CropBooster-P

Deliverable No. D2.4

Title: Integrated impact assessment

Start date of the project: November 1st, 2018 / Duration: 36 months

Planned delivery date: M30 (August 2021)

Actual submission date: 27 August 2021

Work package: WP2

Work package leader: ULANC

Deliverable leader: Jessica Davies

Version: 2

Date of version: 1 august 2022

Partner name(s): *ULANC, WU, ESA, Plant ETP, WR, ACTA, INRA, JKI*

Contributor list: (alphabetical order) *J.P. COHAN[1], M. CORNELISSEN[2], J.A.C. DAVIES[3], J.C. DESWARTE[1], R. DUCHESNE[1], A.R.H. FISCHER[4], A. GUICHAOUA[1], P. JORASCH[5], G. KLETER[6], S. LEMARIE[7], F. LEPRINCE[1], L. LIU[8], J. MENARY[3], A. NAIR[4], A.K. NANDA[9], M. RUFINO[10], M. SALIN[1], S. STETKIEWICZ[3], N., VANGHELUWE[9], R. WILHELM[11]*

Dissemination level Public

Contents

EXECUTIVE SUMMARY

The interlinked challenges of population growth, climate change and shifting diets have put the future of food and farming firmly in the spotlight. CropBooster-P aims to develop a roadmap to future-proof European crops for these challenges – to do so, it is employing a stakeholder-focused approach to determine the impacts of various strategies for crop improvement.

In WP2, three main data collection streams were implemented and the results integrated:

Method	Stakeholders involved*	Aim
Online workshops	Farm-level, consumer-level, and agribusiness	Understand key **issues** surrounding crop breeding as a means to future-proof the European food system
Online survey	Farm-level, consumer-level, agribusiness, plant scientists	Identify crop breeding **priorities** among the WP1 options, and assess the importance of overarching breeding goals
Rapid evidence syntheses	N/A	Assess downstream economic, social and environmental **impacts** for three options which were prioritized in the survey

***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)

These resulted in the following findings.

Priorities

- Farmers, consumers and plant scientists selected sustainability as the priority goal for crop improvement in the EU, whereas agribusiness representatives prioritised yields.
- Stakeholders across the agri-food system broadly agree that crop improvements that enhance sustainability- related traits are important for future-proofing the food system in Europe
- Very few plant breeding options were considered a low priority. The lowest priority options were improving the digestibility of biomass and increasing the size of harvestable parts of the crop.
- Improving plant water use, improving photosynthesis and increasing protein content and quality were identified as priority crop improvements in most stakeholder categories. It should be noted that these issues will not apply to all crops equally – for example, grains, legumes and cereals are the prime targets for improved protein quality, rather than crops such as fruit and vegetables.

Impacts

- Taking forward priority areas for crop improvement (photosynthesis, water use, protein) could have positive impacts on some areas of sustainability, but data is lacking for others
- Very few studies have attempted to analyse or quantify concurrently the economic, social and/or environmental impact of the options reviewed

- Where studies have been made, they are frequently limited to enhanced yield and assumed increased farm profit, land conversion savings and GHG emissions associated with these
- More studies are needed that systematically attempt to quantify the benefits and disbenefits to form a fuller business case and guide development and deployment of improved or new crops

Issues

- Agri-food system stakeholders identify a wide range of issues that need to be considered during the development and deployment of improved crops
- Many issues are shared across farm, business and consumer level actors including the need to:
    - minimise trade-offs between improvements in crop traits,
    - consider geographic variation in prioritising plant breeding innovation, and
    - assess existing alternatives to plant breeding and compare these to crop improvement options.
- There are a number of issues that were identified by only one or two groups, but still have importance for the future success of crop breeding in providing effective systemic solutions, such as the importance of breeding for specific farm management strategies (e.g. intercropping)
- Stakeholders are concerned about trade-offs in plant breeding and prefer strategies which achieve multiple objectives - either via breeding, non-breeding strategies (e.g. farm management), or a combination of these

Recommendations for future research

The rapid evidence reviews and an extensive program of participative research engaging stakeholders across the agri-food sector summarized in this Deliverable in effect outlines a stark and important knowledge gap that is key to the future success of crop improvement research and the impacts it can have on the World. Understanding of the economic, environmental and social impacts of crop improvements is at present very limited due to a lack of evidence and we are unable to benchmark the benefits of crop improvements against alternative measures – an issue which our stakeholders across the food system strongly underlined as decisive in the future of crop innovation and the uptake of improved crops by farmers, supply chains, and society.

We recommend that future interdisciplinary research programmes are established to help address this evidence gap and produce robust research and insights on the potential environmental, societal and economic impacts of crop improvements. This will require participative approaches to define impact indicators, modelling advances, data analysis, targeted empirical and experimental science, and qualitative studies to build a robust understanding of the benefits and potential disbenefits of crop improvements, and how we can best deploy them as part of a food system approach to secure a healthy, sustainable food future for Europe.

1 INTRODUCTION

Work package 2 (WP2) aims to assess the potential economic, social and environmental impact of the CropBooster options for improving yield, sustainability and nutrition arising from Work Package 1 (WP1) of the CropBooster project. We approached this aim taking a mixed-method, multi-stakeholder approach, summarized in the Figure below.

Working papers presented in Deliverables 2.1 through to 2.3 summarised initial analysis of stakeholder views on the impacts of future crop improvements at farm, business and consumer level respectively. In this final paper forming Deliverable 2.4, we present the final findings that integrate perspectives across farm, business and consumer level stakeholders. This integration was supported by a multi-actor workshop, and collaborative working across the WP2 team.

Here, we present a summary of the multi-actor workshop, and a draft paper that summarises the integrated findings of WP2.

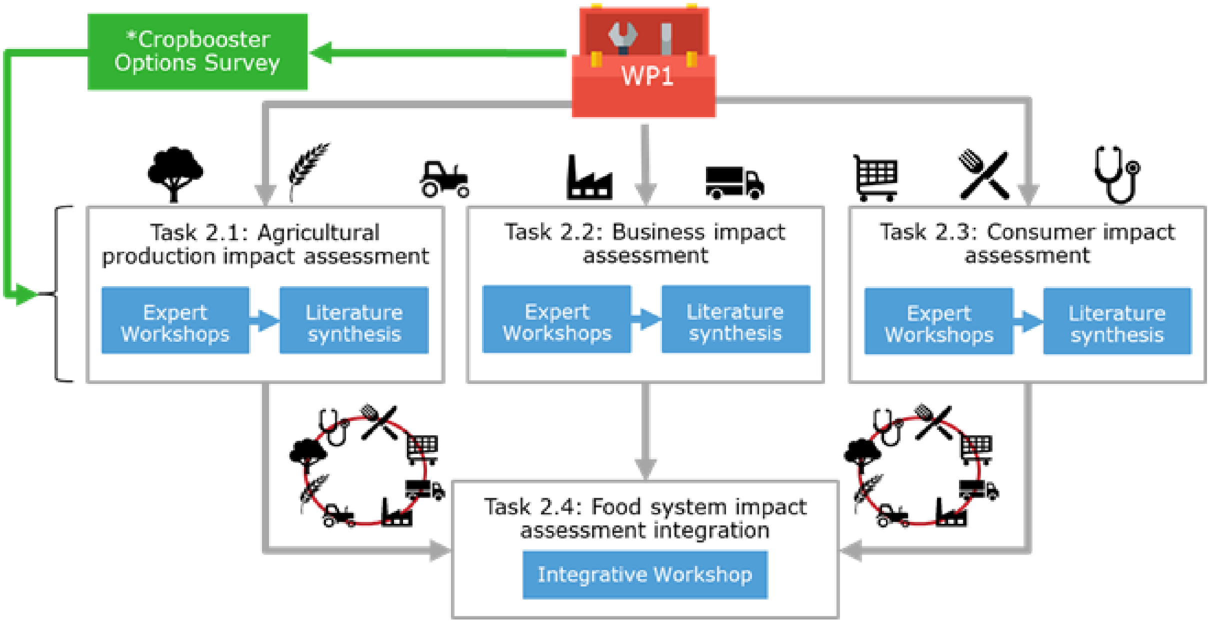


Figure i: Tasks and approach in WP2. *The survey, shown in green, was added to the original plan to increase the robustness and resilience of the data collection and informs the literature synthesis elements.

