31 March 2023

ERA-NET Cofund on Sustainable Crop Production

Assessment of the Potential Impact of Projects under the Co-funded Call

Expert Evaluation Committee Report

- Public version -

www.suscrop.eu

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 771134.

Table of Contents

1. Executive Summary

- **Thirteen projects** were funded in this first call for SusCrop projects. All projects contributed to the **sustainability core theme of the FACCE-JPI** Strategic Research Agendas published in 2016 and 2020, and some to multiple core themes.
- Many of the multidisciplinary projects addressed more than one of the four objectives of the call. Most targeted annual crops but two focused on aspects of perennial weeds.
- The conduct of all projects was affected by the **COVID-19 pandemic**. There were multiple impacts including delayed starts to experimental work, delayed and/or postponed field studies, cancelled project meetings and multiple challenges to dissemination efforts. Despite this, most projects came close to realizing their aim and objectives and delivered agreed outputs and outcomes.
- **Breeding for sustainable production** was a focus for the majority of projects with outputs that included new breeding techniques, identification of markers and specific genes controlling phenotypic traits, and pre-breeding and delivery of commercially viable varieties.
- Many projects sought to develop **new methods and practices for integrated pest and crop management** in response to diseases, pests, weeds and abiotic stresses and to improve nutrient use efficiency. While some breeding projects contributed to this, other approaches including tillage, variety choice, and studies of soil microbe interactions including mutualistic symbioses were employed.
- Projects focusing on **crops as part of an ecosystem were less numerous** although many projects contributed indirectly to this objective.
- **Academic impact** was high with 97 published articles at the time of reporting and 203 planned. Over half of the refereed outputs were published in high impact journals. Overall, there was **high visibility** of outputs in the national and international academic and scientific community through over 40 scientific conferences and other scientific dissemination activities.
- **Technological advances** included the development of new breeding methodologies, identification of loci and genes for desirable traits, release of novel genetic material to other researchers and commercial breeders, together with models and improved management practices to deliver increased sustainability of crop production on farm.
- **Valorisation** was evident in the registration of new crop varieties, the adoption by some commercial stakeholders of model outputs and novel genetic materials in their breeding programmes, and the dissemination of many improved pest and crop management practices in farmer meetings. Serendipity also played a role in providing two outcomes of research that might find commercial application.
- A **perceived gap** in several projects was the lack of detail in both the planning stage and the final report of means of taking any outcomes to a **commercial market**. The absence of awareness of limitations to the exploitation of intellectual property and freedom to operate were also evident.

Overall, these projects have made a sound contribution to the core themes of FACCE-JPI and the SusCrop co-funded call.

2. Introduction

On **17 January 2018**, the Cofund on Sustainable Crop Production (SusCrop) launched its first call. The call aimed to support scientifically excellent transnational research, development, and innovation projects that contribute to improving the sustainability and resilience of crop production.

To deliver this aim, the call invited projects that furthered **four objectives**. The titles of the call objectives were specified as:

I	Enhancement of predictive breeding technologies and the development of new genotypes leading to new phenotypes and crop varieties for improving plant health, protection, production, and resilience
II	Development and exploitation of novel integrated pest and crop management methods and practices
III	Improvement of resource-use efficiency of crops and cropping systems
IV	Systemic research on agricultural crops as part of an ecosystem, including interactions between plants and other organisms ("the plant as a meta-organism")

After peer review, ranking of the full proposals by the same evaluation panel and recommendation to the Call Steering Committee, **13 projects** (listed in alphabetical order) were approved for funding over the period 01 January 2019 until 31 December 2022:

AC/DC-weeds	Applying and Combining Disturbance and Competition for agro-ecological management of creeping perennial weeds
BARISTA	Advanced tools for breeding BARley for Intensive and SusTainable agriculture under climate change scenarios
DIFFUGAT	Diploid Inbreds For Fixation, and Unreduced GAmetes for Tetraploidy – A novel Fixation-Restitution Breeding method for potato
LegumeGap	Increasing productivity and sustainability of European plant protein production by closing the grain legume yield gap
NETFIB	Valorization of fibers from nettle grown on marginal lands in an agro-forestry cropping system
potatoMETAbiome	Harnessing the potato-microbiome interactions for the development of sustainable breeding and production strategies
ProFaba	Developing improved *Vicia faba* breeding practices and varieties to drive domestic protein production in the European Union
PROSTRIG	Delivering novel maize genotypes with improved resilience and PROductivity through the application of predictive breeding technologies to modulate STRIGolactone levels
ROOT	Resilience to salinity in tomato
RYE-SUS	Development of lodging-resistant and climate-smart rye – a contribution to sustainable cereal production in marginal environments
SOLNUE	Tomato and eggplant nitrogen utilization efficiency in Mediterranean environments
SUSCAP	Developing resilience and tolerance of crop resource use efficiency to climate change and air pollution
WheatSustain	Knowledge-driven genomic predictions for sustainable disease resistance in wheat

3. FACCE-JPI Strategic Research Agenda

The core themes of the FACCE-JPI strategic research agenda (SRA) changed during the course of the SusCrop programme.

