (Deliverable 5.7). These documents can be accessed on-line using the QR code.

www.cropbooster-p.eu