2 MULTI-ACTOR WORKSHOP SUMMARY

In October 2020, WP2 hosted an online integrative workshop with 40 participants from across the European agri-food sector via Microsoft Teams. Participants were invited from each stakeholder group included in the research design (farm-level, agribusiness, consumer-level, and plant scientists), with the invitation also extended to CropBooster-P researchers from other work packages. This was a chance to communicate what research outputs WP2 had finalised up to that date, gather feedback and insight on these preliminary data, and explain the next part of the project. It was also an opportunity to understand how different crop improvement strategies fit – or not – within wider European Union policy objectives, particularly with respect to the Farm to Fork strategy (2020), which aims to enhance the sustainability of the European food system.

Participants were invited to take part in an interactive exercise of moving cropboosting options through the European policy 'space', in order to help guide roadmap development. Images were created in the online whiteboard software Mural which showed key aims of the Farm to Fork strategy "Safe, nutritious and sustainable food" "Fairer economic returns" and "Environmental impact" as an overlapping Venn diagram. Each of the 15 cropboosting options were made into virtual post-its, and in break-out groups participants discussed which (if any) of the Farm to Fork aims each option delivered to, and moved these post-it's to reflect these ideas (see Fig XYZ for an example from one group). While not all break-out groups discussed all options in the allotted time, each group did identify some cropboosting options as potentially delivering to the Farm to Fork strategy. The lack of biotic stress and options focusing on breeding to reduce pest and disease burden was raised in several groups. Another common concern was around the mechanics of delivering to these aims, as exemplified by one group stating: "higher economic return does not automatically mean fairer economic return". While the 15 cropboosting options may be capable of delivering to the Farm to Fork strategy therefore, care will need to be taken to ensure that this potential is fulfilled. Insights from this workshop helped to inform the paper integrating WP2 results (see Annex 1, below).

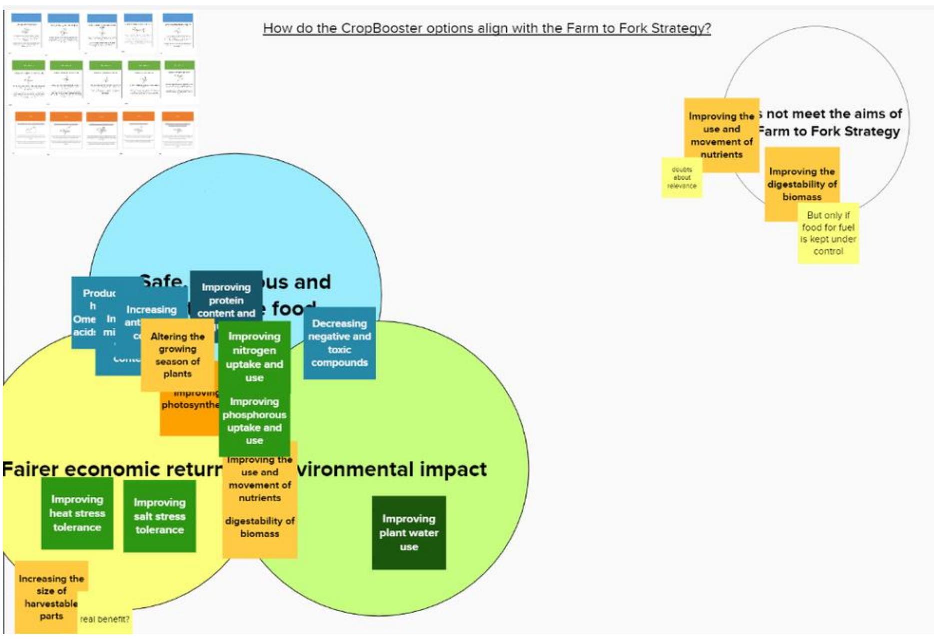


Figure ii: *Example breakout group whiteboard of cropboosting options and the Farm to Fork strategy*

3 INTEGRATIVE PAPER DRAFT

Food system stakeholders' perspectives on future-proofing crops through plant breeding in Europe

Stetkiewicz, S.[1,2], Menary, J.[1,3], Nair, A.[4], Rufino, M.[1], Fischer, A.R.H.[4], Cohan, J.P.[5], Cornelissen, M.[6,7], Duchesne, R.[8], Guichaoua, A.[78], Jorasch, P.[9], Lemarie, S.[10], Nanda, A.K.[7], Vangheluwe, N[7]., Wilhelm, R.[11], Davies, J.A.C.[1,12]

1. Lancaster Environment Centre, Lancaster University, Lancaster, Lancashire, LA1 4YX, United Kingdom
2. Division of Agricultural & Environmental Sciences, University of Nottingham, Sutton Bonington Campus, Loughborough, Leicestershire, LE12 5RD, UK
3. Health Systems Collaborative, Centre for Tropical Medicine and Global Health, University of Oxford, OX1 3SY
4. Marketing and Consumer Behaviour group, Wageningen University, Wageningen, Gelderland, 8130, Netherlands
5. Arvalis, Station Expérimentale, 91720 Boigneville, France
6. BASF Innovation Center Gent, Gent, 9052, Belgium
7. 'Plants for the Future' European Technology Platform, Brussels, 1000, Belgium
8. ACTA -The Agricultural Technical Institutes, Paris, 75595, France
9. Euroseeds, Brussels, 1000, Belgium
10. Université Grenoble Alpes, CNRS, INRA, Grenoble INP, 38400 Saint-Martin-d'Hères, France
11. Federal Research Centre for Cultivated Plants, Julius Kühn-Institut, 06484, Quedlinburg, Germany
12. Centre for Global Eco-Innovation, Lancaster University, Lancaster, Lancashire, LA1 4YW, United Kingdom

Abstract

Crop improvement is a key innovation area in the pursuit of sustainable food systems. However, realising its potential requires integration of the needs and priorities of all agri-food chain stakeholders. In this study, we provide a multi-stakeholder perspective on the role of crop improvement in future-proofing the European food system. We engaged agribusiness, farm- and consumer-level stakeholders, and plant scientists through an online survey and focus groups. Four of each group's top five priorities were shared and related to sustainability goals (water, nitrogen, and phosphorus efficiency, and heat stress). Consensus was identified on issues including considering existing alternatives to plant breeding (e.g. management strategies), minimising trade-offs, and addressing geographical variation in needs. We conducted a rapid evidence synthesis on the impacts of priority crop improvement options, highlighting the urgent need for further research examining downstream sustainability impacts to identify concrete targets for plant breeding innovation as a food systems solution.

Introduction

Future-proofing agriculture is a major global priority [1,2] given the agronomic challenges presented by a changing climate and declining natural resources, the rising needs of a growing global population with changing diets, new targets for a growing bioeconomy, and the necessity to reduce agriculture-driven environmental degradation.