At the launch, the SRA-2016 core themes were:

1. Sustainable food security under climate change
2. Environmentally sustainable intensification of agricultural systems
3. Developing synergies and reducing trade-offs between food supply, biodiversity and ecosystem services
4. Adaptation to climate change
5. Mitigation of climate change

In 2020, the new core themes of the SRA-2020 were:

1. An agricultural sector that contributes to climate neutrality
2. Sustainable and resilient agriculture
3. Nutrition-sensitive agricultural production for food security
4. Trade-offs and synergies between food production, ecosystems and climate

Table 1: The contributions of SusCrop projects to the FACCE-JPI SRA core themes

	SRA-2016 core themes					SRA-2020 core themes			
	1	2	3	4	5	1	2	3	4
	Sust. food security under climate change	Environm. sust. intensification of agric. systems	Synergies & trade-offs betw. food supply, biodiversity & ecosystem services	Adaptation to climate change	Mitigation of climate change	Agric. sector that contributes to climate neutrality	Sust. and resilient agric.	Nutrition-sensitive agric. production for food security	Trade-offs & synergies betw. food product, ecosystems and climate
AC/DC-weeds		x					x		
BARISTA	x	x		x			x		x
DIFFUGAT		x	x				x		
LegumeGap	x	x		x			x	x	x
NETFIB		x					x		
Potato METAbiome		x	x				x		
ProFaba	x	x		x	x	x	x		
PROSTRIG		x			x		x	x	
ROOT		x					x		
RYESUS		x	x		x		x	x	x
SOLNUE		x					x		
SUSCAP	x	x		x			x		
WheatSustain	x	x	x	x	x		x	x	x

The call was launched under the SRA-2016. In this report, we have evaluated the extent to which the core themes (CTs) of the SRA-2016 and SRA-2020 were addressed (Table 1). **All financed projects contributed** to the **SRA-2016 CT2**, 'Environmentally sustainable intensification of agricultural systems', and to the **SRA-2020 CT2**, 'Sustainable and resilient agriculture', although emphasis on the aspect of intensification varied among the projects. Some had their focus on sustainable production under challenging conditions rather than increased production under current conditions. For the SRA-

2016, all core themes were addressed by at least four projects. One of the core themes of the SRA-2020 (CT1, ‘An agricultural sector contributing to climate neutrality’) was addressed by only one project (ProFaba).

Within CT2 of both SRA-2016 and SRA-2020, the projects **addressed a broad range of sustainability challenges** and how they can be dealt with. This included possibilities for reduced pesticide input through development and use of well-adapted crop cultivars with good ability to compete with weeds and resist pests and pathogens (AC/DC-weeds, BARISTA, DIFFUGAT) and better water- and nutrient-use efficiency (LegumeGap, potatoMETAbiome, PROSTRIG, RYE-SUS, SOLNUE, WheatSustain). The latter also partly include SRA-2020 CT3 (‘Nutrition sensitive agricultural production for food security’). Some projects also addressed the possibilities of **preserving and/or stimulating plant- or soil associated biodiversity**, including organisms providing important ecosystem services. Strategies included specific actions such as choice of a suitable cultivar or microbial inoculants, as well as **system approaches** with integrated strategies (potatoMETAbiome, PROSTRIG). These projects also addressed CT3 of SRA-2016.

Core themes 1 and 4 of SRA-2016 (‘Sustainable food security under climate change’ and ‘Adaptation to climate change’) were addressed in projects with major research on **drought effects** (SUSCAP, WheatSustain), **temperature** (LegumeGap), and expected **secondary effects of climate change** such as an increase in pests and diseases (BARISTA, WheatSustain). Simulation models were used to predict the performance of cultivars under expected future climate scenarios (BARISTA, ProFaba). In addition to this, some of the projects addressed challenges to produce food or fibre under other types of changes in the environmental conditions, such as **air pollution** (SUSCAP) or **contaminated soils** (NETFIB, ROOT).

4. Objectives and Overviews of Projects

The 13 multidisciplinary projects targeted mainly annual crops except two that involved perennial weeds (AC/DC-weeds) and stinging nettle (NETFIB). Many of the projects addressed multiple call objectives. Table 2 shows the main topics of the SusCrop call objectives addressed, as mentioned in the final report of each project.

Table 2: Call objectives and target crops of projects; Contribution by projects to the different call objectives is listed as stated in the end-term reports.

Projects	Crop	I	II	III	IV
AC/DC-weeds	Perennial weeds		√		
BARISTA	Barley	√			
DIFFUGAT	Potato	√			
LegumeGap	Soybean and Faba bean			√	√
NETFIB	Nettle (*Urtica dioica*)			√	
potatoMETAbiome	Potato	√	√	√	√
ProFaba	Faba bean	√	√		√
PROSTRIG	Maize	√			√
ROOT	Tomato	√	√		√
RYE-SUS	Rye	√	√	√	
SOLNUE	Tomato and Eggplant			√	
SUSCAP	Wheat	√		√	
WheatSustain	Wheat	√			
Total	13	9	5	6	5

4.1 Objective I) Enhancement of predictive breeding technologies and development of new genotypes leading to new phenotypes and crop varieties for improvement of plant health, protection, production and resilience

Table 3 shows the main types of outcome delivered by projects in which enhancement of predictive breeding technologies was a major objective.

