The socio-economic and environmental values of plant breeding in the EU and for selected EU member states

Steffen Noleppa, Matti Cartsburg

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An ex-post evaluation and ex-ante assessment considering the "Farm to Fork" and "Biodiversity" strategies

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Content

HFFA Research Paper 2021

Acknowledgement

This research was initiated and financed by Euroseeds. We would like to thank Garlich von Essen and Petra Jorasch as well as the entire project steering group from Euroseeds and its partner organisations for the continuous and valuable feedback throughout the research phase. Moreover, we would like to thank Isabel Hackenberg, Juliane Kaufmann, and Lina Staubach for technical support. The results of this study are the sole responsibility of the authors and have never been influenced by the initiator and supporters of the study.

Executive summary

The overall working hypothesis of this study is that plant breeding in the European Union (EU) contributes to various socio-economic and environmental benefits. Accordingly, this research aims at analysing if and to what extent plant breeding in the EU contributes to increased yields and production in arable farming and subsequently to improved market and trade conditions, increased world food supply, higher economic prosperity and increased social welfare, additional farm income and more jobs, lower land use, reduced greenhouse gas (GHG) emissions, preserved biodiversity, and the saving of water resources.

The picture drawn is based on sophisticated modelling and calculation tools of agricultural and environmental economics, as well as on a comprehensive assessment of plant breeding contributions to yield and overall productivity growth in EU arable farming. To analyse the afore-mentioned impacts and to provide more insights into the various benefits of plant breeding in the EU, a threefold approach is used. First, an *ex-post* evaluation is carried out. The assessment looks back and aims at a discussion of the various impacts of plant breeding in the EU for the past two decades. Second, an *ex-ante* assessment is made. The evaluation looks forward and seeks to analyse similar effects of future plant breeding in the EU in the next decade on the one hand and in the next two decades on the other hand considering an implementation of the EU's "Farm to Fork" and "Biodiversity" strategies. Third, the two analyses are accentuated and substantiated by case studies discussing specific potential values of plant breeding with new plant breeding technologies (NPBT).

The first two parts of the study are conducted for the EU in total, still including the United Kingdom (UK), and five selected EU member states: Germany, France, Italy, Spain, and the UK. Moreover, the focus is on arable farming, and major target (groups of) crops of the analysis are wheat, corn, other cereals, oilseed rape (OSR), sunflower seeds, other oilseeds, sugar beets, potatoes, and pulses as well as green maize. In the following, the results are presented for the EU in total and all arable crops on aggregate. For further details per crop and individual EU member states, see the main text.

Accordingly, it turns out that plant breeding-induced innovations count a lot: On average and across all major arable crops cultivated in the EU, plant breeding contributes approximately 67 percent to innovation-induced yield growth. This is equal to an increase of yields by 1.16 percent per annum and, thus, slightly higher than the statistically observable yield development since the turn of the millennium. Based on this plant breeding-induced yield growth, plant breeding progress towards major arable crops in the EU in the past two decades has resulted in benefits which can be characterised, quantified, and summarised with the following ten key statements:

1. With plant breeding for major arable crops in the EU in the past two decades not only yields per hectare have increased, but also arable production. On average and across all major arable crops harvested in EU member states, production would have been more than 20 percent lower in 2020 without genetic crop improvements since the turn of the millennium.

2. Higher yields per hectare increase the supply of primary agricultural products on international markets. For example, an additional 53 million tons of cereals and almost 8 million tons of

oilseeds can currently be produced in the EU with plant breeding progress for these crops in the past two decades. This contributes to stabilising markets and reducing price volatility.

3. This also improves the EU agricultural net trade balance. Without plant breeding progress in the past 20 years, the EU would have become a net importer in all major arable crops in 2020, including wheat and other cereals.

4. Plant breeding in the EU is also indispensable for combating hunger and malnutrition as it improves the world food security situation. Given current European and global food baskets, genetic crop improvements in the EU in the past 20 years have assured additional availability of food for 114 million EU citizens or alternatively 168 million humans at global scale.

5. Furthermore, plant breeding in the EU generates additional economic prosperity by increasing the gross domestic Product (GDP). The entire agricultural value chain benefits from input suppliers to final consumers. Genetic crop improvements in EU arable farming since the turn of the millennium have generated in the agricultural sector of 2020 alone an additional social welfare gain of more than EUR 14 billion and have added more than EUR 26 billion to the GDP of the EU in total.

6. Plant breeding for arable farming in the EU also secures employment and increases the income of farmers and agricultural employees. Approximately 6 100 EUR per fully employed farmer (or agricultural worker), that means approximately one third of the current arable farm income in the EU, on average, have been induced by plant breeding in the past two decades. Moreover, almost 90 000 jobs have been created and secured in the arable sector this way, and many more upstream and downstream the agricultural value chain in the EU.

7. Plant breeding in the EU does not only bring about positive economic and social effects, but it also generates substantial environmental impacts. It particularly helps save scarce land resources around the globe by generating higher yields per unit of area. Therefore, it can be stated that plant breeding minimises the net virtual land imports of the EU. In the absence of plant breeding for major arable crops in the EU in the past 20 years, the global agricultural acreage in 2020 would have to be expanded by more than 21.5 million hectares.

8. This contributes to preserving natural habitats and to reducing GHG emissions resulting from an expansion of the global acreage. Plant breeding in the EU, thus, also secures less GHG being emitted by helping avoid negative land use change. Until 2020, a total of almost 4.0 billion tons of direct CO_2 emissions have been avoided by genetic crops improvements in major arable crops in the EU in the past two decades.

9. In addition, plant breeding in the EU generates a large positive biodiversity effect. Without plant breeding in the EU in the last 20 years, global biodiversity equivalent to the species richness found in 8.3 million hectares of rainforest and savannahs in Brazil or in 11.8 million hectares of natural habitats in Indonesia would have been lost until 2020 in addition to what has already disappeared.

10. Plant breeding in the EU for major arable crops in the past two decades has finally contributed to saving scarce water resources around the globe. Without plant breeding almost 50 billion m^3 of water would be additionally needed today at global scale. This is as much as the water volume of Lago di Garda.

It can preliminarily be summarised: Plant breeding for arable crops in the EU has contributed a lot to yield progress since the turn of the millennium. This surely creates opportunities for the agrarian economy and the rural environment. In fact, it becomes obvious that EU plant breeding in arable farming is an essential part of the overall economic and social performance of the agricultural and food sector as it creates not only additional output but thereby also farm and societal income, jobs on farm and along the value chains, as well as market and trading opportunities which not only benefit the farmer but also the consumer. It becomes obvious, too, that plant breeding for arable crops in the EU additionally offers various environmental benefits: Due to a more efficient land use in the EU, it helps avoid additional use of still natural or nature-like habitats for agricultural purposes at global scale. This leads to less GHG emissions and biodiversity losses in other regions of the world being our trading partners. A more efficient use of water being a globally scarce resource as well can also be attributed to plant breeding progress in the EU.

Looking ahead, this perspective changes only a bit. Most of the indicators which have been analysed with respect to plant breeding for major arable crops in the EU in the past 20 years, that means since the turn of the millennium, show a rather stable and similar or an even higher value level if applied to potential plant breeding progress in the analysed upcoming decades until 2040. This allows to condense that successfully innovated genetic crop improvements in the EU have been and will be essential for economic, social and environmental benefits at large scale and should indeed be considered a highly effective measure for adapting to new challenges and very dynamic settings.

Fulfilling the various objectives of the "Farm to Fork" and "Biodiversity" strategies of the EU in this context marks a considerable new challenge for farmers in the EU and its member states as agricultural production would tend to considerably decrease until 2030 if the two strategies were fully implemented. Plant breeders are certainly able to help compensate negative effects that may arise from a production decline triggered by the strategies. However, plant breeding-induced innovations at current pace might obviously not be enough to fully counteract the potential impact arising from an implementation of the two strategies until 2030. The following can be highlighted in this respect:

- Production and subsequent market supply losses due to the two strategies until 2030 could potentially be halved with plant breeding in the next decade at current pace.
- Continually occurring genetic crop improvements in the next ten years have the potential to counteract approximately 55 percent of the apparent sectoral income and GDP shrinkages in 2030 that must be attributed to production and supply impacts of the strategies until then.
- Negative consequences on the use of global natural resources such as land and related GHG emissions and biodiversity issues as well as water that can be attributed to an enforcement of the two strategies until 2030 can be alleviated by 50 to 60 percent, assuming the same progress of plant breeding as in the past for the next ten years.

The question is: What can possibly fill the still existing gaps in the near future as plant protection and fertilisation shall be reduced with the two strategies and land machinery and other technologies have long-lasting investment intervals? It is, again, plant breeding that must be considered a potential "game changer". However, this requires speeding up processes aiming at genetic crop improvements. Therefore, all available technologies must be used, especially those able to provide genetic crop improvements in a more targeted way and a shorter time. In addition, the overall policy and regulatory framework must encourage and not hinder the necessary investments into future plant breeding.

In this respect, various case studies on potential impacts of resistant varieties developed through NPBT illustrate on an exemplified base that very specific genetic crop improvements may lead to remarkable benefits at farm and societal level if successfully implemented. Fungi-resistant wheat and grapevine varieties developed through NPBT, for instance, may be able to considerably reduce the number of applications of fungicides in European agriculture, thus, contributing to environmental protection. And pod shatter-resistant OSR varieties, virus-resistant sugar beet varieties, as well as drought-resistant maize varieties bred with modern sophisticated technologies, to take other examples, have the potential to remarkably increase yields thereby minimising pressure on scarce natural resources such as arable land.

However, it is not the individual case of a particular NPBT application that should count, but the overall potential these technologies have to contribute to plant breeding progress in general and over time. The mere time saving embedded in the NPBT due to accelerated trait integration and early generation selection will be substantial and will certainly lead to a considerable additional pant breeding-induced yield growth supporting reaching the ambitious goals of, for instance the "Farm to Fork" and "Biodiversity" strategies at European scale and the Sustainable Development Goals at global scale. Provided that the EU sees itself as a responsible actor that accepts the global and regional challenges involved herein and wants to play its part in meeting these challenges, it follows that economic, social, and environmental considerations must be taken into account in a balanced way when making decisions.

Plant breeders should be aware that their efforts have helped and can continuously help create synergies and avoid trade-offs embedded in multiple objective settings. In fact, plant breeding counts and shall be seen as a highly effective measure for adapting to new challenges and mitigating negative consequences which may arise while addressing these challenges. However, one question remains: Is plant breeding able to even do more than it has already contributed? It certainly should since increased crop productivity through the development of superior plant varieties may play not only a more accentuated but even substantiated role in the future as the adaptation of other improved land and crop management practices might be limited.

This makes plant breeding an extremely important area of research and development (R&D) and plant breeders must take responsibility by investing even more (than before) into innovation not only targeting higher harvestable yields but also other characteristics of a plant such as pest and disease resistance, other agronomic traits, product quality, crop adaptation and genetic diversity and orphan crops. This will also help meet specific objectives of the EU balancing environmental, social, and economic issues.

Plant breeders in the private but also public science sector are certainly willing and have the tools to do so. Yet, the success of, for instance, NPBT is not guaranteed at the science level alone – it is also influenced by social acceptance and policy decisions. To encourage plant breeders to further (and even more) invest into the development of new and better seed varieties and the therefore needed sophisticated breeding technologies, appropriate policy decisions and, in addition, public support are a must. Such support should include strengthening R&D as well as fundamental research in plant breeding and making evidence-based policy decisions for regulating.