Plant breeding offers one important area of focus for future-proofing food systems. In recent decades, in line with growing global prioritisation of sustainability, plant breeding has made advances in increasing crop resilience to abiotic stresses such as heat [3], drought [4] and soil salinity [5] and improving nutrient [6] and water use efficiency [7], in addition to the established history of breeding for increasing yields [8]. These improvements at the plant level offer the potential to help agriculture remain productive in the face of climate change, water scarcity, and adverse growing conditions whilst reducing fertiliser use and other inputs.

Despite clear evidence of tangible benefits from crop improvement such as yield gains [9], we lack an integrated multi-stakeholder food system view on the potential for plant breeding to contribute towards resilient, healthy food systems and sustainability goals. Gaining such a systemic understanding of in-plant innovations and their associated benefits, pitfalls, and unintended consequences is vital to guide research, development, and policies that contribute to future-proofing agriculture; the more so given the complexity of food systems, the diverse array of stakeholders engaged in them, and their multiple drivers and outcomes. Whilst participatory plant breeding approaches have been deployed in some contexts [10], the majority of breeding efforts do not take a holistic approach to incorporating the views and knowledge of wider food system actors and outcomes. Understanding whether food system stakeholder views, needs and priorities on plant breeding are aligned or in tension is essential in directing innovation and key to its subsequent success.

This paper provides a first food system-based multi-stakeholder perspective on the priorities for plant breeding for future-proofing crop production in Europe, the key broader, systemic issues that need to be considered, and the potential social, economic and environmental impacts of in-crop improvements. To achieve this, we combine evidence from a mixed-method three stranded approach, as shown in Figure 1, engaging four key groups of stakeholders: farm-level (farmers, farmer representatives, NGOs and policy makers working on agri-environmental issues), agribusiness (including plant breeders and seed companies), consumer-level (consumers and consumer experts), and plant scientists. We triangulate the evidence by combining survey data to establish priorities in a larger group of stakeholders, rapid evidence reviews to represent the scientific state-of-the-art on impacts of the crop breeding options with more elaborated in-depth insights from expert focus groups on societal issues.

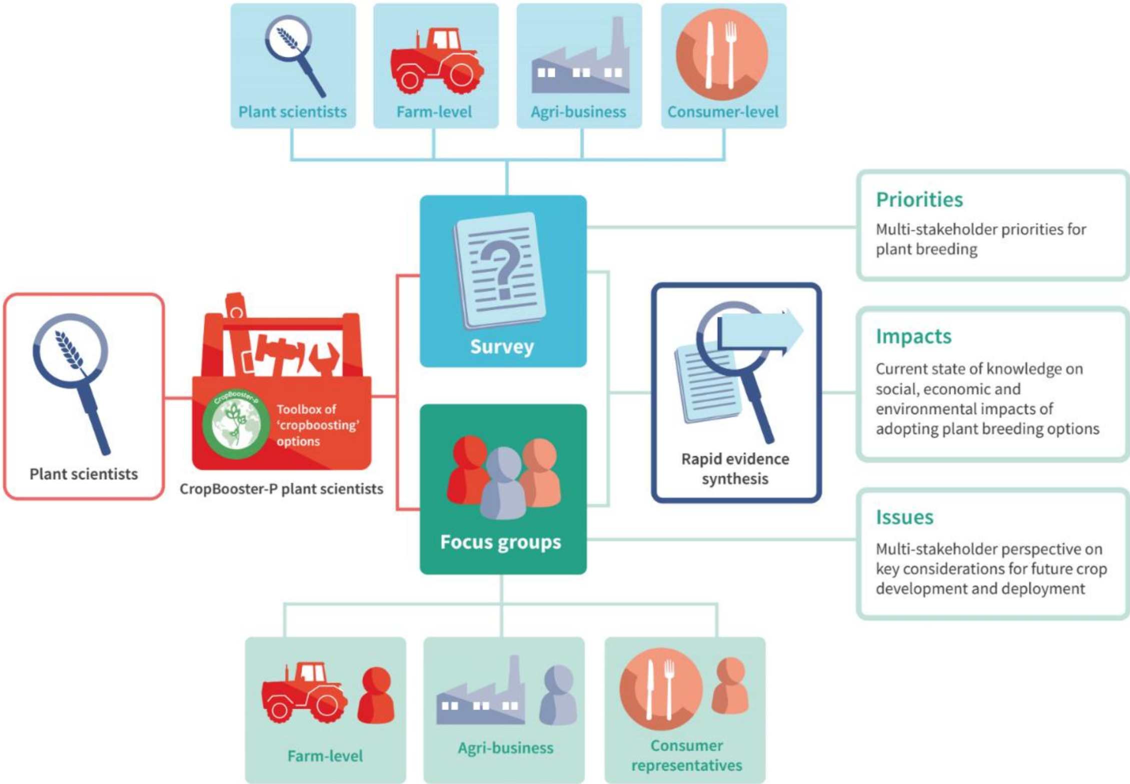


Figure 1: Summary of mixed method approach

Results

Priorities

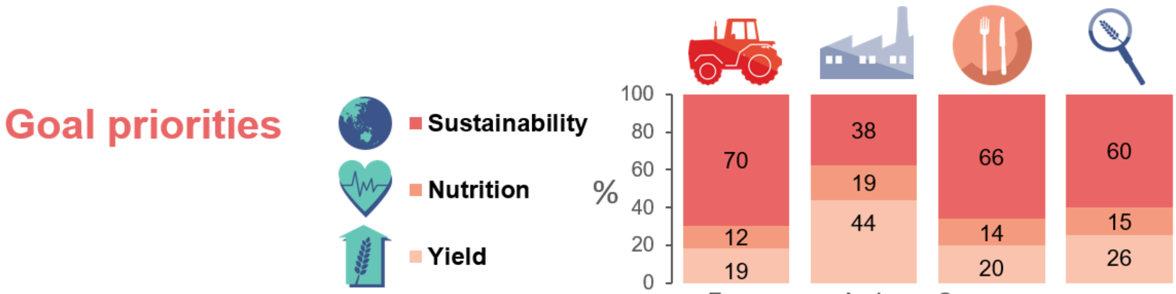
When presented with sustainability, yield or nutrition as potential overarching plant breeding goals, of the 254 respondents completing this survey section the majority of farm-level (70%), consumer-level (66%), and plant scientist (60%) respondents to the survey selected sustainability as most important for crop improvement in Europe, whereas agri-business respondents were more evenly split between yield (44%) and sustainability (38%) as most important (Fig 2). Nutrition was the least frequently selected priority for every stakeholder group, with less than 20% selecting it as most important in any group; however, when nutrition-related crop breeding options were presented individually, over half of participants selected these as important or very important. This importance is reflected in the relatively high percentage of respondents choosing nutrition as the second most important goal: 58% of farm-level, 44% of agri-business, 49% of plant scientist, and 46% of consumer-level respondents (see Supplementary 1).

When examining more specific options for plant breeding – based on areas identified by plant breeding researchers as having significant potential value for future-proofing European crop production (with a focus on abiotic stress) – the 201 stakeholders across the food system completing this survey section broadly agree that crop improvements which enhance sustainability are important for future-proofing the food system in

Europe. Four of the five options most commonly identified as important are shared across stakeholder groups and fall within the category of sustainability, namely: 'improving plant water use,' 'improving heat stress tolerance,' 'improving Nitrogen uptake and use,' and 'improving phosphorus uptake and use' (Fig 2). These options were also relevant to several important issues in stakeholder focus groups where a key overarching theme around the need for resilience to climate change was identified (See Fig 4). The fifth option most frequently selected as important varied between stakeholder groups, with priority given to 'improving photosynthesis' by the farm-level stakeholders, 'improving protein content and quality' by agri-business and plant scientist groups, and 'increasing vitamin and mineral content' by those in the consumer-level group.