Table 3: Main types of outcome delivered by projects addressing objective I; dark green: significant contribution by project as stated in the project reports; light green: intermediate contribution by project as assessed during this evaluation

Projects	Enhancement of predictive breeding technologies	Development of new genotypes / new phenotypes / crop varieties		
		Improvement of plant health and protection	Improvement of production	Improvement of resilience
AC/DC-weeds				
BARISTA	√	√	√	√
DIFFUGAT	√	√	√	√
LegumeGap				
NETFIB	√			√
potatoMETAbiome	√	√	√	√
ProFaba	√	√	√	√
PROSTRIG	√		√	√
ROOT	√		√	√
RYE-SUS	√	√	√	√
SOLNUE	√		√	√
SUSCAP	√			
WheatSustain	√	√	√	√
Total	11	6	9	10

Results from 11 projects shown in Table 3 include breeding approaches to enhance predictive breeding technologies and have the potential to develop new genotypes, phenotypes, and crop varieties that are more resilient to biotic and abiotic stress.

The project *BARISTA* aimed to develop **new barley varieties** adapted to climate change in a wide range of European environments. It developed a new crop simulation model providing the necessary information for marker-assisted selection of new barley varieties. The model was used to identify novel loci controlling culm diameter, a trait correlated with lodging resistance, and also targeted traits including flowering time, disease resistance, and ABA-related genes for water use efficiency and drought resistance. *DIFFUGAT* contributed to developing **improved potato varieties resistant to pests and parasites**. Within the project, the partnership developed all the components required to be used in fixation-restitution breeding, which provide many of the benefits of diploid hybrid breeding; this is of particular interest to small and medium-sized (SME) potato breeding companies. The project successfully developed molecular markers for self-compatibility that can routinely be used in breeding and identified marker systems to monitor the genomic composition of breeding lines. Once thoroughly tested, the system has the potential to enhance potato breeding and develop varieties with tolerance to different abiotic and biotic stresses. The contribution of *NETFIB* to this objective was marginal, as expected, even if some nettle clones were identified for tolerance to heavy metal concentration (Zn) and drought.

potatoMETAbiome used a step-down selection process through their interactions with beneficial **microorganisms or microbiomes** and identified 50 potato genotypes with a wide range of microbiome interactive traits such as quality and quantity of root exudates. These were further studied for their ability to select soil bacteria and fungi. The results achieved by *ProFaba* will substantially contribute to **faba bean breeding strategies**. It contributed to the development of grain legume improvement by genotyping 2,700 accessions and facilitated high-confidence trait-marker associations for use in future breeding programs. The project also identified pest-, acid-, and frost-tolerant faba bean germplasm and a set of highly competitive and efficient rhizobium strains. *PROSTRIG* focussed on **maize** improvement using genome editing, targeting higher productivity and improved **nutrient efficiency**. This was undertaken through modulation of the hormone strigolactone, which alters root architecture. The target sites were identified, and improved maize lines will be generated with potential for reduced fertiliser applications.

The project *ROOT* identified key regulating genes in tomato roots and quantitative trait loci (QTL) and markers that are predictive for adaptive root architectures and resilience to **salt stress in tomatoes**. It also tried to identify the mode of action of biostimulants for crop yield under saline conditions. *RYE-SUS* developed gibberellin-sensitive semi-dwarf **rye** genotypes with optimized harvest index using a novel breeding model, improved **lodging resistance**, yield potential, drought tolerance, and minimized risk of ergot infestation. In the *SOLNUE* project, a range of studies identified QTL for **nitrogen use efficiency (NUE)** in genotypes of **tomato and eggplant**. Contrasting genotypes were grown with different forms and quantities of nitrogen, and genes and genomic regions were identified for N-uptake and assimilation. Introgression and backcrossing allowed the development of novel pre-breeding lines. The results of the *SUSCAP* can be used for future breeding programs, but breeding was not included in the current project. The project *WheatSustain* made notable innovations in disease resistance breeding against two common **wheat diseases** and improved crop production sustainability and resilience**.**

4.2 Objective II) Development and exploitation of novel integrated pest and crop management methods and practices

Table 4: Main types of outcome delivered by projects addressing objective II; IPM= integrated pest management, ICM= integrated crop management; dark orange: significant contribution by project as stated in the project reports; light orange: intermediate contribution by project as assessed during this evaluation

Projects	Novel IPM and ICM methods and practices			
	Disease Resistance	Pest Resistance	Weed control	Resistance to abiotic stress
AC/DC-weeds	√	√	√	
BARISTA	√			√
DIFFUGAT	√	√		√
LegumeGap			√	√
NETFIB	√		√	√
potatoMETAbiome	√			√
ProFaba	√	√		√
PROSTRIG				√
ROOT				√
RYE-SUS	√			√
SOLNUE	√			√
SUSCAP				√
WheatSustain	√			
Total	9	3	3	11

Table 4 shows the main types of outcome delivered by projects in which development and exploitation of novel pest and crop management practices was a major objective.

Results from all 13 funded projects contributed to the development of novel IPM and ICM methods and practices in a variety of ways.