In this respect, the "Farm to Fork" strategy does already acknowledge that latest research and subsequent innovative techniques, including biotechnology, may play a more important role in increasing sustainability. However, what is still missing are concrete policies and measures for this specific strategic aim of advanced R&D to enter into force.

Another option for policy support is public awareness raising. This study is also meant to increase such an awareness by providing evidence for the multiple benefits of plant breeding in agriculture and beyond based on reproducible findings and scientific facts. As such, this study should be considered an initial step in supporting and motivating this public debate. However, further foremost interdisciplinary research and evidence-based information campaigns need to follow and should be supported by policy makers and other public decision-makers including scientists.

Finally, a proportionate and result-focussed regulatory framework is needed to establish clear and sustainable rules for the European plant breeding sector. Instead of delaying or even hindering European plant breeders to spend the necessary resources on urgently needed future economic productivity increase and environmental resource use efficiency growth, such a legal setting should encourage them. In this respect, NPBT constitute a diverse group of techniques, each of which can be used in various ways to achieve different results and products. Therefore, safety considerations depend on the individual technique, how it is used and the characteristics of the resulting product and cannot be made on all techniques in total. Moreover, expert opinions consider that genetically and phenotypically similar products deriving from the use of different techniques are not expected to present significantly different risks. EU policy makers and regulators should take this into consideration when discussing potential future regulatory options.

To conclude, we have shown that plant breeding in the EU has made and will continue making important contributions towards sustainable agriculture covering all pillars of sustainability. Meeting the sustainability criteria is also a major impetus that comes from the "Farm to Fork" and "Biodiversity" strategies. In this respect, plant breeding and the two strategies can be considered congenial partners that depend on each other and can reinforce each other's positive effects. In other words: Without accelerating plant breeding in the EU in the future, the objectives of the "Farm to Fork" and "Biodiversity" strategies and, hence, the European Green Deal can hardly be achieved. To credit this importance, European plant breeders must be increasingly recognized by policy makers, regulators, and the society as supporters of sustainable development in agriculture and beyond.

List of figures

List of abbreviations

AOP	-	Appellation d'Origine Protégée
AWU	-	Annual Working Unit
BDP	-	Bundesverband Deutscher Pflanzenzüchter e.V.
BNYVV	-	Beet Necrotic Yellow Vein Virus
BYV	-	Beet Yellows Virus
CBD	-	Convention on Biological Diversity
CIS	-	Commonwealth of Independent States
DE	-	Germany
DEFRA	-	Department for Environment Food, and Rural Affairs
DMK	-	Deutsches Maiskomitee e.V.
DOC	-	Denominazione di origine controllata
EC	-	European Commission
EEA	-	European Environment Agency
EFSA	-	European Food safety Authority
ES	-	Spain
EU	-	European Union
FAO	-	Food and Agriculture Organization
FNVA	-	Farm Net Value Added
FR	-	France
GDP	-	Gross Domestic Product
GEF-BIO	-	Global Environment Facility Benefits Index of Biodiversity
GHG	-	Greenhouse Gas(es)
GIPB	-	Global Partnership Initiative for Plant Breeding Capacity Building
IMF	-	International Monetary Fund

INRAE	-	Institut National de la Recherche l'Agronomique, l'Alimentation et l'Environnement
IT	-	Italy
IWGSC	-	International Wheat Genome Sequencing Consortium
JKI	-	Julius Kühn-Institut
KTBL	-	Kuratorium für Technik und Bauwesen in der Landwirtschaft
MENA	-	Middle East/North Africa
MMM	-	Multi Market Model
NBI	-	National Biodiversity Index
NIST	-	National Institute of Standards and Technology
NPBT	-	New Plant Breeding Technologies
OECD	-	Organisation for Economic Co-operation and Development
OSR	-	Oilseed Rape
PPP	-	Plant Protection Products
R&D	-	Research and Development
RoW	-	Rest of the World
SITC	-	Standard International Trade Classification
TFP	-	Total Factor Productivity
UBA	-	Umweltbundesamt
UK	-	United Kingdom
UN	-	United Nations
UNEP	-	United Nations Environment Programme
USDA	-	United States Department of Agriculture
WBG	-	World Bank Group

1 Introduction: objectives and structure of the report

Five years ago, HFFA Research (2016) arrived at the conclusion that plant breeding in the European Union (EU) contributes to various socio-economic and environmental benefits. It particularly turned out that plant breeding innovations in EU member states around the turn of the millennium provided, on average, approximately three quarters of total productivity growth on arable land, i.e., increased yields in arable farming of the EU by more than 1.2 percent per annum. Based on this substantial plant breeding-induced land productivity growth, activities targeting genetic crop improvements resulted in numerous other benefits. Plant breeding did not only act to increase yields but also tended to increase potential world food supply, stabilize market prices, generate economic prosperity, increase social welfare, create additional farm income, secure agricultural jobs, improve the agricultural trade balance, minimize net virtual land imports, reduce CO_2 emissions, preserve biodiversity, and save agriculturally used water resources. In other words: Investments into EU plant breeding enabled European farmers to cope with manifold socio-economic and environmental challenges the agricultural sector was facing at that time.

Most of the challenges still have to be envisaged by farmers today, and additional tasks are currently on the agenda for the broader society. In terms of consumption of agricultural products, global population is projected to increase from an estimated 7.7 billion people in 2019 to around 8.5 billion in 2030 and 9.7 billion in 2050 (UN, 2019). This alone, ceteris paribus, implies an increase in demand for agricultural commodities of 0.75 percent per annum. However, global agricultural demand is projected to increase at a much higher rate. Islam and Karim (2018) as well as Fukase and Martin (2020), for instance, argue that food consumption until 2050 will annually increase by 1.72 percent. Apart from population growth, the main reason behind this development is income growth which also results in dietary shifts.

This considerable increasing global food demand, however, still excludes changes in non-food demand. Most probably, agricultural raw materials will also be used more frequently and intensively as inputs in various industrial and energy producing processes. Examples are the increasing use of crops for the generation of bioenergy – i.e., biodiesel and bioethanol – (Nakada et al., 2014; Malico et al., 2019) and as a source for the broader chemical industry (Yadaw et al., 2020), as well as the growing demand for cotton and other bio-fibres to, simply speaking, dress people (EC, 2018; USDA, 2020). Accordingly, a demand growth rate for agricultural raw materials in total in the range of 2.0 percent and more per annum seems plausible (OECD and FAO, 2020).) In other words: Within the next decades, global agriculture must provide considerably more output to satisfy accelerating demands.

This alone already constitutes a substantial challenge, which is even tougher considering the broader environment in which farmers in the EU will have to work. Climate change, various societal objectives and numerous environmental constraints narrow the alternatives they may opt for to produce healthy food and other agricultural produce. In fact, an ever-increasing use of natural and technical resources is considered a "no go" in the European context. The "Farm to Fork" strategy as well as the "Biodiversity" strategy of the EU (see EC, 2020a; b) are exemplifying and condensing this societal process. Not more inputs, but better inputs are needed to cope with the attributable challenges. For crop production, this means not to look at more land to be converted from natural or nature-like habitats and cultivated for agricultural purposes, but at higher yields enabled through better and not more machinery, better and less fertilizer, better and less plant protection products (PPP) – and of course: better seeds – on less agricultural land.

In this respect, it is the general objective of this research to provide sophisticated quantitative information and additional qualitative arguments highlighting major socio-economic values and environmental benefits of plant breeding as it is performed in the EU and its member states. More particular, the study aims at providing an update and enlargement of what has already been discussed within HFFA Research (2016). What was and potentially will be the impact of European plant breeding in terms of the economy and the environment? This is the underlying question to be holistically answered in the following, thus providing facts on to what extent plant breeding supports a sustainable agricultural and food system. Consequently, specific answers shall be given in terms of overall land productivity and plant breeding-induced yield growth. Moreover, the subsequent impacts on supply and trade volumes, market prices, producer income and gross domestic product (GDP), as well as food availability and security shall be derived. Furthermore, successive land-use changes and impacts on greenhouse gas emissions, as well as biodiversity effects and agricultural water use impacts are intended to be specified.

To analyse these impacts and, thus, to provide more insights into benefits of European plant breeding, a threefold approach will be used hereafter:

- First, an *ex-post* evaluation will be carried out. The assessment looks backwards and aims at a discussion of the various impacts of plant breeding in the EU for the past two decades.
- Second, an *ex-ante* assessment will be made. The evaluation looks forward and seeks to analyse similar effects of future plant breeding in the EU between 2020 and 2030 on the one hand and 2020 and 2040 on the other hand thereby considering an implementation of the EU's "Farm to Fork" and "Biodiversity" strategies.
- Third, the two analyses will be accentuated and even substantiated by selected case studies highlighting very specific potential values of plant breeding considering currently ongoing discussions in the EU on new plant breeding technologies (NPBT).

The two evaluation/assessment parts of the study will be conducted for the EU-28 in total, i.e., still including the United Kingdom (UK), and five selected EU member states, namely Germany (DE), France (FR), Italy (IT), Spain (ES), and the UK[1]. Thereby, the focus is on arable farming, and major target (groups of) crops of the analysis are wheat, corn, other cereals, oilseed rape (OSR), sunflower

1 The member states of the EU are abbreviated in accordance with the two-letter ISO code (ISO 3166 alpha-2). In addition, the Roman alphabet gives order for the naming of the EU member states.

seeds, other oilseeds, sugar beets, potatoes, and pulses[2]. This is to allow for a sound comparison with data discussed in HFFA Research (2016). Green maize, which was not analysed five years ago, will also be covered hereafter to ensure proper inclusion of this rather important element of arable land use within the EU into the analysis.

The structure of this report mirrors the just mentioned threefold approach and the above-described workload of research:

- After these introductory remarks in chapter 1, chapter 2 will provide the *ex-post* evaluation based on standard models and approaches of agricultural and environmental economics. The chapter will particularly look at primary productivity impacts first (sub-chapter 2.1) to properly derive secondary socio-economic consequences (sub-chapter 2.2) and tertiary environmental effects (sub-chapter 2.3), then.
- The following chapter 3 will deliver the *ex-ante* assessment based on a sound scenario definition including a consideration of the "Farm to Fork" and "Biodiversity" strategies of the EU (sub-chapter 3.1). In addition, it will analyse the particular value of plant breeding for meeting the objectives of the two strategies (sub-chapter 3.2) before specific socio-economic consequences (sub-chapter 3.3) and environmental effects (sub-chapter 3.4) will be discussed.
- Then, chapter 4 will deal with the case study analyses. Altogether, six sub-chapters, 4.1 to 4.6, referring to specific crops, regions and NPBT will be used to highlight very specific potential values of ongoing and future plant breeding in the EU.
- Finally, recommendations for private as well as public decision making will be given in chapter 5.
- In addition, various annexes will point at specific sources embedded into the analysis, methods applied, data used, and assumptions made to conduct the research in accordance with the scientific state of the art of science and statistics.

A specific aim of this study is to provide quantitative information and qualitative arguments not only for the EU in total, but also for five selected EU member states. Hence, each chapter and sub-chapter will be structured – whenever appropriate and despite unavoidable redundancies– to properly distinguish an overview from a more detailed discussion of findings for the EU in total and a description of particularities for each of the included EU member states.