Very few options where plant breeding could help improve sustainability, yield or nutrition were considered a low priority for future-proofing the European food system. The lowest priority categories were improving the digestibility of biomass and increasing the size of harvestable parts of the crop. However, a substantial minority did select these options as important or very important (43% and 40%, respectively). Focus group discussions with stakeholders around these options suggest digestibility of biomass may have been perceived as less important due to stakeholders prioritising food over biofuel. With respect to increasing the size of harvestable parts, concerns were raised regarding the impact on product quality, harvest, processing, and biomechanical stress on plant structures (e.g. overly large fruits causing the breakage of stems), though potential increases in profit were also noted (see [insert details of anonymised focus group data DOI]).

Improving plant water use efficiency, improving photosynthesis and increasing protein content and quality were identified as the priority crop improvements for their respective goal categories. They had the highest average percentage of respondents across the food system selecting them as important/very important – 95.5%, 70%, and 70%, respectively. It should be noted that these issues will not apply to all crops equally – for example, grains, legumes and cereals are the prime targets for improved protein quality, rather than crops such as fruit and vegetables.



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 2: The percentage of respondents from each stakeholder group selecting a given goal as their top priority is indicated in red (top right). 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.

Impacts

The rapid evidence synthesis aimed to understand the potential sustainability impacts of the three crop improvement options assessed based on their importance to surveyed stakeholders: yield increase, water use, and protein content/quality. However, few studies were found which have attempted to analyse or quantify the economic, social and environmental impacts of these options. A total of 21 papers were reviewed following initial screening of 1,398 papers (10 papers were retained relating to water use; 5 for yield increase; and 6 for protein content and quality – see Supplementary 3) most of which were removed as downstream impacts were not explicitly reported on. Nearly half (9 out of 21) of the papers reviewed reported on a single impact indicator only (see Fig 3). The majority of papers relating to water use focused only on yield impacts (8 out of 10 papers). Protein-related papers frequently reported on two indicators, both quality and yields (5 out of 6 papers). Four of the five papers reviewed relating to yield reported on three or more indicators. Across all 21 papers, quality was the second-most frequently assessed impact, with a total of 8 papers reporting on this indicator (two in the yield and six in the protein categories). The prevalence of yield-related papers in the water use and protein categories, along with the small number of papers retained in the yield review (and the fact two of these are 'grey literature' funded by plant breeding associations), points to the ongoing importance of yield as a plant breeding aim, despite the fact that the downstream impacts of improving yield were not well-elaborated in the reviewed literature.

Only one study reported overall disbenefits of breeding; a paper assessing potential yield loss due to climate change [11] (see Supplementary 2, protein section). No studies reviewed focused specifically on assessing potential disbenefits of in-plant solutions, such as trade-offs between reducing nutritional quality and yield, or reduced food sovereignty with increased reliance on upstream industry.

More studies are needed that systematically quantify the benefits and trade-offs of plant breeding solutions to form a fuller business case and guide the development and deployment of improved crops. In particular, while focus group participants stressed the need to consider resilience to climate change, few studies reported on the broader environmental impacts of these breeding goals. Stakeholder concerns regarding market driven needs and value chain impacts were echoed in only the minority of studies that looked at economic indicators. Yield stability over the long term, a trait highlighted by both farm-level and agribusiness stakeholders, was also not widely assessed, with the maximum length of the field trials included in the literature syntheses being four years [12].

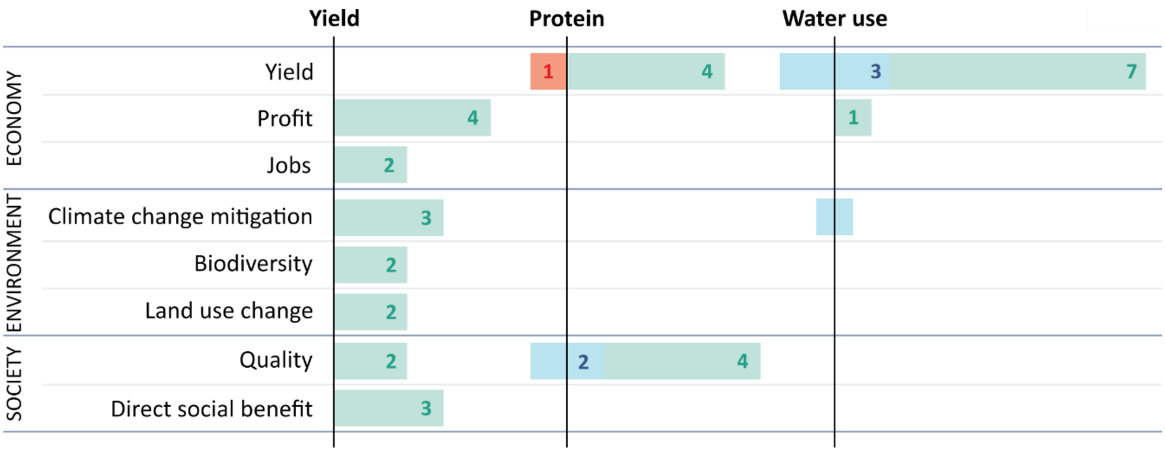


Figure 3: Summary of the impact areas and direction of change identified in the rapid evidence syntheses. Numbers indicate the number of papers assessed with a given result. The following definitions were used for impact classification: **Benefit (green)**: Positive changes in the impact being assessed were reported in the literature; **Neutral or Variable (blue)**: No clear changes in the impact being assessed were reported in the literature, or some combination of beneficial, neutral, and/or disbenefit impacts were reported in the literature, with no clear general direction; **Disbenefit (red)**: Negative changes in the impact being assessed were reported in the literature.

Emerging Issues

Stakeholder focus groups were conducted to provide in-depth, qualitative data to complement and provide context to the quantitative data described above, and gather insights into issues of importance to consider in developing breeding programmes. Five key issues were identified and shared across the agri-business, farm- and consumer-level stakeholders in online focus groups, as shown in Fig. 4 and described as follows.

1. Alternatives to plant breeding options. Assessing existing alternatives to plant breeding was considered important across all groups. The experts stressed that it is important that alternative means of reaching the same outcomes (i.e. changing farm management practice, use of heritage crops, and changing diets) are explored and weighed against plant breeding solutions (see Supplementary 3).

2. Minimising trade-offs in plant breeding. Minimising trade-offs when breeding was a significant concern, for example, breeding to reduce negative and toxic compounds potentially being traded-off against crop pest and disease resistance, thus requiring more pesticide use.

3. Variation and universality in plant breeding needs: Many stakeholders raised the importance of understanding variation and universality in plant breeding needs, highlighting that specific issues, such as salt stress vary in importance geographically and/or temporally. In contrast, others, such as heat stress, will affect a wide range of crops and geographical regions.

4. Resilience: The need to build resilience into food systems was stressed, particularly concerning climate change and the extreme weather events expected to increase in the coming decades.

5. Plant biotechnology and regulation: The overarching regulatory framework within which plant breeding and plant biotechnology operate was also raised by stakeholders who wondered what plant breeding gains were realistically achievable within the current EU breeding restrictions and what the future might bring for plant biotechnology.