AC/DC-weeds project investigated use of **reduced tillage** by farmers and thus reduced the use of non-renewable energy. It developed new methods to suppress weeds and increase soil organic matter, which is essential for healthy soil. The project implemented **better agroecological management** for creeping perennials in arable farming by reducing plough-tillage in organic and conventional agriculture and replacing glyphosate use. *BARISTA* identified loci underlying important traits such as controlling culm diameter, meaning that **barley** varieties have **better lodging resistance**. The project also developed barley varieties with disease resistance against multiple pathogens leading to more robust **climate adaptation**. *DIFFUGAT* developed an improved system for breeding **potatoes**, enabling beneficial traits to be combined in new varieties that previously could not be achieved. This includes rapidly combining disease and pest resistance genes into high-performing genotypes thereby boosting **integrated pest management strategies**. *LegumeGap* developed alternative crop models to predict how crops will yield in **different growing conditions** with emphasis on a mid-season water deficit and weed suppression. Disease and pest control were not the main focus of the *NETFIB* project but some aspects were addressed by characterising the specific rhizosphere microbial communities of nettle and identifying fungal endophytic isolates promoting growth with evidence of antagonism against a major root pathogen.

potatoMETAbiome contributed with new knowledge on how combinations of cultivar choice, use of microbial products, and fertilisation can be used in integrated crop management. The project showed that the selection of cultivars supporting beneficial microbiomes is essential in developing more sustainable cropping systems. It characterised a large number of bacterial consortia that can **improve potato pest and disease resistance**. *ProFaba* contributed to IPM and ICM strategies by identifying new **insect-resistant genotypes of faba bean**. The project developed new methods for faba bean breeding for plant disease resistance and identified accessions and rhizobium tolerant of acidic conditions under abiotic stress that can increase productivity. *PROSTRIG* utilised novel genome editing tools to modulate the strigolactone content and composition for maize improvement. The project has the potential to alter the maize root architecture encouraging stimulation of hyphal branching of mycorrhizae and improving uptake of N and P thus improving resilience and productivity.

The *ROOT* project developed new methods for more sustainable agriculture by providing possibilities for **reduced use of chemical fertilisers** by partially replacement with biostimulants or more resilient crops. *RYE-SUS* developed and modelled gibberellin-sensitive semi-dwarf **rye genotypes** with optimized harvest index, improved lodging resistance, high yield potential, drought tolerance, and minimized risk of ergot infestation for sustainable intensification. Although disease control was not a major objective of the *SOLNUE* project, an interesting observation resulted from an experiment in which different forms of **nitrogen fertiliser were applied to eggplant**. The form of nitrogen affected the response of eggplant to Fusarium infection, providing novel information that might reduce pesticide application and lead to more sustainable agriculture. *WheatSustain* contributed to genomic prediction methodologies for **resistance against diseases**.

4.3 Objective III) Improvement of resource-use efficiency of crops and cropping systems

Table 5 shows the main types of outcome delivered by projects in which improvement of resource-use efficiency was a major objective.

Table 5: Main types of outcome delivered by projects addressing objective III; dark blue: significant contribution by project as stated in the project reports; light blue: intermediate contribution by project as assessed during this evaluation

	Resource-use efficiency			
Projects	**Fertiliser use efficiency**	**Pesticides use efficiency**	**Water use efficiency**	**Improvement of cropping systems**
AC/DC-weeds		√		√
BARISTA	√	√	√	
DIFFUGAT	√	√	√	
LegumeGap	√		√	√
NETFIB	√	√	√	√
potatoMETAbiome	√	√	√	
ProFaba	√	√		
PROSTRIG	√			
ROOT	√			
RYE-SUS	√		√	
SOLNUE	√	√		
SUSCAP	√		√	√
WheatSustain		√		
Total	11	8	7	4

The 13 funded projects were located in different agro-climatic regions, involved different crops/cropping systems and different cultivation systems. 11 of the projects aimed to improve fertiliser use efficiency, eight to reduce pesticide use, seven to improve water use efficiency or drought tolerance, and four to improve cropping systems (Table 5).

Outcomes from *AC/DC-weeds* help to reduce the use and reliance on pesticides by developing new methods to suppress perennial weeds thereby allowing farmers to **reduce tillage and the use of non-renewable energies.** *BARISTA* identified loci for several valuable traits including lines carrying multiple disease resistance genes and enhanced water use efficiency. These will **reduce agrochemical inputs in barley cropping systems.** The *DIFFUGAT* project developed a novel breeding method for potatoes to manage potentially favourable traits, such as stacked pest and disease resistance to multiple biotic stresses. Together these have potential to **reduce use of agrochemicals**. The project *LegumeGap* developed a crop model to predict how legume crops yields in different conditions including appropriate rhizobium inoculation and under conditions of a mid-season water deficit. Together these affect **fertiliser use efficiency**. One of the main hypotheses of the *NETFIB* project was that nettle was a promising crop for producing high-quality fibre in marginal or polluted land and generating some **circular economy**, both from the production cycle or from the recycling of waste (e.g. animal effluents). The field experiments failed to substantiate this idea in a poplar/nettle agroforestry cropping system but for the outcomes did contribute to understanding the potential for significant sustainability gains from the NETFIB approach.

potatoMETAbiome included suggestions for improved resource-use efficiency through cultivar choice in combination with the use of biological products stimulating **nutrient cycling**. *ProFaba* contributed to this call objective through the knowledge developed in trait-marker associations (e.g. bruchid resistance, acid soil tolerance, frost tolerance). New Rhizobium strains matching plant genotypes to soil types were identified. *PROSTRIG* aimed to improve N and P use efficiency by modulating the strigolactone, but evidence such improvement has yet to be produced. In *ROOT*, identification of Quantitative Trait Loci (QTL) and markers for root adaptability to salt stress may **improve tomatoes' resilience** in the long term. Applying effective biostimulants and understanding their mechanism of action also may help improve water use efficiency.