2 The crops and groups of crops are defined in full accordance with FAO (2021). Wheat, for instance encompasses soft and hard wheat, and other cereals include barley, buckwheat, rye, oats, and triticale as well as seven other cereals. Similarly, other oilseeds are the aggregate of altogether thirteen oil-crops including soybeans, linseed, and mustard seed; and pulses refer to nine mainly dry pulses comprising, among others, dry beans, chickpeas, dry peas, and lentils.

2 Ex-post evaluation of the importance of plant breeding in the EU since the turn of the millennium

2.1 Primary productivity impacts

Basic requirements for the entire analysis of this study are to examine the yield development in EU arable farming and to determine a land productivity impact that can solely be related to plant breeding in the EU respectively its member states. This can be achieved by using a gradual approach: It looks at yield growth of arable crops first, calculates an innovation-induced yield growth in terms of hectare-related total factor productivity (TFP) growth for these arable crops then, and finally determines the plant breeding-induced yield growth of arable crops based on the share of plant breeding in innovation-induced yield growth. Applying this straightforward concept for the EU as a whole and its member states leads to the following results for the arable crops being in the focus of this study.

Yield growth of EU arable crops

Overview

Based on FAO (2021) data and in the case of missing information Eurostat (2021b) data, figure 2.1 displays the yield growth rates in arable farming for the core crops of this study since the year 2000 for the EU in total and the selected five member states. Therefore, statistically observable yields per region and crop were indexed by setting the yield of the year 2000 equal to 100 percent. This easier to compare information was then translated into annual percentage increases of yields.

Figure 2.1: Annual yield growth rates of arable farming in the EU and selected member states between 2000 and 2019 (in percent)

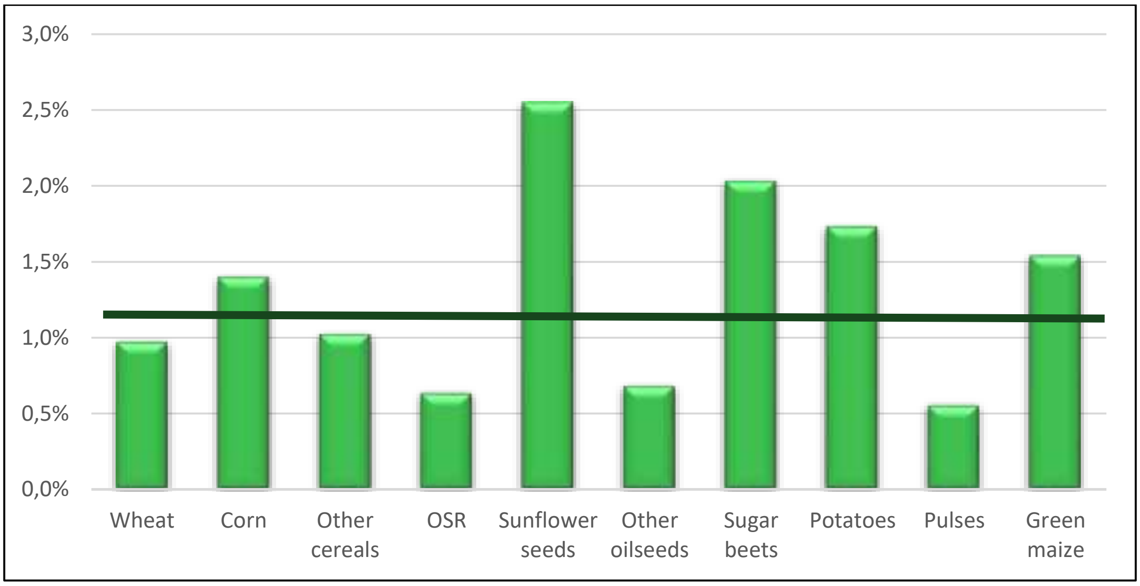
Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	0.97	0.21	0.09	1.51	0.94	0.40
Corn	1.40	0.39	0.27	0.55	1.38	0.45
Other cereals	1.02	0.64	0.19	0.96	0.51	0.41
OSR	0.63	0.09	0.55	4.41	2.01	1.02
Sunflower seeds	2.55	0.50	0.30	0.83	0.94	N.A.
Other oilseeds	0.68	2.60	0.40	0.25	1.18	2.94
Sugar beets	2.03	1.59	1.13	1.97	2.12	1.92
Potatoes	1.73	0.26	0.18	0.88	1.22	0.50
Pulses	0.55	0.48	0.23	1.09	1.59	0.19
Green maize	1.54	0.20	0.71	0.14	2.36	1.39

Source: Own calculations and figure based on FAO (2021) and Eurostat (2021b).

Analysis for the level of the EU in total

Looking more specifically at the EU in total, the yield developments since the turn of the millennium can be summarized as visualized with figure 2.2. Accordingly, it can be stated that yields in arable farming of the EU in total are still increasing. However, the crop-specific yield growth rates vary a lot. Yield growth is comparably high (more than 1.0 percent) with respect to sunflower seeds, root crops and green maize respectively corn, it is around 1.0 percent in the cases of wheat and other cereals, and it is rather low (between 0.5 and 1.0 percent) as regards various oilseed and protein crops. Weighted by hectare[3], the average yield growth rate in EU arable farming is, thus, 1.15 percent per annum (see the bold dark green line displayed in figure 2.2)[4], which is much lower than necessary to better cope with the manifold European and global challenges (see chapter 1).

Figure 2.2: Annual yield growth rates of arable farming in the EU between 2000 and 2019



Source: Own calculations and figure based on FAO (2021) and Eurostat (2021b).

Analysis for the level of EU member states – the case of Germany

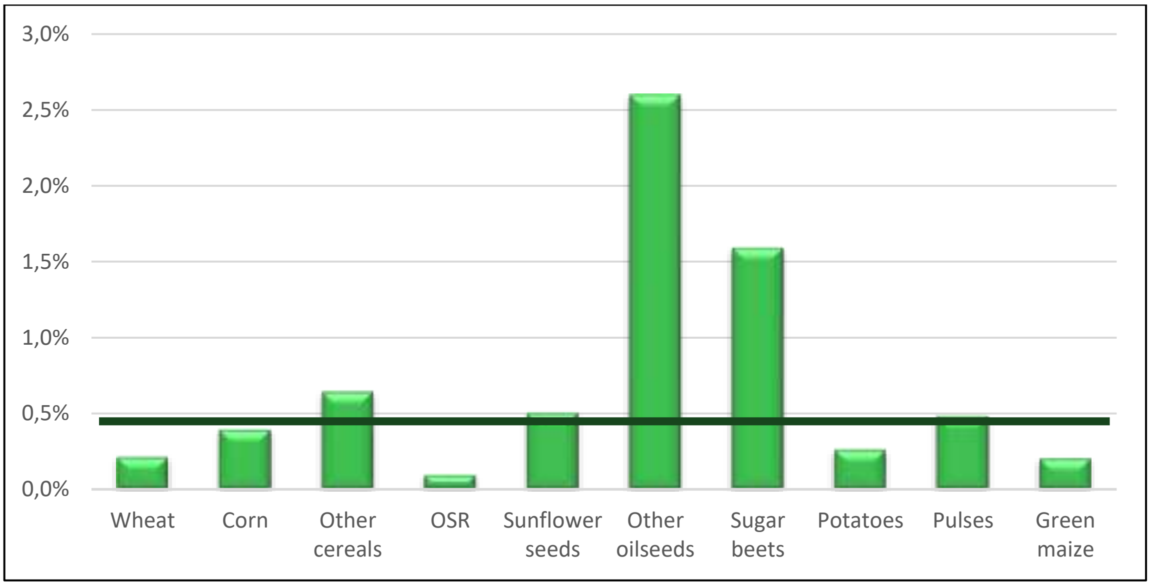
Looking now at the case of Germany, it turns out that the hectare-weighted average yield growth rate in arable farming is lower than on average for the EU in total. It is just 0.44 percent per annum as the bold dark green line displayed in figure 2.3 symbolizes. In Germany, yield growth rates post the millennium are still rather high (above 1.0 percent) per annum with respect to sugar beets and

3 Eurostat (2021b) data have been used to determine the share of acreage cultivated with a specific (group of) crop(s) and the EU and its member states for proper weighting.

4 To compare, HFFA Research (2016) calculated a corresponding hectare-weighted average yield growth rate of 1.10 percent. The specific finding, however, excluded green maize.

other oilseeds. They are in a corridor between approximately 0.5 and 1.0 percent per year in the cases of other cereals, sunflower seeds, and pulses. All other five arable crops are characterized by rather low annual yield increases below 0.5 percent.

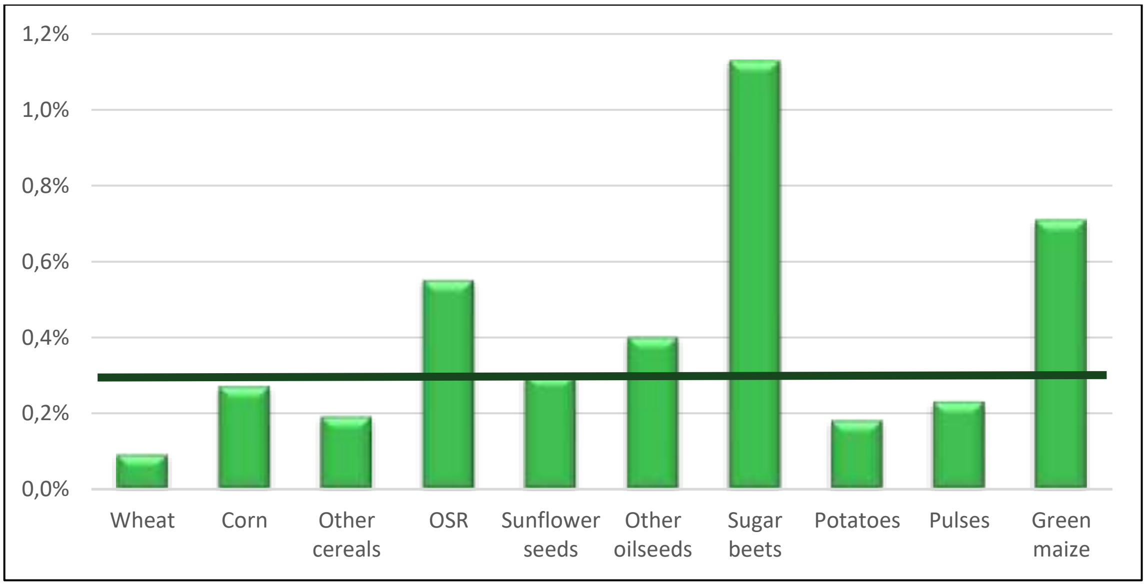
Figure 2.3: Annual yield growth rates of arable farming in Germany between 2000 and 2019



Source: Own calculations and figure based on FAO (2021) and Eurostat (2021b).