There were many further issues identified by only one or two groups, which have importance for the future success of crop breeding (Fig. 2). For example, the farm-level group discussed the need to breed crops to align with sustainable farm management. They discussed ideas such as breeding pairs of crops together specifically to be sown in an inter-cropping system, which could increase the efficiency and attractiveness of such systems and bring the related benefits of reduced input needs. Those in the consumer-level group discussed the need for regulation that fostered innovation while considering associated risks. They mentioned that regulation needs to be updated and made more proactive in order not to hinder innovation in plant breeding. Both farm- and consumer-level groups highlighted the need for improved communication and knowledge exchange, with better integration between scientists, policymakers, farmers, and consumers, as key to improving sustainable scientific advances, policy outcomes, and informed-decision making. Several issues were shared between farm-level and agribusiness stakeholders, including the importance of striving for interconnected breeding plans. For example, breeding new crops that meet multiple needs to cope with future climate uncertainties (e.g. crops with improved water use, improved heat stress tolerance, and improved Nitrogen use). Consumer-level and agri-business stakeholders also shared concerns about consumer (non)acceptance of plant biotechnology and the need to engage with consumers around this issue. When asked what additional items should be focused on in plant breeding beyond those options presented in the project, both focus group and survey participants raised the need to consider future pest and disease pressure as key breeding issues (see Supplementary 1 and 3).

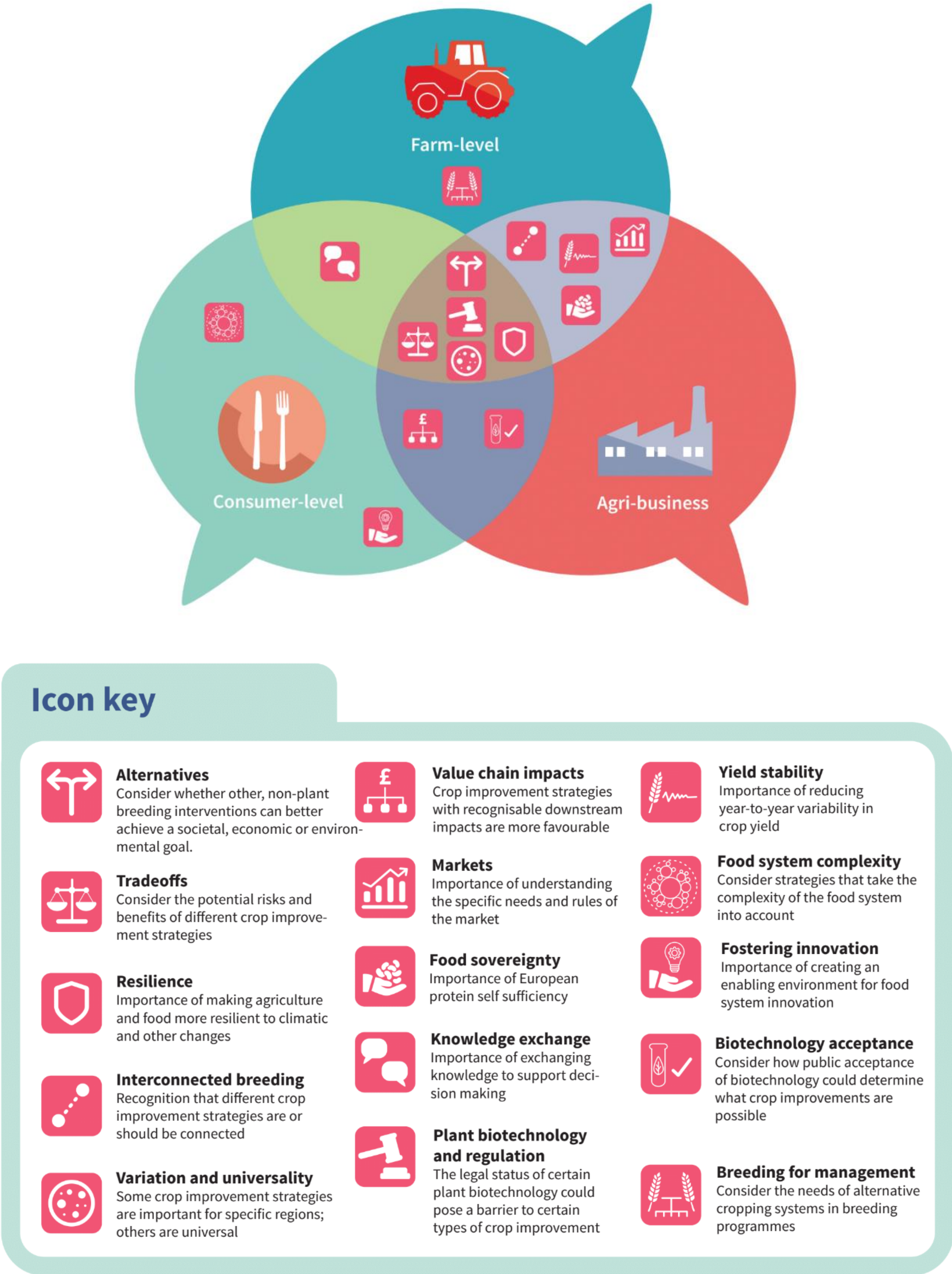


Figure 4: Summary emerging issues identified by stakeholders.

Discussion

This study highlights several overarching agreements between diverse food-system stakeholders regarding what is necessary to future-proof crops for the European food system. Stakeholders broadly agree about the importance of sustainability-related crop breeding options, with a particular consensus around the need to improve plant water use to build resilience in preparation for more extreme climatic conditions. Shared concerns regarding variation in the utility of the options presented, existing alternatives to plant breeding solutions, and the need to avoid trade-offs must be incorporated into plant breeding programmes' prioritisation and strategic planning.

Whilst many priorities between stakeholders are aligned, this multi-stakeholder perspective study highlights that a negotiated agenda for plant breeding is needed: one which brings together stakeholders from across the food system to strategically prioritise crop breeding objectives and consider their role within a wider suite of actions. A holistic approach to plant breeding is needed which takes into account several interlinked breeding goals, and assesses potential trade-offs, synergies, and alternatives across a wide range of transparent sustainability metrics, with aligned incentives, to encourage sustainable and effective breeding innovations.

The rapid evidence synthesis conducted stresses the need for further research that examines the wider impacts of in-plant solutions beyond yields, compares and contextualises these to other alternative solutions, and is open to examining potential disbenefits to the food system. Very few studies have attempted to directly quantify or detail the effects that adopting in-crop solutions have for the food system. For example, to what extent can crop improvements help reduce on-farm greenhouse gas emissions or help sequester carbon in the soil? To what extent can it help protect water resources by reducing irrigation and reducing fertilizer run-off? To what extent can crop improvement help reduce micronutritional deficits in socioeconomically deprived groups of society?

Bringing together these three data sources (focus groups, surveys, and rapid evidence synthesis) for a range of stakeholders involved across the food system highlights both broad agreements on the need to prioritise sustainability in plant breeding, as well as context and group-specific issues of importance, such as regional and crop-level variation in need and the potential to breed for specific farm management contexts. These differences in aspects raised across stakeholder groups underline the need to include various voices in prioritisation and planning exercises for plant breeding. While this study provides a first, systemic insight from key groups across the food system, further work is needed to bring additional stakeholder groups of relevance into the conversation, including those involved in the processing, storage, and retail sectors. Broadening the dialogue between plant breeders and other stakeholders is crucial for providing a ground-truthed direction for future-proofing our crops for the food system.

Recommendations for future research

Through the rapid evidence reviews and an extensive program of participative research engaging stakeholders across the agri-food sector undertaken in WP2, we have in effect highlighted that knowledge of the economic, environmental and social impacts of crop improvements is at present very limited due to a lack of evidence. We lack the ability to benchmark crop improvements against alternative measures such as agronomic practices, dietary changes, business innovation, or anticipate how when combined with these alternatives, crop improvement may form an important part of the solution. Our stakeholders across the food system underlined how important this understanding of how crop improvements compare and complement other measures in achieving a safe, secure, sustainable and healthy food system is critical for the development of crops and their uptake by farmers, supply chains, and society. This, therefore, constitutes a major gap, which must be addressed with primary research.