RYE-SUS developed semi-dwarf rye hybrids to make more grain of better quality on limited arable land without increasing **water and fertiliser use**. The genetic **lodging resistance** of semi-dwarf rye may enable farmers to explore higher planting densities and remove the need to spray conventional varieties with plant growth regulators. *SOLNUE* identified QTL in genotypes of **tomato and eggplant for nitrogen use efficiency (NUE)**. Genotypes grown with different forms and quantities of nitrogen allowed identification of genes and genomic regions regulating N-uptake and assimilation. *SUSCAP* developed a new generation of process-based crop models to assess resource use efficiency, growth, and yield under **air pollution and climate variability stress.** *WheatSustain* provided a durable disease-resistance solution for wheat that utilises resistant cultivars to reduce the need for **fungicide applications** and the risk of mycotoxins in the grains.

4.4 Objective IV) Systemic research on agricultural crops as part of an ecosystem including interactions between plants and other organisms ("the plant as a meta-organism")

Table 6 shows the main types of outcomes delivered by projects in which systemic research on crops as part of an ecosystem was a primary objective.

Table 6: Main types of outcome delivered by projects addressing objective IV; dark purple: significant contribution by project as stated in the project reports; light purple: intermediate contribution by project as assessed during this evaluation

Projects	Weed-plant Interactions	Plant-pest interactions	Plant-pathogen interactions	Plant-microbe symbiotic interactions	Agroecological management decisions
AC/DC-weeds	√	√			√
BARISTA			√		
DIFFUGAT		√	√		
LegumeGap	√			√	√
NETFIB			√	√	
potatoMETAbiome			√	√	
ProFaba		√	√	√	
PROSTRIG				√	
ROOT				√	√
RYE-SUS			√		
SOLNUE			√		
SUSCAP					√
WheatSustain			√		
Total	2	3	8	6	4

AC/DC-weeds helps **arable farming systems** become more resilient when managed with fewer external inputs and supports agroecological management decisions. *BARISTA* developed crop models that predict how barley will perform under different environmental and climatic conditions and identified 1 to 4 quantitative resistance loci against the primary **barley pathogens**. The project also provided new populations and targeted introgression lines for carrying specific loci/alleles relevant to climate change adaptation of barley cropping systems and the evaluation and calibration of different crop simulation models for crop disease response. *DIFFUGAT* developed a novel breeding system that contributes to improving potato agronomic performance in diverse ecosystems focusing on improving the genetic **resistance of potato** crops to **pests and diseases** with a plant breeding perspective. The main focus of *LegumeGap* was to determine ways to improve the performance of legume crops within a production system dominated by cereals. An interesting finding was that inoculation with rhizobium generally increased soybean yields but not faba bean and that rhizobium isolated from fields after a soybean crop was more effective in subsequent soybean crops than inoculum from commercial sources. The modelling activities of the project, coupled with the field data obtained, mean that the soybean model can now be used to ask questions about how changes to management practices and climate might affect **soybean yields and production**. Optimal management practice also has the potential to reduce weed biomass in soybean. The *Cirsium arvense* model in *NETFIB* relies on the IPSIM platform as a choice for selecting the explanation of the injury profile of the pest or pests. In the NETFIB project, the field tests on the nettle cropping systems mostly failed, showing that the cultivation of this crop in an agroforestry system in marginal land is highly problematic. The interactions between **plant and rhizosphere microorganisms** were successfully characterised, and this is one of the main and novel achievements of the project. The NETFIB proved that the root fungal endophytic species of nettle harbour plant growth promotion (PGP) traits and also show antagonistic activity against Phomopsis sp., a significant root pathogen of nettle.

The main interest of *potatoMETAbiome* was on interactions between **potato crops and their associated microorganisms**. A systems approach was used to identify the best practices regarding cultivar choice with or without mineral fertilisation, chemical crop protection, and microbial inoculants. *ProFaba* produced substantial new knowledge on the rhizobium-plant symbiosis by testing several Rhizobia strains able to improve the overall sustainability of the faba bean cropping system under unfavourable conditions. The systems perspective of the project did neither include ecosystem-scale dynamics nor the complexities associated with the policy implications for enhancing **faba bean** cultivation in the EU. However, it effectively contributed to **boosting plant breeding programs** that may ultimately result in expanding this crop into new areas. ProFaba identified pest-, acid-, and frost-tolerant faba bean germplasm. New methods have been developed for screening for disease resistance, and a significant effort to identify insect-resistant genotypes and determine genetic mechanisms has been undertake. *PROSTRIG* focused on optimising the performance of **maize** by improving the symbiosis with **mycorrhizae**, which influence crop nutrition and N and P inputs. However, the difficulties encountered in implementing this project did not produce results that can yet be put into practice.