Analysis for the level of EU member states – the case of France

Figure 2.4: Annual yield growth rates of arable farming in France between 2000 and 2019



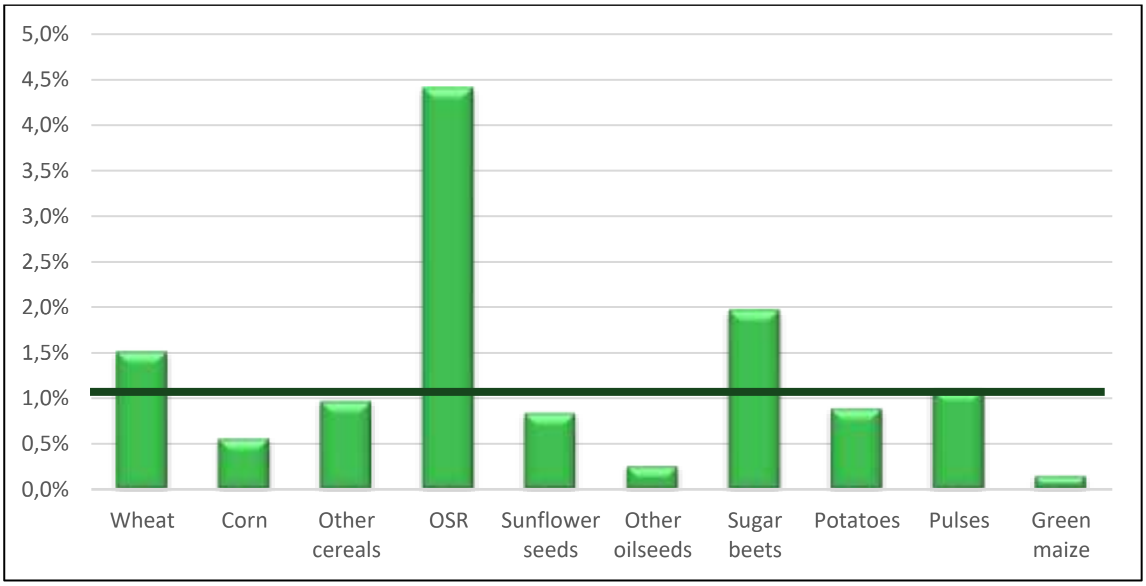
Source: Own calculations and figure based on FAO (2021) and Eurostat (2021b).

In the case of France, the hectare-weighted average yield growth rate in arable farming is also lower than on average for the EU in total. Here it is only 0.29 percent per annum as the bold dark green line displayed in figure 2.4 symbolizes. In France, the yield growth rate after the year 2000 is still rather high (above 1.0 percent per annum) in one case: sugar beets. It is between 0.5 and 1.0 percent per year in the cases of OSR and green maize, but below 0.5 percent per annum in all the other seven crops.

Analysis for the level of EU member states – the case of Italy

Looking more specifically at Italy, the yield developments since the turn of the millennium can be summarized as visualized with figure 2.5. Accordingly, it can be stated that yields in arable farming of the country are still increasing at a hectare-weighted average rate of 1.03 percent per annum, as the bold dark green line shows. This is close to the EU average annual yield growth rate. However, the crop-specific yield growth rates vary a lot. Yield growth is very high (more than 4.0 percent per annum) with respect to OSR and still rather high (more than 1.0 percent per year) in the cases of wheat, sugar beets and pulses. It is between 0.5 and 1.0 percent per annum as regards corn, other cereals, sunflower seeds, and potatoes and below 0.5 percent per year for other oilseeds and green maize.

Figure 2.5: Annual yield growth rates of arable farming in Italy between 2000 and 2019

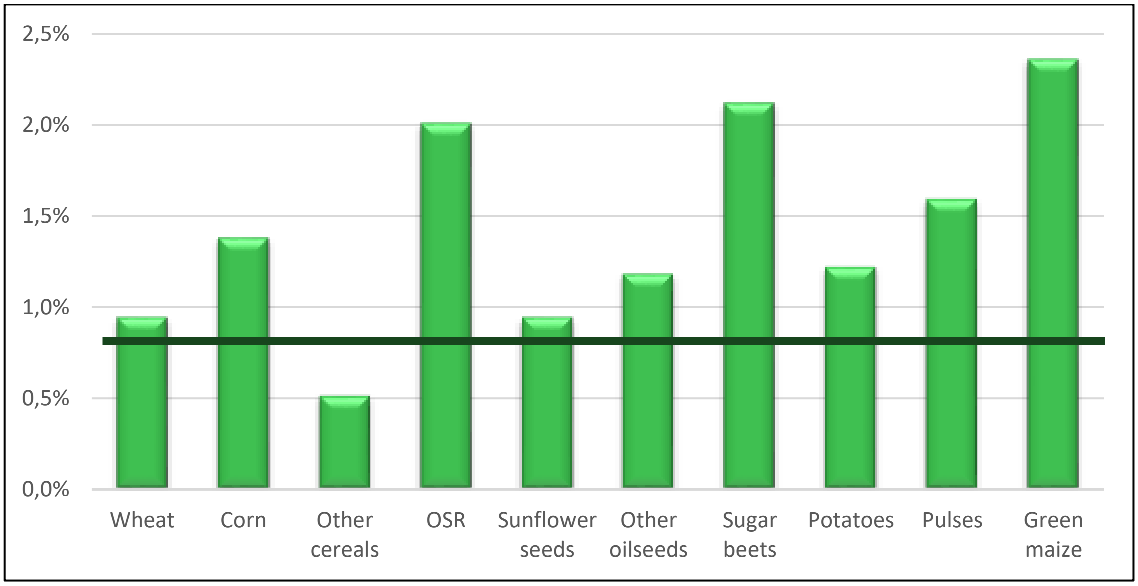


Source: Own calculations and figure based on FAO (2021) and Eurostat (2021b).

Analysis for the level of EU member states – the case of Spain

Figure 2.6 displays the outcome of the yield growth analysis for Spain. It turns out that the annual yield growth after the millennium is still well above 1.0 percent in the cases of corn, OSR, other oilseeds, root crops, pulses, and green maize. However, the hectare-weighted average yield growth rate is just 0.83 percent per annum (see the bold dark green line) since the yearly growth rate for other cereals, which occupy a rather large share of arable land, is only around 0.5 percent, while the yield growth of wheat and sunflower seeds is slightly below 1.0 percent per annum.

Figure 2.6: Annual yield growth rates of arable farming in Spain between 2000 and 2019



Source: Own calculations and figure based on FAO (2021) and Eurostat (2021b).

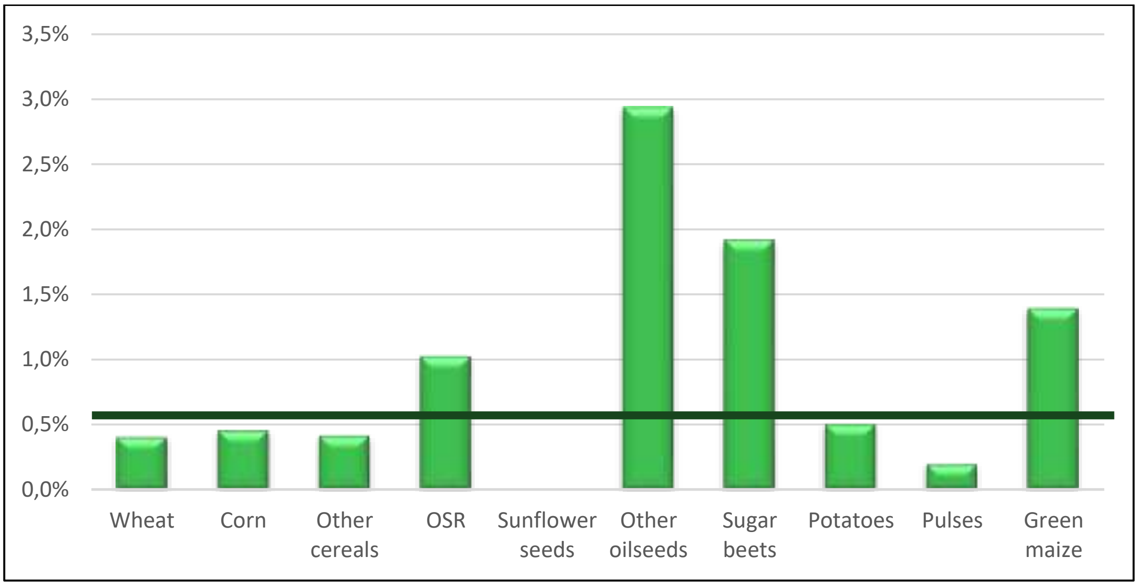
Analysis for the level of EU member states – the case of the UK

Looking at the case of the UK it can be stated that the hectare-weighted average yield growth rate in arable farming is – as in the cases of Germany, France, Italy, and Spain – lower than on average for the EU in total[5]. It is 0.57 percent per annum as the bold dark green line displayed in figure 2.7 symbolizes. In the UK, yield growth rates post the millennium are still rather high (above 1.0 percent) per annum with respect to OSR, other oilseeds, sugar beets, and green maize. It is around 0.5 percent per annum for potatoes, and within a corridor of around 0.2 and 0.5 percent per year in the cases of wheat, corn, other cereals, sunflower seeds, and pulses[6].

5 In fact, all five selected EU member states have experienced a lower average yield growth since the millennium than the EU in total. Obviously, other member states than the ones included herein have had higher yield growth rates. This seems plausible if EU enlargement and subsequent access to, for instance, better seeds and other inputs after 2005 in new member states are considered.

6 Note that reliable long-term data for sunflower seeds in the UK are not available due to the very small area cultivated with the crop in the country.

Figure 2.7: Annual yield growth rates of arable farming in the UK between 2000 and 2019



Source: Own calculations and figure based on FAO (2021) and Eurostat (2021b).

Innovation-induced yield growth of EU arable crops

Considering the complexity of managerial and technological processes applied in arable farming, such observable yield growth rates are normally a multifactorial outcome. By using long-term observations, the influence of weather phenomena and other short-term distortions and externalities such as ad-hoc policy interventions on the outcome of the analysis can be minimized (although not entirely excluded), but yield growth can still be induced by agricultural intensification or innovation respectively (see, e.g., Sayer and Cassman, 2013; Pretty et al., 2018). Considering the term "agricultural intensification" essentially referring to a process where intermediate inputs, capital and/or labour are increased to raise the productivity (in this case the yield of a fixed land area) and the term "innovation" pointing at the introduction of new inputs and better services that add value to agricultural production, one might say: Higher yields depend on more inputs per hectare of land and/or better inputs applied on a given area (Struik and Kuyper, 2017).