We recommend that future interdisciplinary research programmes be established that help address this evidence gap and produce robust research and insights on the potential environmental, societal and economic impacts of crop improvements. This will ensure that the positive benefits and unintended consequences of plant breeding are robustly analysed and considered.

A mixed-method interdisciplinary collaborative approach is vital to develop suitable impact indicators, that help evaluate the multiple social, economical and environmental impacts that new crop developments will have. These indicators need to be transferable across crop types and traits and need to be meaningful for multiple farming systems, geographies and value chains. We recommend that these indicators are developed using a participative approach, engaging multiple experts across distinct disciplines and key stakeholders of the agri-food system and the bio-economy.

To estimate and evaluate environmental impacts, we suggest combinations of modelling advances and applications, data analytics and strategic gap-filling through empirical and fundamental science will be required. We need to estimate the impact of crop innovations on environmental aspects such as soil health, water quality and flows, air quality, GHG emissions and biodiversity (for example in soils and at landscape scales). Incorporating the modification of plant traits into models that provide insights into environmental functioning and quality, as well as integrating models to explore potential biophysical feedbacks are a significant scientific undertaking.

To estimate the socio-economic consequences more robustly, combinations of qualitative and quantitative primary research will be needed to explore impacts for example on farm profitability, employment, value chain resilience, trade and commodity, and consumer markets, as well as considering nutritional quality, health and cultural values of food and landscapes.

Acknowledgements

This research was funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 817690. We would like to thank all the participants of our focus groups, pilots, and online surveys for their invaluable input, and Branwen Miles from COPA COGECA for her assistance in recruiting farm-level participants. We also thank all the members of the CropBooster-P consortium who gave feedback and attended events throughout this stream of work, particularly Gijs Kleter, Christian Kohl, Dörthe Krause, and Martin Parry, as well as those colleagues at who provided useful insight to our work, notably Ian Dodd at Lancaster University for his contribution to contextualising the water use evidence synthesis.

References

1. UN General Assembly. *Transforming our world : the 2030 Agenda for Sustainable Development*. *A/RES/70/1* https://www.refworld.org/docid/57b6e3e44.html (2015) doi:10.1163/157180910X12665776638740.
2. European Union. *Farm to Fork Strategy. For a fair, healthy and environmentally-friendly food system*. https://ec.europa.eu/food/sites/food/files/safety/docs/f2f_action-plan_2020_strategy-info_en.pdf (2020).
3. Akter, N. & Rafiqul Islam, M. Heat stress effects and management in wheat. A review. *Agron. Sustain. Dev.* **37**, (2017).
4. Nadeem, M. *et al.* Research Progress and Perspective on Drought Stress in Legumes: A Review. *Int. J. Mol. Sci.* **20**, (2019).
5. Huang, R. dong. Research progress on plant tolerance to soil salinity and alkalinity in sorghum. *J. Integr. Agric.* **17**, 739–746 (2018).
6. Welch, R. M. & Graham, R. D. Breeding for micronutrients in staple food crops from a human nutrition perspective. *J. Exp. Bot.* **55**, 353–364 (2004).
7. Farooq, M., A.Wahid, Kobayashi, N., Fujita, D. & Basra, S. M. A. Review article Plant drought stress : e ff ects , mechanisms and management. *Agron. Sustain. Dev* **29**, 185–212 (2009).
8. Reynolds, M. *et al.* Achieving yield gains in wheat. *Plant, Cell Environ.* **35**, 1799–1823 (2012).
9. Steffen Noleppa, M. C. The socio-economic and environmental values of plant breeding in the EU and selected EU member states. (2021).
10. Ceccarelli, S. & Grando, S. Participatory plant breeding: Who did it, who does it and where? *Exp. Agric.* 1–11 (2019) doi:10.1017/S0014479719000127.
11. Martre, P., He, J., Le Gouis, J. & Semenov, M. A. In silico system analysis of physiological traits determining grain yield and protein concentration for wheat as influenced by climate and crop management. *J. Exp. Bot.* **66**, 3581–3598 (2015).
12. Středa, T., Dostál, V., Horáková, V. & Chloupek, O. Effective use of water by wheat varieties with different root system sizes in rain-fed experiments in Central Europe. *Agric. Water Manag.* **104**, 203–209 (2012).
13. Lammerts van Bueren, E. T., Struik, P. C., van Eekeren, N. & Nuijten, E. Towards resilience through systems-based plant breeding. A review. *Agron. Sustain. Dev.* **38**, (2018).

Methods

Participants and design

The study used a sequential mixed-methods design with three stages: a survey, rapid evidence synthesis, and stakeholder focus groups (Fig. 1). Ethical approval was granted by Lancaster University Faculty of Science and Technology Research Ethics Committee (FST19070).

Participants for the survey and focus groups were purposively sampled from three pre-defined stakeholder groups:

- Farm-level:
    - Farmers, farmer associations or cooperative representatives

  - Farm- or agri-environment-focused non-governmental organisation representatives
  - Farm- or agriculture-focused policy makers
- Agri-businesses
  - Plant breeding representatives
  - Food producer/processor association representatives
  - Other agribusiness stakeholders (survey only)
- Consumer-level
  - Consumer group representatives
  - Consumer experts
  - Consumers (survey only)

Participants were recruited by the moderator of the related focus group with input from relevant consortium members: SS recruited farm-level representatives, JM agri-business representatives and AN consumer representatives.

Materials

To present stakeholders with the discussion topics, we developed crop improvement "option cards", which displayed 15 potential crop improvement options organised into three categories: yield, nutrition and sustainability. These were used in both the survey and focus groups to appraise different crop improvement strategies in quantitative and qualitative terms. Option cards were double-sided. The front offered a simple explanation of the improvement (e.g. improving plant water use) and the reverse an example of that improvement being applied through research (see [Supplementary 4]). A blank card labelled "Option Card #16" was provided to allow for opinions missing from other cards.

Priorities survey

Participants

Participants of the survey were volunteer stakeholders identified through the professional networks of the consortium belonging to each one of the predefined groups. Participants were asked to further distribute the survey link (snowball-sampling) to increase the number of participants. Project partners shared the survey links widely within their professional networks, on social media, and through direct contact with external organisations of relevance (such as the Food Climate Research Network, EAT forum, and IFPRI). The survey was could be filled in by anyone who received the link.

Survey instrument

The survey was designed to identify which of the CropBooster-P crop improvement options were priorities among a wide group of European food system stakeholders. The survey consisted primarily of closed questions, with some open-ended qualitative questions included to elicit more complex responses to key questions. It was programmed and administered using *Qualtrics* (www.qualtrics.com). Reporting follows CHERRIES guidelines (Eysenbach 2004).

Preferences for crop improvement goals (e.g. sustainability) were elicited on a 1 – 3 scale, with 1 being the most preferred, using a forced ranking. Preferences for crop improvement options (e.g. increasing plant water use) was assessed on a single item Likert scale labelled 1:'Very important'; 2: 'Important'; 3: 'Neither important nor unimportant'; 4: 'Unimportant'; 5: 'Very unimportant' 6:'Don't know'. Rating was selected over forced ranking as this allows participants to indicate ties, and to rate as many options high or low as they prefer.

After reviewing the 15 option cards, respondents were asked: “Are there any other goals which were not included in the above list, but which you feel are important for future-proofing crops?”. This question was included in order to compare with the focus group Option Card #16.

Surveys contained some specific question depending on the target stakeholder group. Farmers, for example, were asked questions regarding their farm size and level of agricultural education to allow for comparisons with the target population. (See [Supplementary 5] for a copy of the survey in English for further detail regarding the precise questions included for each stakeholder stream.)