ROOT produced results that can support **agroecological management decisions**. The identified Quantitative Trait Loci (QTL) in genotypes of eggplant for nitrogen use efficiency (NUE) resulted in a significant reduction of *Fusarium oxysporum* f.sp. *melongenae* symptoms in eggplants supplied with NO- compared to NH+ in the *SOLNUE* project. *SUSCAP* has developed a new generation of process-based crop models to incorporate such ozone-induced changes in photosynthesis and senescence and estimate impacts on biomass and yield. *RYE-SUS* resulted in new semi-dwarf rye hybrids with strong lodging resistance and high yield potential, and promoted sustainable grain production for food and feed by **minimizing the risk of ergot**. The accelerated plant-breeding model implemented by *WheatSustain* has substantial potential for new cereal cultivars with increased productivity and enhanced **disease tolerance/resistance** for the agricultural sector in the future.

5. Academic Impact of Projects

Overall, **97 partners** were involved in the 13 projects, ranging from 4 to 13 partners each, for a total funding from SusCrop of some 16 Mio Euro. Within the consortia, mainly universities or research organisations focused on the achievement of academic impact, whereas private partners often had a greater interest in valorising the outputs. It is well known that, particularly for those projects relying on field experiments, most of the publications can be expected far beyond the end of the projects. Hence a more thorough evaluation of the academic impact achieved should be expected some two years after the end of the projects which, in most cases means that a further evaluation should be made at the end of 2024 / early 2025.

Of the **publications** produced (some **200 products**) by the 13 projects, less than 50% were published by the date of the report submission. About 50% of these published papers appear in **high impact journals** (Q1 on Scimago), which is a proxy indicator of the quality of the research outcomes. The majority of the publications have acknowledged the funding of SusCrop. On average, each of the 13 projects produced 5.1 (min 0 max 9) published articles in Q1 journals and 15.6 (min 2 max 58) total publications (including abstracts and conference proceedings) per project. The **involvement of partners** was also very variable: on average, some 2.3 partners were involved in each publication. The great majority of the publications were **open access** (within these 54% were gold OA) and involved a number of researchers from other **countries in the EU or outside**, not involved in the SusCrop programme. In total, the 13 projects also contributed about **180 oral presentations** including 39 invited speakers or keynotes, and 62 posters to **international or national conferences**.

Overall, the data show a **high** (and sometime very high) **academic impact**, resulting from a robust number of high-impact publications and high visibility of the outcomes in the international academic and scientific community through scientific conferences and other scientific dissemination activities. Given the constraints to mobility generated by the pandemic, these results are impressive.

One very successful project in terms of overall academic impact was *BARISTA*, conducted by a well-established partnership that had fruitfully collaborated before SusCrop and is well integrated into a global network of researchers (e.g. AgMip). It produced 21 invited presentations in international and national conferences,

In addition to written outputs and conference presentations, the 13 projects were involved in the organisation of more than 20 international, 9 European and 16 national **scientific events** involving hundreds of researchers worldwide. Such events were constrained by the pandemic with many of these meetings occurring online during the lockdown.

Some differences emerged when comparing the different projects in terms of academic impact with the best performance by those partnerships created within existing consolidated international networks of researchers that had already worked well together before the launching of the programme. **New partnerships** always take time to become successful so their academic outputs will be smaller initially, compared with established partnerships. Nevertheless, SusCrop was an opportunity to **boost the networking** of these new partners and this has already generated more than 20 new projects, which is also an important outcome of the programme. From another perspective, such an outcome may also be related to the particular characteristic of research on cropping systems which requires long-term investments that are often incompatible with short-term (i.e. 3-5 years) research programmes.

6. Technological Impact of Projects

The concepts included in many of the projects had already shown their potential to achieve several technological impacts in application to agricultural practice. However, for all projects, further development of the technologies for specific applications to practice is generally required. This further development in many of the projects was negatively affected by the Covid-19 pandemic, which, to a greater or lesser extent, limited the possibilities for consortium members to implement the results and practices a rising from the research results.

Most of the projects concern technological advances in plant breeding. On a global scale, plant breeding is an important element of activities that allow for better adaptation of cultivated plants to changing environmental conditions or to pro-ecological methods of cultivation. For example, *PROSTRIG* set out to develop **genome editing for maize, for reduced fertiliser inputs**. A technology platform is expected to be established, that can be used by breeding companies.
Genomic selections developed in the *WheatSustain* project using markers covering the whole genome, enable better selection decisions, reducing phenotyping and the number of candidates. The technological innovations of the project exploit new ways to combine recent advancements in **bioinformatics** with Information and Communications Technology sciences, such as machine learning and statistical modelling. The model may improve the ability to predict disease resistance in wheat.

Results from *ProFaba* provide a robust basis for technological development in the public and private domains. The identification of genotypes that are tolerant to bruchids, soil acidity and frost will facilitate future breeding programs. The development of a phenological model for **faba bean** is a fundamental tool for understanding the **impact of climate change** on the phenology of this crop. The identification of marker-phenotype links and the studies on the global diversity of faba genotypes forms a basis for further genomic prediction analysis.
DIFFUGAT had several technological outcomes including a **novel breeding method for potato** and a cost effective, multi-allelic marker system (POTATOMASH) that can be applied to multiple traits in practical breeding.