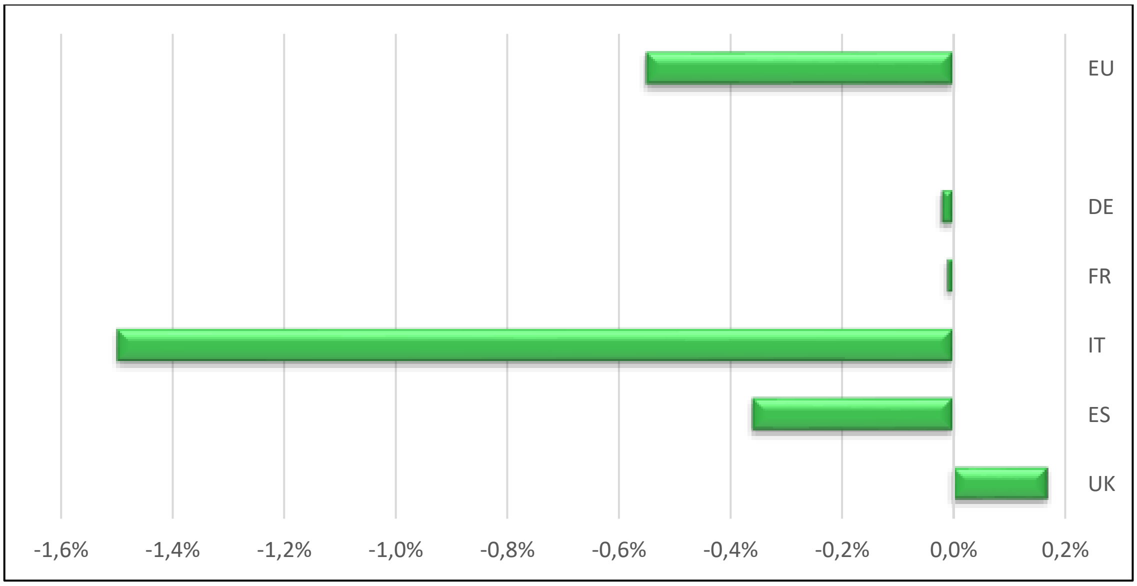
Economic assessments use the TFP indicator to demonstrate which parts of an observable change in overall productivity are induced by what here is called innovation and, thus, should not be related to increased (or decreased) factor use intensities (see, e.g., Lotze-Campen et al., 2015; Wang et al., 2020). Numerous theoretical and pragmatic applications of the TFP concept allow to state that this approach is standard in socio-economic science and particularly in agricultural economics (see, e.g., Alston and Pardey, 2014; Barath and Fertö, 2016; DEFRA, 2020; Fuglie and Toole, 2014; Fuglie, 2013; Piesse and Thirtle, 2010; Villoria, 2019).

This study counts on a rather straightforward and comparably few data demanding TFP calculation approach originally developed by Lotze-Campen et al. (2015), which is described in more detail in annex A and was already applied in HFFA Research (2016). Accordingly, an indicator will be established which measures the land productivity (or yield) progress that would have occurred if not more or less input, but always the same amount of better (innovative) input had been applied. In the following, we will call it innovation-induced yield growth. Consequently, developments in factor use need to be identified and incorporated into the analysis by subtracting them from statistically measurable yields leading to innovation-induced yield growth. The next paragraphs relate to this specific analysis and concentrate on the discussion of the development in factor use first, before the subsequent innovation-induced yield growth will be considered.

Overview on developments in factor use

The discussion starts with the identification of the annual growth rate in the use of arable land to mainly produce the ten (groups of) crops being in the focus of this study[7]. In this respect, figure 2.8 visualizes the development for the EU in total and the five selected EU member states since the year 2000 again using FAO (2021) data stress-tested by using national statistics, if available[8].

Figure 2.8: Annual growth rates of the use of land in arable farming of the EU and selected member states since the year 2000



Source: Own calculations and figure based on FAO (2021).

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7 Although not explicitly needed for the TFP formula discussed in annex A, this inclusion into the analysis is necessary to calculate meaningful TFP growth rates because several other input factors (see below) are not available per hectare and must therefore be adjusted for area developments.

8 Consistent and comparable data on factor use is not always given for 2000 to 2019. In a few cases, information is only available until 2018 or 2017. Therefore, the wording in headlines of figures partially switches from "between 2000 and 2019" to "since the year 2000".

Obviously, the use of land for arable farming has decreased over time in the EU in total as well as in four of the five selected EU member states. More precisely, average annual land use growth rates since the turn of the millennium are -0,55 percent for the EU in total, -0.02 percent in Germany, -0.01 percent in France, -1.50 percent in Italy, and -0.36 percent in Spain. In opposite to that, the land use growth rate is positive in the UK (0.17 percent per year). In other words: Arable land in the EU in total and various of its member states has become an increasingly scarce resource[9] and cannot be considered an important factor contributing to meet future demand growth at global scale.

Instead, land productivity growth is needed. In this respect, other input factors than land must be assessed for the calculation of meaningful TFP rates, i.e., the innovation-induced yield growth in EU arable farming following the approach described in annex A. Foremost, this concerns fertilizers, PPP, and seeds, as well as labour and capital embedded in, for instance, machinery and irrigation. Subsequently, figure 2.9 displays the developments as regards the three first-mentioned intermediate inputs often also referred to as variable production factors, again using FAO (2021) data stress-tested by using national statistics, if available, and already corrected for the above-described hectare developments.

Figure 2.9: Annual growth rates of the use of selected intermediate/variable inputs per hectare in the EU and selected member states since the year 2000 (in percent)

Input/Region	EU	DE	FR	IT	ES	UK
Fertilizers	0.4	-1.1	-1.9	-2.5	-0.8	-1.5
PPP	0.3	0.5	-1.2	-1.1	3.5	-1.2
Seeds	-0.7	-1.0	0.3	-0.6	0.6	-0.4

Source: Own calculations and figure based on FAO (2021).

Looking at the displayed developments of input use, the following must be highlighted in terms of volume growth rates for the EU in total and the selected member states:

- The use of fertilizers in terms of tonnages per hectare slightly increased in the EU in total, but has always slightly decreased in the selected EU member states being in the focus of this study[10].
- The application of PPP in terms of active ingredients per hectare also increased a bit for the EU in total. Here, also some of the focus EU member states show a slight decrease (France,

[9] The downward trend in the EU in total may simply be related to two well-known facts: First, a publicly desired and policy-induced saving of land for various environmental schemes can be assumed (van der Zanden et al., 2017), and second, a conversion of agricultural land towards infrastructure and urban settlements (EEA, 2017), as well as afforestation (Wood, 2019) must be noticed in the EU.

[10] Obviously, a considerable catch-up effect in the new EU member states contributed the most to the divergent picture (see, Eurostat, 2011).

Italy, and the UK), whereas the specific development in Germany (Spain) indicates a slight (considerable) increase of the use of PPP per unit of land.

- Diverging developments can also be found in the use of seeds per hectare. However, annual changes are low and within the range of +/-1.0 percent.

But what about the developments with respect to labour and capital, i.e., not entirely variable but more fixed input factors? Based on Eurostat (2021a) and EC (2010; 2019a) data – again stress-tested by using national statistics, if available, and already corrected for the above-described hectare developments – figure 2.10 provides information to answer this question.

Figure 2.10: Annual growth rates of the use of selected more fixed inputs per hectare in the EU and selected member states since the year 2000 (in percent)

Input/Region	EU	DE	FR	IT	ES	UK
Labour	-2.3	-1.9	-1.7	-1.2	-1.2	-0.8
Capital	1.2	1.1	0.5	1.3	1.4	-0.3

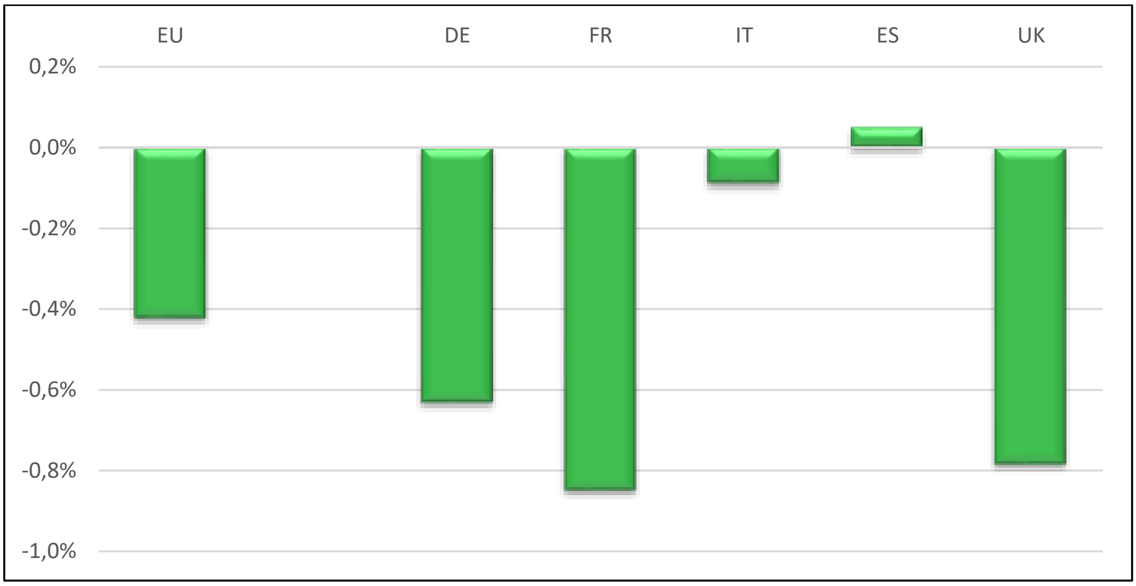
Source: Own calculations and figure based on Eurostat (2021a) and EC (2010; 2019a).

It turns out that labour input has also decreased in EU arable farming since the turn of the millennium. The annual growth rate is -2.3 percent. All the five selected EU member states also show a partly considerable decrease of labour input over time. In opposite to that, capital use in real terms[11] (including machinery, energy, rents, and interests) has somewhat increased since 2000 for the EU in total. The annual growth rate is 1.2 percent. All EU member states in the focus of the study belonging to the EUR-zone also show a corresponding increase in capital use. Only the UK (due to diverging inflation developments) experienced a slight decrease of real capital use.

Weighting the various change rates of the specific three intermediate inputs, as well as of capital and labour with the individual input shares of these production factors in the entire input in arable farming obtained from EC (2019) and KTBL (2021) results in the average growth rates of the overall input use displayed in figure 2.11. Accordingly, it can be stated that the aggregated use of variable and fixed production factors in EU arable farming changed at an annual rate of -0.42 percent. This very specific finding of decreasing input use per hectare should be considered an important message at this stage of the analysis as it points to the fact that agricultural production on available acreage in the EU in total has not intensified since the turn of the millennium. This is particularly noteworthy as public belief often claims an ongoing intensification of agriculture in the EU (UBA, 2015; Czyzewski et al., 2020; Fonderflick et al., 2020).

11 The nominal values obtained from EC (2010; 2019) were transformed into real values using annual inflation rates for the EUR-area as well as the UK as provided by WBG (2021).

Figure 2.11: Annual growth rates of the overall input use in arable farming of the EU and selected member states since the year 2000



Source: Own calculations and figure.

Looking at the various EU member states, some differences can be observed. The following shall be highlighted:

- It turns out that Germany (with -0.63 percent), France (with -0.85 percent) and the UK (with -0.79 percent) experienced a higher average annual decline of input use in arable farming than the EU in total.
- Italy also shows an annualized shrinking (-0.09 percent).
- Spain, however, has implemented a very small – almost negligible – annual increase of the overall input use in arable farming since the year 2000 (0.05 percent).

Overview on innovation-induced yield growth

According to equation (1) in annex A, these share-weighted annual growth rates of the overall input use must be subtracted from yield growth rates as displayed in figures 2.1 to 2.7 to calculate meaningful crop-specific annual innovation-induced yield growth rates for arable farming in the EU. However, before this can be done, at least two necessary structural adjustments must be considered.