The survey was developed and piloted in English. A total of 17 participants piloted the English survey, with at least three testing each stakeholder specific survey variant. To access as many participants as feasible, it was translated and piloted in German and French using a modified TRAPD method (Harkness, 2003). Six participants piloted the German and four the French versions, with at least one participant per language per survey variant. Changes made following pilot feedback included improved signposting, minor corrections to grammar and the updating of some terminology.

Procedure

Participants were informed of the purpose and length of the survey, how the information they provided would be managed and their right to withdraw at the start of the survey. The investigators were named and professional email addresses listed in case of questions. The survey was open between April and May 2020. After informed consent the main survey (specific to the stakeholder group) started.

Some personal data was collected including: email addresses (collected so that participants could be kept up to date with the project), postal code (to determine the effects of socio-economic factors) and institution or company. IP addresses collected by *Qualtrics* were used to check for duplicates. To ensure the confidentiality of these data, several measures were in place. *Qualtrics* assures GDPR compliance and offers substantive data protection measures. Data were accessed and managed from encrypted, password-protected institutional cloud storage systems. All data submitted to [WUR repository] have been anonymised.

Response and completion rates

A total of 324 participants took part in the online survey (288 in English, 22 in French, and 14 in German). Sixty-five responses were removed from analysis, as the respondents had not completed any data collection question blocks. Five survey responses were deleted as duplicate responses. This resulted in a total of 254 responses from participants who completed at least the first data collection segment of the survey (goal prioritisation). 201 respondents completed all core data collection segments (goal prioritisation and option card prioritisation): 39 for farm-level stakeholders, 26 for agribusiness level stakeholders, 38 for consumer level stakeholders, and 98 for plant scientists. Of the 254 surveys, 120 had some missing data but were retained for analysis as the respondents had completed the initial data collection segment regarding goal prioritisation. The majority of participants came from the UK (83), with additional participation from: Belgium (8), Croatia (1), Cyprus (2), Czech Republic (1), Denmark (2), France (15), Germany (11), Greece (1), Italy (31), Luxembourg (1), Netherlands (7), Portugal (2), Romania (1), Spain (10), and a further 12 responses from individuals currently living outside Europe.

Analysis plan

For each stakeholder group, the total number of valid responses was used to analyse: 1) goal prioritisation and 2) the option prioritisation questions.

The percentage of each stakeholder group ranking a given goal (yield, nutrition, or sustainability) as one (top priority), two (medium priority) and three (lowest priority) was recorded, and the most frequently selected priority goal highlighted. Data from the free text question asking participants to briefly describe why they had prioritised their selected goal was separated into three categories: data from participants choosing 'yield' as their top priority; data from participants choosing 'sustainability' as their top priority, and data from participants choosing 'nutrition' as their top priority. This data was exported to *Nvivo 12* and thematically analysed to identify key issues raised to explain a goal priority.

The 15 Likert-style items relating to the 15 option cards were treated as individual responses. Each of the choices was tallied and the percentage of participants choosing each statement calculated. Differences were reviewed for: top goal priority, and between stakeholder groups.

The free text data on additional goals was thematically analysed for each stakeholder group to identify recurring themes and key options which respondents felt were missing from the survey.

Impacts - Rapid evidence synthesis

A rapid evidence synthesis (RES, sometimes called rapid evidence assessments or rapid reviews) made up of three strands was used to explore the empirical impact of different crop improvement strategies. Rapid evidence syntheses provide relatively quick, tactical answers to key questions and are increasingly favored by policymakers (Donnelly et al. 2018; Garritty et al. 2021). Given the range of possible combinations of crop types, location and types of impacts, the three highest-ranked options were selected from the survey priorities: 1) improving plant water use (sustainability), 2) improving photosynthesis (yield) and 3) improving protein content and quality (nutrition). Due to a lack of relevant peer-reviewed papers assessing the impact of photosynthesis on sustainability indicators, this category was broadened to focus on yield impacts more generally.

A common research question framed the evidence synthesis: "What are the social, economic and environmental impacts of improving [plant water use/yield (photosynthesis)/protein content and quality]?". Slight adjustments were made depending on specifics of the priorities.

A query combining several multi keyword concept operationalisation's was similarly created for the three synthesis categories (see Table 1). Search strings were adjusted based the specific needs of the priority in question: for example, the targeted improvement of photosynthetic pathways is only a recent field with relatively few impact studies (Kohli et al. 2020), so more generic improvement in yield – and the social, economic or environmental impacts this has – was targeted.

Table 1 Search string development

	GOAL	OPTION	APPROACH	IMPACT	LOCATION
EXAMPLE	"yield" OR "efficiency" OR "productivity"	"photosynthesis" AND "improve" OR "enhance"	"plant breeding" OR "crop improvement"	"impact" OR "benefit" AND "social" OR "economic" OR "environmental"	"Europe" OR "EU"

Identified papers were abstract and title screened on relevance and contents, and subsequently methodologically screened by the researcher leading that part of the synthesis within the project team on the basis of methodological norms in the relevant field of research. In cases of doubt experts in relevant fields were asked for advice on the quality assessment. When a given paper did not meet basic methodological criteria (e.g. because of issues with field trial design, model validation, or statistical analysis) the paper was removed and no further analysis of it undertaken. Papers were identified in the scientific literature using Scopus and Web of Science.

Initial searches yielded 1,398 papers, 390 relating to water use, 491 relating to protein, and 515 relating to yield. After content and quality screening 10 papers remained for water use, 6 for protein and 3 for yield. Given the lack of peer-reviewed publications assessing impacts of yield, two additional papers in the grey literature were identified through Google-Scholar, bringing the total number of yield-relevant papers up to 5. Included papers were coded on relevant impact indicators.

Emerging issues - stakeholder focus groups

Between April and June 2020, 10 participatory focus groups were held to identify emerging issues with the CropBooster crop improvement options, whilst also probing how plant breeding targets can be determined and what the challenges are for European agriculture.

Focus groups complement the survey and rapid evidence synthesis as they permit the generation of new ideas, the assessment of potential ideas and insights into the differences in opinion that exist between members of particular groups (Breen 2006; Rabiee 2004). Face to face focus group protocols were adjusted to an online format to deal with coronavirus restrictions in Europe in 2020. A detailed description of these adjustments is described in Menary et al. (2021). Reporting follows COREQ guidelines (Tong, Sainsbury, and Craig 2007).

Key questions and prompts

A detailed semi-structured focus group protocol was developed to guide the moderator and ensure consistency and comparability between the data from each stakeholder group (for the full protocol, see [Supplementary 6]). The protocol was piloted at Lancaster University and Wageningen University (n=16). Primary topics were:

- The biggest challenges for the European agri-food sector over the next 30 years
- The most important CropBooster option
- The least important CropBooster option
- The social, environmental or economic impacts of a particular option
- The relevance of the options for the challenges facing the European agri-food sector
- What other things should be included in the CropBooster options?

Topics were discussed around the 15 option cards also used in the survey. Participants were asked to fill in a blank option card (#16) with a crop improvement they thought was missing from the 15 option cards and this additional input was discussed at the end of the focus groups.

Participants were encouraged to discuss the relative merits of their suggestions and agree on the most important. Prompts were used to probe participant choices – or why certain options had not been mentioned.