The *BARISTA* project also produced significant technological outcomes based on models of genome prediction and crop growth and yield simulation. Research with barley mutants led to molecular markers for **improved water use efficiency** that can be used in breeding. Novel loci have been developed and lines with stacked resistance genes have been produced. A web portal is being developed for the modelling tools to provide a useful source of information for stakeholders.
Novel salt regulators and resistance genes were identified in the *ROOT* project that will be useful for breeders of tomato in different countries. It also selected **tomato** genotypes that were more **resilient to salt stress**. *RyeSus* produced prototypes of semi-dwarf hybrid rye using a new breeding technology that may serve as a model for wheat and other cereals. The project outcomes are already being **commercialised** and are expected to make can make profitable contributions to researchers, plant breeders, biotech companies, and the European Technology Platforms.
In *SOLNUE* a common strategy and methodology was developed that permitted selection of **high Nitrogen Utilisation Efficiency (NUE)** genotypes across a range of Mediterranean environments. QTL for NUE identified by two different approaches allowed the pyramidisation of genomic regions of interest in breeding programmes and is being explored by commercial associates.

Several projects contributed to the advancement of practices that can be classified as general agricultural technology. They focused on several aspects of plant cultivation, including pro-ecological methods of plant protection against pathogens, the use of new sources of plant biostimulants, and the potential to increase production of protein-rich plants. These aspects are important for both economic and nutritional reasons.

In the case of *AC/DC-weeds*, application of pelargonic acid achieved good control of weeds seven days after application. The project findings suggest that farmers can **reduce tillage** and thus reduce the use of non-renewable energies. There was a perceptible effort to bring the technologies to higher Technology Readiness Levels (TRLs) with, for example, prototypes of a new horizontal root cutter tested in three locations in Northern Europe. Thistle Tool, a program developed in AC/DC-weeds has been integrated into two user-friendly IT-platforms and tested in large commercial fields in Denmark.
In *potatoMETAbiome* results highlighted that the selection of genotypes that are better capable of interacting with the soil microbiome, with or without the combination of microbial products that boost plant-microbial interaction, represents a sustainable strategy to **reduce pesticides** in the environment.
SUSCAP developed high accuracy **crop models** that can be used as tools to assess combined effects of pollution and drought stress on cereal crops. The approach allowed development of robust models that were calibrated and evaluated with empirical data along with remotely sensed data collected and analysed to describe leaf area index, evapotranspiration and soil moisture across Europe.
In *NETFIB,* new strains of microorganisms for **biostimulation** were isolated. They may be suitable for future of industrial valorisation.
The modelling outputs of *LegumeGap* demonstrate the potential for increased production of autumn-sown faba bean and the northward progression of suitable **climates for soybean** as the climate warms. Together these can enhance the potential production of plant protein in Europe.
Some projects had significant achievements in **stakeholder engagement**. For example, in the case of *NETFIB* stakeholder engagement activities involved companies and SME or farmers, mostly at national or regional scale.

7. Valorisation

Exploitation of the results (valorisation) has taken several forms depending on the focus and types of outputs from the various projects. Breeding for sustainable production was a major objective for many projects with outputs that included new breeding techniques, identification of markers and specific genes controlling phenotypic traits, and pre-breeding and finished varieties. *DIFFUGAT* produced a novel breeding method for potato using fixation – restitution in diploid inbred lines that was employed to produce starter clones with ideal ideotypes. This technology allows stacking of disease and pest resistance genes for increased resilience and is being **disseminated to commercial breeders**. Similarly, *SOLNUE* identified common methodologies and strategies within the partnership to select for high nitrogen use efficiency (NUE) among **tomato and eggplant** accessions. Quantitative trait loci (QTL), molecular markers, introgression and advanced backcross lines were all deployed to develop pre-breeding lines with **high NUE** that can be disseminated to commercial breeders.

WheatSustain and *BARISTA* used modelling combined with new germplasm to speed up the genetic improvement of wheat and barley crops with partners. *WheatSustain* developed an innovative data harmonisation tool that facilitated the combination of partial datasets of wheat genotype to phenotype information. This has been actively **used by breeding companies** to develop validated marker assays (particularly markers for disease resistance determined by QTL) and advanced genomic prediction models. Similarly, in *Barista* a genomic prediction model was developed to predict crop performance in different climatic conditions; **barley breeders are using** this with new genetic material to accelerate the production of new varieties adapted to climate change, with higher water and nitrogen use efficiencies and with increased disease resistance.

PROSTRIG was a methodologically focused project that aimed to develop novel **maize genotypes** with altered strigalactone activity using gene editing. Commercial exploitation was not expected during the project but proof of concept was anticipated to be taken up by other laboratories. In contrast, *RYE-SUS* has delivered two new semi-dwarf rye varieties (HYH-369 and HYH-370P1) and **applied to the German Federal Plant Variety Office** for national listing as the first semi-dwarf P-type CMS hybrids.

A second major objective of many SusCrop projects was the improvement of crop performance through the application of various management practices. In most cases, the exploitation of these projects was via direct interaction with farmers and their agronomic advisors. *SUSCAP* employed a combination of modelling and **interaction with key stakeholders and farmers** to identify appropriate adaptation options for climate change in different European regions. Semi-structured interviews with farmers showed that their concerns were with immediate and near time changes and that they had already adapted irrigation, soil management and crop ideotypes to cope with altered rainfall and growing season temperature patterns and extreme events such as storms and heat waves. **Combined crop modelling and farmer responses** identified four major adaptation strategies (sowing time, soil management, irrigation and genotype selection). However, demonstrating financial outcomes (including financial support mechanisms) and robust evidence for any benefits of adaptation in their own farming context was crucial in the adoption by farmers of any adaptation measures.