The final objective of this part of the research is to calculate plant breeding-induced yield growth rates being determined by the share of plant breeding in innovation-induced yield growth. Therefore, the innovation-induced yield growth should not be biased by factors that cannot be fully captured by just looking at numeric yield and factor use growth rates which mask substitutional effects over time in yield generation and factor use. The two aspects to be considered here – because respective data is available – are:

- A structural change in the yield formation due to a switch to more organic farming

  Organic farming causes a lowering of average national yields if this agricultural management option becomes more popular in an EU member state. In other words: Without this shift in land management practice and assuming that the change in input intensities discussed with figures 2.9 and 2.10 applies to both, conventional farming (with mainly chemical fertilizers and PPP) and organic farming (with organic fertilizers and, for instance, biological and other approved PPP), the statistically observable yield growth – and subsequently following equation (1) of annex A also the innovation-induced yield growth – is higher than calculated with the approach chosen here. Using information on the growth of organic arable farming provided by EC (2019b) and on yield differences between organic and conventional farming in an EU context taken from Noleppa et al. (2013) as well as Noleppa (2016), the bias can be calculated and amounts on average to less than 0.1 percent of yield growth for the EU in total as well as all the selected EU member states[12].

- A structural shift in the use of PPP caused by the ban of neonicotinoids

  Slightly more important in terms of a bias to be excluded is the suspension of neonicotinoids in the cultivation of corn, OSR and sunflowers. The ban of this specific group of PPP entered into force in 2013. Since the end of that year farmers have been unable to purchase or sow seeds of crop varieties known to be attractive to bees if the seeds had been treated with neonicotinoids (Noleppa, 2017), with a few exceptions. Assessments of yield impacts post the ban (Kim et al., 2016; Market Probe, 2015; Noleppa, 2017) suggest that harvests have become lower despite the substitution of neonicotinoids through other PPP, mainly pyrethroids. Accordingly, an average yield depression of 4.0 percent can be assumed for harvests of corn and sunflower seeds since 2014 and (winter) OSR since 2015. The corresponding annualized yield growth bias since the turn of the millennium is, thus, around 0.22 percent.

Incorporating these two biases into our analysis and applying equation (1) of annex A leads to the crop-specific annual innovation-induced yield growth for the EU and its selected member states in the past two decades displayed in figure 2.12. Not surprisingly, it turns out that the vast majority of values of innovation-induced yield growth rates per year is slightly higher than the values of annual yield growth rates based on statistical observations (see, again, figure 2.1).

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12 One might argue now that organic farming particularly uses less (chemical) fertilizers and PPP, and that this should be considered in the calculation of the overall input growth rate. Data restrictions do not allow to do so. Apart from that, one should then also include a comparably higher use of labour and capital into the calculations. In fact, organic farming tends to increase production costs (see, e.g., KTBL, 2021), or in other words: It increases overall input use per hectare. Consequently, we are underestimating the bias of this structural change (moving from conventional to organic farming in the EU) and, hence, the innovation-induced productivity growth in the following.

Figure 2.12: Annual innovation-induced yield growth rates of arable farming in the EU and selected member states between 2000 and 2019 (in percent)

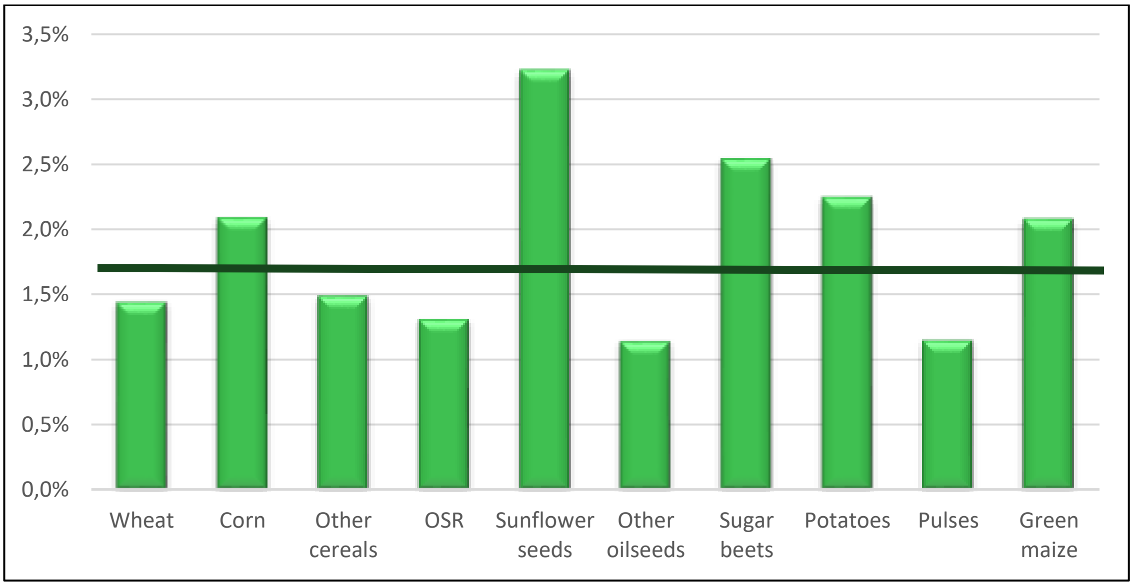
Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	1.44	0.91	0.98	1.67	0.93	1.21
Corn	2.09	1.38	1.44	0.93	1.59	1.45
Other cereals	1.49	1.34	1.08	1.12	0.50	1.22
OSR	1.31	1.05	1.71	4.76	2.21	2.02
Sunflower seeds	3.23	1.46	1.46	1.18	1.14	N.A.
Other oilseeds	1.14	3.27	1.28	0.38	1.16	3.75
Sugar beets	2.55	2.29	2.05	2.28	2.20	2.76
Potatoes	2.25	1.05	1.10	1.19	1.30	1.34
Pulses	1.15	1.29	1.19	1.71	1.86	1.05
Green maize	2.08	1.02	1.67	0.44	2.44	2.25

Source: Own calculations and figure.

Analysis for the level of the EU in total

The values listed in figure 2.12 and additionally displayed in figure 2.13 can again be used to generate a hectare-weighted average innovation-induced yield growth rate for EU arable farming.

Figure 2.13: Annual innovation-induced yield growth rates of arable farming in the EU between 2000 and 2019

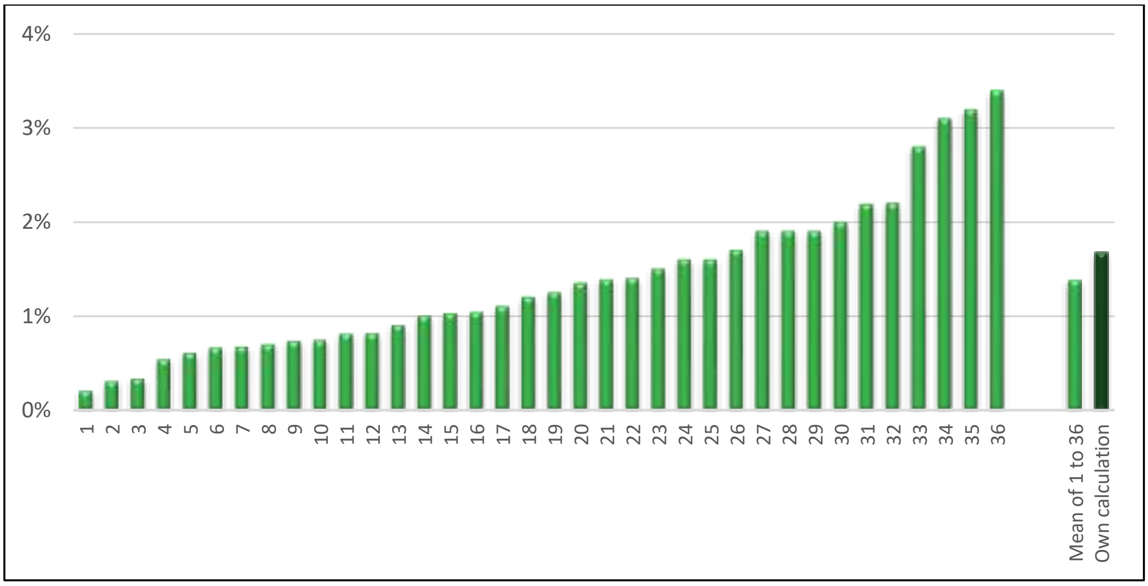


Source: Own calculations and figure.

Accordingly, it can be stated that innovations in EU arable farming have principally enabled a yield growth since the turn of the millennium of 1.68 percent per annum and hectare of arable farming (see the bold dark green line in figure 2.13)[13]. This is 0.53 percent more than what the statistically observable yield suggests and echoes what USDA (2019) analysed, namely that TFP growth outpaces production growth in high income countries after the turn of the millennium.

In this respect, figure 2.14 confronts the own finding on innovation-induced yield growth – or TFP growth – in arable farming for the EU in total with the outcome of several other analyses. It is based on an own meta-analysis looking at science-based TFP calculations for EU agriculture in general and particularly arable farming done in only the past decade. Accordingly, 16 publications listed in annex B comprising a total of 36 individual TFP growth rates were identified[14].

Figure 2.14: Annual TFP growth rates in EU agriculture vs. own calculation for innovation-induced yield growth



Source: Own calculations and figure.

It turns out that the outcome of a calculation of TFP growth rates for EU agriculture in general and particularly arable farming is highly dependent on the used methodology and data. However, it

13 To compare, HFFA Research (2016) calculated a corresponding hectare-weighted average innovation-induced yield growth rate of 1.70 percent. The specific finding, however, excluded green maize. A modest decline should have been expected and simply mirrors what recent science suggests, namely that a positive TFP growth in EU agriculture is still given but less dynamic as in the past (see, e.g., Barath and Fertö, 2016; EC, 2016).

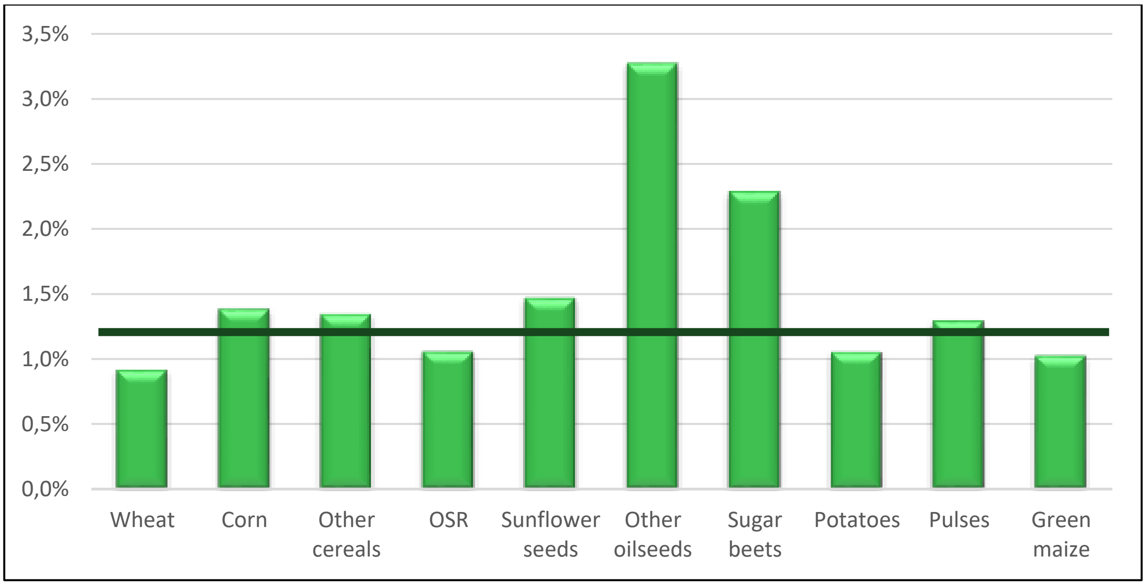
14 Various methodologies and data sources form the base for the different outcomes of these publications. Each methodology, thereby, has its pros and cons. Thus, the displayed picture should be considered a plausible "range of scientific wisdom".

always results in a non-negative growth rate, which simply points at ongoing innovation contributing – on average of the identified sources – 1.38 percent to overall productivity growth. This is just a bit lower than our own calculation of an average innovation-induced yield growth rate. In other words: Our own calculation passes a stress test and fits condensed scientific wisdom.