Microsoft Teams was used as a hosting platform alongside virtual whiteboarding website *MURAL* (www.mural.co). The 15 option cards and the empty Option Card #16 were incorporated into a whiteboard as a discussion tool, allowing "sticky notes" with suggestions to be added. Different copies of the whiteboard were made with randomised ordering of options to minimise anchoring bias. Focus group participants accessed the MURAL whiteboard via internet browser or smartphone without log in or account creation. Moderators shared their screens to guide participants through the option cards and to ensure recordings captured the visual elements of the discussion. More explicit cues had to be used to instigate group discussions as natural pauses or body language were suppressed by the online format.

Moderators for each stakeholder group had no existing relationships with any participants. In the agri-business focus groups, the project was introduced by a representative of *Euroseeds* (PJ), who has a professional relationship with several of the participants – after which the representative left before the actual focus group commenced. The moderators were experienced in the used interviewing technique (SS and JM in focus groups; AN in semi-structured interviewing).

Sampling frame, selection criteria and recruitment

The sampling frame was purposive. Participants were selected and approached on the basis of belonging to one of the pre-defined groups described above. Selection criteria were: 1) participants currently belong to one of the above professional groups, 2) Europe is the focus of participants' work and 3) could consent to being involved in the online focus groups. Potential participants were recruited primarily via email, which included a poll to determine the most convenient date. Some farm-level participants were also contacted via a European agricultural association newsletter. Forty-five respondents indicated interest in participating in the focus groups. Interested participants were then sent a participant information sheet, which outlined the goals of the project, what the focus groups would involve and how personal data would be managed. Potential participants were asked to pass on the email invitation to other members of their organisation if they could not attend, as well as anyone they thought relevant to the project. Thirty-five participants participated in one of ten focus groups (five with farm-level, two with agribusiness, and three with consumer-level participants).

Consent and data management

Prior to the start of the focus groups an online digital consent form was presented to participants which specified:

- Focus groups will be audio and video recorded
- Only the research team will have access to those recordings
- Contributions will be treated confidentially and participants will be pseudo-anonymised – any quotations used in reporting will be anonymised
- Data will be stored in a secure, password-protected location
- Participant's right to withdraw from the study
- Any data belonging to the project would be destroyed after 10 years

Hosting the focus groups

The focus groups were video and audio recorded via *Teams* with duplicate audio recordings made via Dictaphone as a back-up. A number of contingencies were put in place to cope with online-specific technical or personnel difficulties faced by the research team (see Tuttas 2015).

Participants were made aware of the role of the moderator and the goals of the project via the participant information sheet and at the start of the focus groups. Ground rules were established that emphasised the importance of patience and turn-taking given the online format and lack of certain natural cues. Notes were recorded on a standardised form.

The focus groups lasted an average of 100 minutes, the longest being 125 and the shortest 70.

Focus group analysis

The video recordings of each focus group were sent to a private GDPR-compliant company for transcription – non-disclosure agreements were signed in advance. Once the transcripts had been returned, they were checked for errors and anonymised by removing identifying information.

Adopting a *Framework Analysis* approach (Ritchie et al. 2014; Srivastava and Thomson 2009) an initial coding framework was developed by open coding of transcripts associated with each stakeholder group by the moderator responsible for that group. After these were agreed through consultation with at least one other member of the research team, the transcripts were fully coded and analysed using *NVivo* software. Emergent themes were cross-referenced by the moderators of the focus groups (AN, JM and SS) and an overview of themes was discussed within the wider research team. Mutual language was agreed upon for the purposes of illustrating shared themes for integrative analyses based on agreement between stakeholder specific coding trees and code books; which include non-identifying coded data and show the underlying quotes for each theme.

Methods references

Boone, Harry N. and Deborah A. Boone. 2012. “Analysing Likert Data.” *Journal of Extension* 50(2).

Breen, Rosanna L. 2006. “A Practical Guide to Focus-Group Research.” *Journal of Geography in Higher Education* 30(3):463–75.

Donnelly, Christl A., Ian Boyd, Philip Campbell, Claire Craig, Patrick Vallance, Mark Walport, Christopher J. M. Whitty, Emma Woods, and Chris Wormald. 2018. “Four Principles to Make Evidence Synthesis More Useful for Policy Comment.” *Nature* 558(7710):361–64.

Eysenbach, Gunther. 2004. “Improving the Quality of Web Surveys: The Checklist for Reporting Results of Internet E-Surveys (CHERRIES).” *Journal of Medical Internet Research* 6(3).

Garritty, Chantelle, Gerald Gartlehner, Barbara Nussbaumer-Streit, Valerie J. King, Candyce Hamel, Chris Kamel, Lisa Affengruber, and Adrienne Stevens. 2021. “Cochrane Rapid Reviews Methods Group Offers Evidence-Informed Guidance to Conduct Rapid Reviews.” *Journal of Clinical Epidemiology* 130:13–22.

Kohli, Ajay, Berta Miro, Jean Balié, and Jacqueline D’A Hughes. 2020. “Photosynthesis Research: A Model to Bridge Fundamental Science, Translational Products, and Socio-Economic Considerations in Agriculture.” *Journal of Experimental Botany* 71(7):2281–98.

Rabiee, Fatemeh. 2004. “Focus-Group Interview and Data Analysis.” *Proceedings of the Nutrition Society* 63(4):655–60.

Ritchie, Jane, Jane Lewis, Carol McNaughton Nicholls, and Rachel Ormston. 2014. *Qualitative Research Practice*. 2nd ed. edited by J. Ritchie, J. Lewis, C. McNaughton Nicholls, and R. Ormston. SAGE.

Srivastava, Aashish and S. Bruce Thomson. 2009. “Framework Analysis : A Qualitative Methodology for Applied Policy Research.” *Journal of Administration & Governance* 4(2):72–79.

Tong, A., P. Sainsbury, and J. Craig. 2007. “Consolidated Criteria for Reporting Qualitative Research (COREQ): A 32-Item Checklist for Interviews and Focus Groups.” *International Journal for Quality in Health Care* 19(6):349–57.

Tuttas, Carol A. 2015. “Lessons Learned Using Web Conference Technology for Online Focus Group Interviews.” *Qualitative Health Research* 25(1):122–33.

4 CONTRIBUTORS TO THE WP2 DELIVERABLES

************* ***ALPHABETICAL ORDER*** *************

J.P. COHAN[1], M. CORNELISSEN[2], J.A.C. DAVIES[3], J.C. DESWARTE[1], R. DUCHESNE[1], A.R.H. FISCHER[4], A. GUICHAOUA[1], P. JORASCH[5], G. KLETER[6], S. LEMARIE[7], F. LEPRINCE[1], L. LIU[8], J. MENARY[3], A. NAIR[4], A.K. NANDA[9], M. RUFINO[10], M. SALIN[1], S. STETKIEWICZ[3], N., VANGHELUWE[9], R. WILHELM[11]

************* ***ALPHABETICAL ORDER*** *************

[1] ACTA – The Agricultural Technical Institutes, France
[2] BASF Innovation Center Gent, Gent Belgium
[3] Centre for Global Eco-innovation, Lancaster Environment Centre, Lancaster University UK
[4] Marketing and Consumer Behaviour group, Wageningen University, Wageningen the Netherlands
[5] Euroseeds, Brussels, Belgium
[6] Wageningen Food Safety Research, Wageningen University, Wageningen the Netherlands
[7] Univ. Grenoble Alpes, CNRS, INRA, Grenoble INP, France
[8] Pentland Centre for Sustainability in Business, Lancaster University, Lancaster, United Kingdom
[9] 'Plants for the Future' European Technology Platform, Brussels, Belgium
[10] Lancaster Environment Centre, Lancaster University, Lancaster, United Kingdom
[11] Federal Research Centre for Cultivated Plants, Julius Kühn-Institut, Quedlinburg, Germany

5 REFERENCES

Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system COM/2020/381 final (European Commission, 2020).