Similarly, the two legume projects *LegumeGap* and *ProFaba* interacted with farmers and industry stakeholders throughout. *LegumeGap* employed crop modelling, local expert knowledge to **ground-truth model outputs and farmer surveys** to identify key limitations and potential enabling technologies to improve **faba bean** and **soybean** production in regions of Spain, France and

Germany. Model outputs were demonstrated to farmers and policy shapers indicating the potential for autumn-sown faba bean and the northward progression of suitable climates for soybean cultivation as climate warming proceeds; these will enable increased European production of plant protein. Outputs from *ProFaba* complemented this work by characterisation of a large germplasm collection of faba bean that revealed great potential for exploiting the genetic diversity that exists throughout Europe. Several **stakeholders engaged** with the dissemination of these findings and partners were starting to promote the exploitation of this diversity for production in specific regions.

Although attempts to develop sustainable cropping practices for nettle with farmers were mixed in *NETFIB*, a new, **commercialisable method for extracting the fibres** (retting) was developed along with two technologies for the use of the fibres in composites.

AC/DC-weeds (investigating methods to control creeping thistle (*Cirsium arvense*)), *ROOT* (investigating variations in root system architecture in tomato) and *potatoMETAbiome* (investigating interactions of potato roots and rhizosphere organisms) had **longer-term sustainability objectives** with limited opportunities for immediate exploitation of the results.

Serendipity produced two results with potential commercial opportunity that are now being investigated by the teams responsible. In *SOLNUE*, the observation of crosstalk between forms of **nitrogen fertiliser** applied and the reaction of eggplant to inoculation with a common **pathogen**, *Fusarium* spp., provided novel information about how plants minimise the impact of biotic stress. This could be exploited to reduce pesticide applications. The *LegumeGap* project demonstrated that, at first planting, yields of soybean could be improved by inoculation with commercial strains of rhizobium. This is not unexpected. However, the finding that rhizobium inoculum isolated from soil previously used to grow soybean was a very effective promoter of growth and yield of a subsequent crop offers **possibilities for European commercial** exploitation.

8. Perceived Gaps

The projects were often focussed on specific traits or species but the results might be expanded to include other traits, or to validate models in other species. In many cases, further large-scale field trials or validation is required. Future work, which can lead to the research being routinely utilised should be clearly stated in the initial application, as well as in the final reports.

A perceived gap identified across many projects was the **lack of foresight** into how the results **might be practically implemented** in breeding programs or integrated into business, with a route to market identified. This should be addressed in future calls, with a re-assessment 3-5 years after a project ends to determine the extent of implementation or **route to market**. It is also recommended that there should be a stronger description of the implementation within the applications and final reports. To support this, **stakeholder activity** and participation in the projects should be intensified and the role of stakeholders clearly stated in the initial application. New research projects based on new breeding technologies developed within this research can enhance national and regional breeding for more sustainable and resilient crop production.

It would be valuable to develop **databases** from the data generated within the projects, which might be exploited globally by the relevant research communities. These were sometimes planned within the projects, but not delivered in all cases. A clear route to **make the data easily accessible** is of considerable potential benefit to users. In future calls it is also essential to monitor the dissemination of results.

A gap across many of the projects was around the **intellectual property (IP)** position for the material to be used within the research, as well as the material generated from the project. The issues around **regulation of the technologies** needs to be addressed. Whilst some technologies are valuable for research, end products using them are not acceptable to all countries and strategies to overcome this, or acknowledgement of these limitations should be documented. There was also a lack of acknowledgement of **potential licensing issues**, for example for some technologies or material, as well as freedom to operate for the material used, such as the germplasm. It is therefore recommended that any future call highlights the need for the proposals to include both a preliminary study of the IP position and project activities to develop an IP strategy.

9. Disclaimer

This report is based on statements of project coordinators and project partners (final project report, submitted 31 September 2022). Errors cannot be ruled out entirely. Questions were phrased in a way to avoid ambiguity; however, differences in interpretations and understanding cannot be excluded entirely. Moreover, all projects were still running at the time of the reporting, implying that more results will be available in the future.

10. Annex

10.1 Expert Evaluation Committee (EEC) / Authors

Hanna Friberg, Associate Professor, Swedish University of Agricultural Sciences, Sweden

Jacqueline Batley, Professor, School of Biological Sciences, University of Western Australia, Australia

Kemal Benlioğlu, Emeritus Professor of the Plant Protection Department of the Faculty of Agriculture, Aydin Adnan Menderes University, Turkey

Marek Gajewski, Emeritus Professor of Warsaw University of Life Sciences - SGGW, Poland

Peter Gregory, Emeritus Professor of Global Food Security, University of Reading, United Kingdom

Pier Paolo Roggero, Full professor, Agronomy and crop science, Department of Agricultural sciences, University of Sassari, Italy

10.1 SusCrop Consortium member / Task 4.3 lead

Stefanie Margraf, Monitoring and Evaluation Officer, Project Management Jülich, Germany