Analysis for the level of EU member states – the case of Germany

Looking at figure 2.15 and the displayed innovation-induced yield growth in the case of arable farming in Germany, it turns out that the hectare-weighted average increase per year since the turn of the millennium has been 1.21 percent (see the bold dark green line in figure 2.15). This is 0.76 percent more than what the statistically observable yield suggests and points to the fact, that innovations in German arable farming have a particularly high importance for overall yield development.

Figure 2.15: Annual innovation-induced yield growth rates of arable farming in Germany between 2000 and 2019

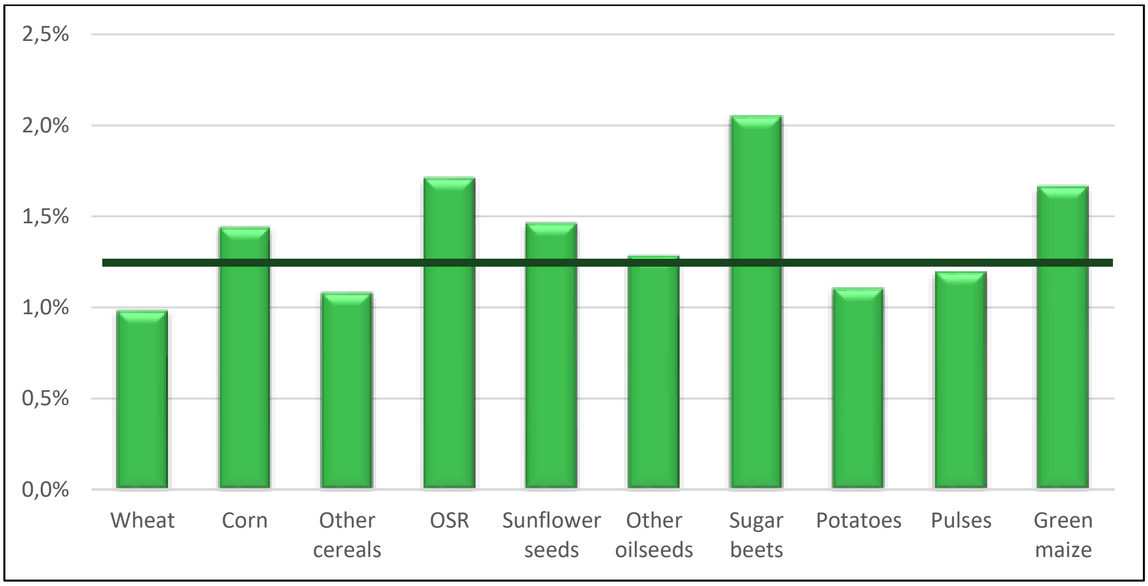


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of France

Similarly, figure 2.16 displays the innovation-induced annual yield growth in the case of arable farming in France between 2000 and 2019. Accordingly, it can be stated that the hectare-weighted average increase is 1.26 percent (see the bold dark green line in figure 2.16). This is 0.97 percent more than what the statistically observable yield growth suggests and indicates that innovations play a very pronounced role in arable yield development in France. In fact, this is the highest increase compared to measurable arable yields on fields of all the five EU member states being in the focus of this research approach.

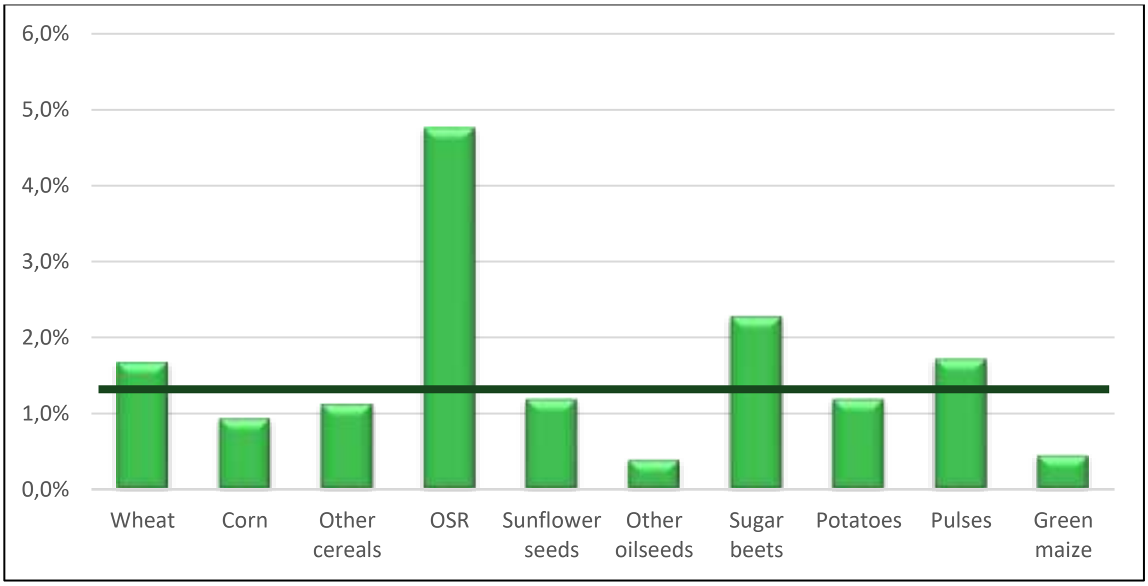
Figure 2.16: Annual innovation-induced yield growth rates of arable farming in France between 2000 and 2019



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Italy

Figure 2.17: Annual innovation-induced yield growth rates of arable farming in Italy between 2000 and 2019



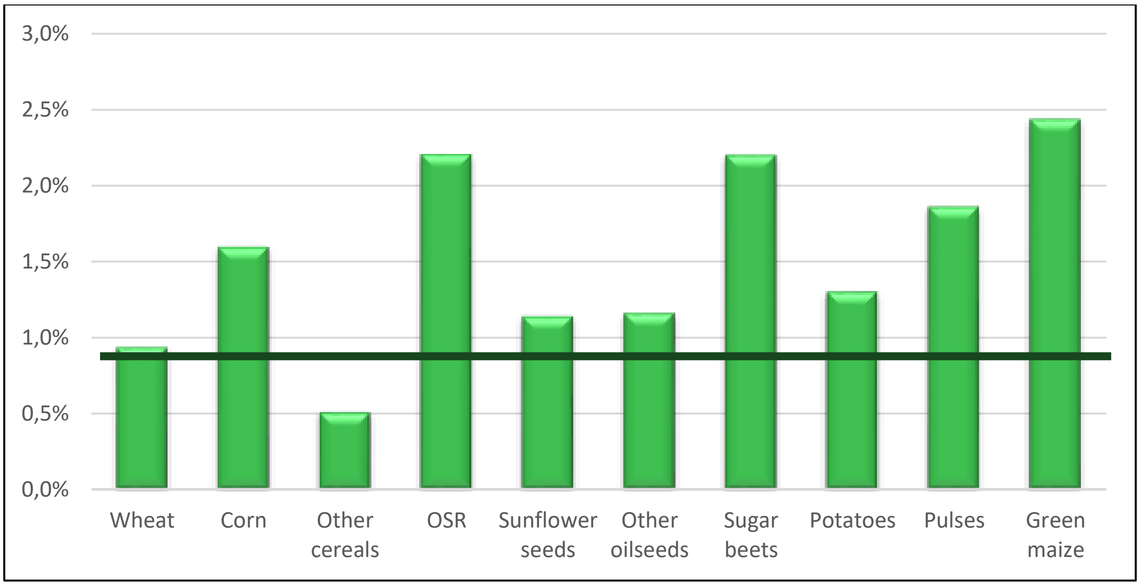
Source: Own calculations and figure.

Looking now at figure 2.17 and the visualized innovation-induced annual yield growth in the case of arable farming in Italy since the year 2000, it turns out that the hectare-weighted average increase is also 1.26 percent (see the bold dark green line in figure 2.17) as in the case of France. Again, innovations apparently play a very positive role although the innovation-induced yield growth is "just" 0.23 percent higher than the statistically observable yield growth.

Analysis for the level of EU member states – the case of Spain

Figure 2.18 shows similar information for the case of arable farming in Spain. Looking at the displayed values, it can be said that the hectare-weighted innovation-induced average yield increase is 0.88 percent (see the bold dark green line in figure 2.18). Again, this is higher than the statistically observable yield growth and suggests that innovation-induced yield growth has been very important for overall yield formation in the country in the past two decades.

Figure 2.18: Annual innovation-induced yield growth rates of arable farming in Spain between 2000 and 2019

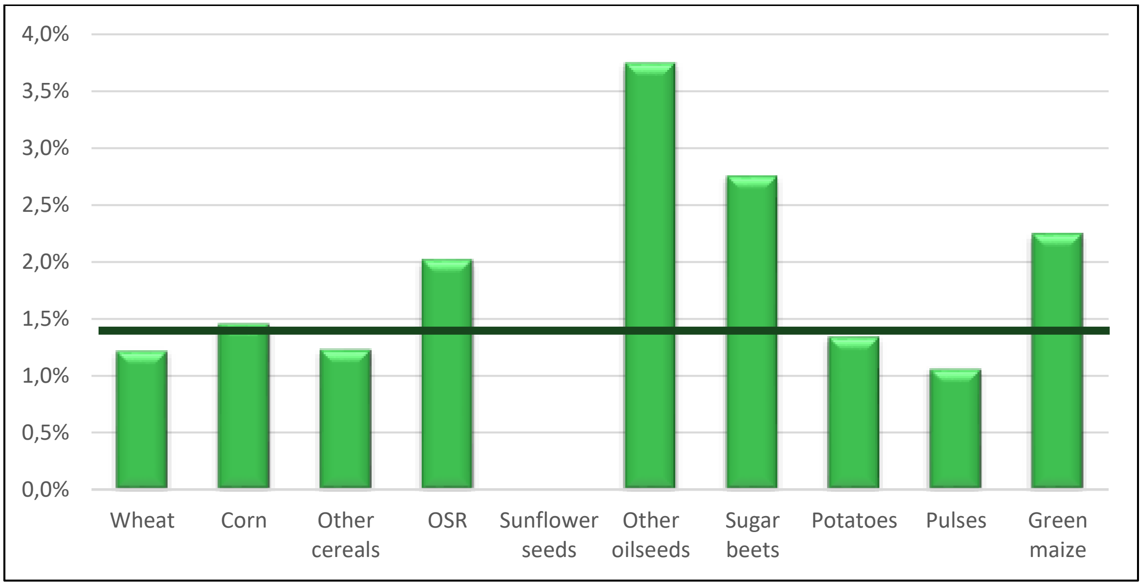


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of the UK

Finally, figure 2.19 shows similar information for the case of arable farming in the UK since the year 2000. Accordingly, it can be stated that the hectare-weighted average increase is 1.42 percent (see the bold dark green line in figure 2.19). This is 0.84 percent higher than the statistically observable yield growth, what points to the fact, that innovations have a particular high importance for overall yield development in UK's arable farming.

Figure 2.19: Annual innovation-induced yield growth rates of arable farming in the UK between 2000 and 2019



Source: Own calculations and figure.

Plant breeding-induced yield growth of EU arable crops

At this stage of the analysis, it can be highlighted that crop-specific innovation-induced yield growth in the various EU member states has varied between almost 0.4 percent and more than 4.0 percent in recent years (see, again, figure 2.12). These just derived rates can be considered the most appropriate measure to discuss "real" (unbiased) yield developments in EU arable farming. Focusing on the topic of this study, however, the discussed improvements can still be borne by innovations in plant breeding on the one hand and/or by advances in crop nutrition, crop protection, irrigation, machinery, etc. on the other hand (see also HFFA Research, 2016; EC, 2016). To allow for an assessment of the share of plant breeding in sectoral innovation in total, i.e., to calculate the plant breeding-induced yield growth for the crops and regions of interest, it is now necessary to identify the relative importance of activities related to genetic improvements for yield growth in EU arable production. Therefore, a meta-analysis "squeezing out" available scientific literature and expert wisdom on the specific topic that has been published past the millennium was conducted.

In fact, various expert opinions, numerous academic calculations, and several science-based variety trials allow to determine the share of plant breeding vs. other innovation for yield determination in EU crop production. Some of them are very specific, others are more general. And all of them apply different kinds of methodology – with pros and cons. A single information might, thus, not be perfect, in total, however, the identified knowledge provides the most complete picture and condensed wisdom on what is considered a fair share of innovations to be attributed towards plant breeding.

In this respect, most of the identified sources – all of them not published before 2000 – already attribute a specific percentage share of real yield development to plant breeding. Other sources allow for a direct comparison of real land productivity growth over time vs. yield manifestation of varieties (distinguishable in terms of the year of release) or for more indirect conclusion, e.g., when all other but plant breeding innovations are discussed as drivers of productivity growth. Altogether, 111 sources providing respective information were identified. They are listed in annex C.

The sources allow for the specification of 365 data points[15] and constitute, to our knowledge, the most comprehensive data base on the subject ever established. Besides, it constitutes a considerably enlarged evidence base in comparison to HFFA Research (2016)[16]. The findings can be summarized with figures 2.20 and 2.21., which already exclude extreme outliers and, thus, include "only" 342 instead of 365 data points[17]. Before the figures will be discussed, a brief specific explanation shall be added: While analysing the displayed frequency distribution of shares of plant breeding in innovation-induced yield growth, it becomes apparent that there are data points – altogether 9.5 percent of all data points – indicating a share of plant breeding which is higher than 100 percent. A share of more than 100 percent is possible due to improper management and at least two other reasons:

- First, externalities must be considered (see above). The TFP calculation approach used here (and in many other studies) is not able to filter out impacts of, for instance, devastating and not annually occurring climate change events such as droughts and/or cold spells on yields. Unfortunately, such events become more frequent (see, e.g., Cammarelli et al., 2020; Jiménez-Donaire et al., 2020) and always tend to lower (a) real yield growth rates and by subtracting input use developments from such rates also (b) innovation-induced yield growth rates.

- Second, negative innovation is possible. Apart from the already excluded negative impacts on yield that arise from the enlargement of organic farming and the ban on neonicotinoids, this can also be related to decreasing efficiencies of certain inputs. For instance, well accepted PPP become less protective over time due to resistances (see, e.g., Heap, 2018), certain fertilizers are time-wise restricted and may not be applied when they are needed most, etc.

Against this background, figure 2.20 displays a box plot diagram of the frequency distribution of the identified innovation-induced yield growth shares of plant breeding.

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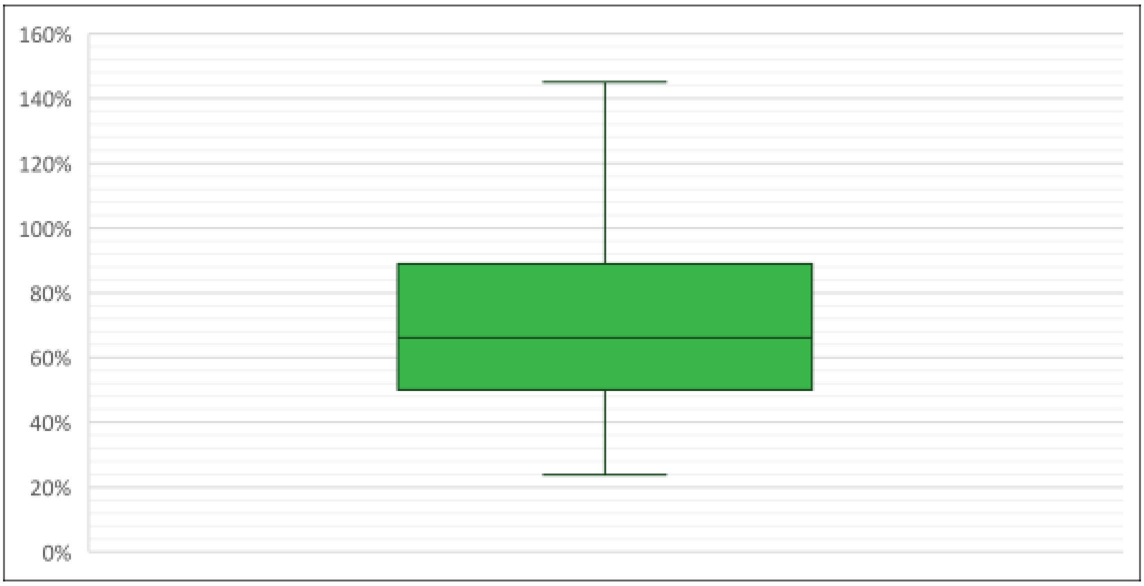
15 . Each data point refers to a specific share of plant breeding on innovation-induced yield growth with respect to a certain crop and region (i.e., the EU in total or one of its member states).

16 In HFFA Research (2016), 27 sources and 85 data points were used to conduct the analysis of plant breeding values. That means, the data base has been tripled.

17 Extreme outliers are removed from the following figures and the subsequent analyses since such extremes act to push statistical indicators of tendency and/or spread into merely "one direction", thus, tending to overinterpret a particular analytical aspect. However, there is no scientific consensus about what must be considered "extreme". The definition is usually left up to the analyst. As a "rule of thumb", a data point beyond the so-called outer fence on either side of the frequency distribution (i.e., the first quartile minus 3.0 times the interquartile range and the third quartile plus 3.0 times the interquartile range) is considered an extreme outlier to potentially be excluded from further analyses (NIST, 2012).

Figure 2.20: Box plot of frequency distribution of shares of plant breeding in innovation-induced yield growth in EU arable farming



Source: Own calculations and figure.

Accordingly, most of the identified data points refer to a share of plant breeding in productivity within the range from 50 to 90 percent (located within the inner fences of the box plot). The mean value is 66.8 percent[18]. A similar picture can be drawn by looking at figure 2.21, which displays the histogram of the frequency distribution of the identified shares of plant breeding. Again, it turns out that specific shares are located within a rather broad interval. However, more than three quarters of all shares are within the narrower range of 45 to 95 percent.

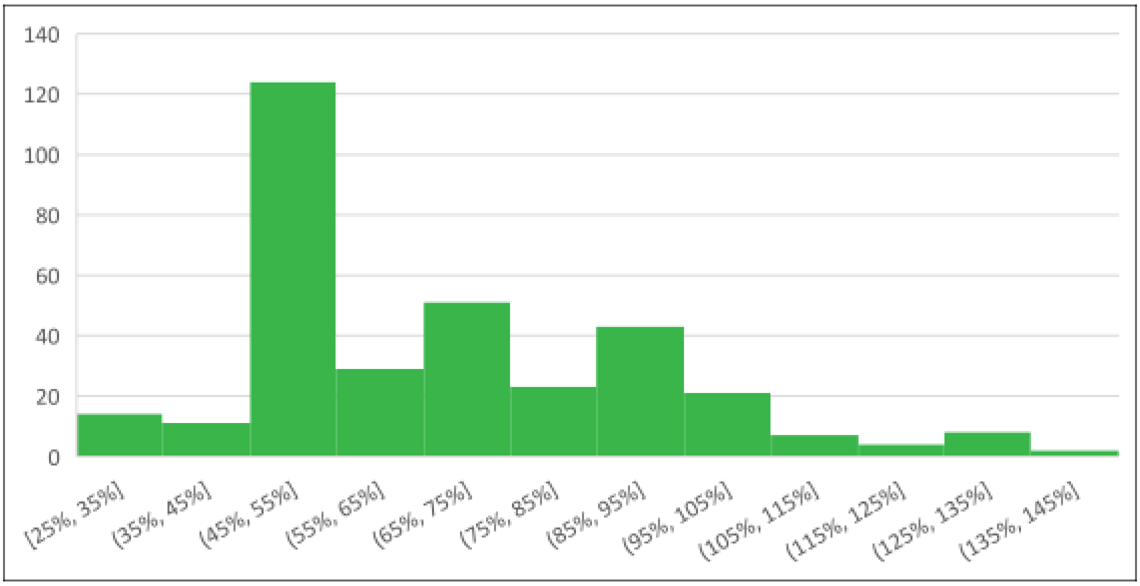
The various sources and information thereof also allow to allocate specific findings to certain crops and individual regions since many sources included or separated information to do so[19]. In this respect, figure 2.22 shows the calculated average shares of plant breeding in innovation-induced yield growth per crop and EU member state being in the focus of this study. Subsequently, it can be stated for the entire region that crop-wise and country-specific the importance of plant breeding for innovations is between 58 and 88 percent[20].

18 To compare, HFFA Research (2016) used a corresponding mean value of 70 percent.

19 Basically, available country-specific information was double-weighted in comparison to information which relate to the EU in total. This foremost applies to data for Germany, France, and the UK. With respect to Italy and Spain only wheat data could be used for such a country-specific finding due to limited information for the other arable crops.

20 Calculated as a weighted mean of all specific data per crop and country out of the data set displayed in figures 2.20 and 2.21 excluding extreme outliers.

Figure 2.21: Histogram of frequency distribution of shares of plant breeding in innovation-induced yield growth in EU arable farming



Source: Own calculations and figure.

Figure 2.22: Shares of plant breeding in innovation-induced yield growth rates of arable farming in the EU and selected member states between 2000 and 2019 (in percent)

Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	66	67	70	62	61	71
Corn	68	80	74	68	68	71
Other cereals	72	75	72	72	72	77
OSR	75	78	86	75	75	88
Sunflower seeds	74	75	88	74	74	N.A.
Other oilseeds	74	75	88	74	74	81
Sugar beets	59	61	77	59	59	61
Potatoes	59	62	60	59	59	63
Pulses	66	71	83	66	66	80
Green maize	67	72	82	67	67	68

Source: Own calculations and figure.

Consequently, the following preliminary summary can be drawn: Considering academic literature and the noticeably broad consensus in science it becomes obvious that plant breeding across all arable crops in the EU and its member states has a tremendous impact on innovation-induced yield growth in arable farming. In the past two decades, genetic crop improvements have been responsible for the (vast) majority of innovation-driven progress.

Overview on plant breeding-induced yield growth

The information on rates (see, again, figure 2.12) and the share of plant breeding in this innovation-induced change (see, again, figure 2.22) can now be merged. Multiplying the innovation-induced yield growth rate with the share of plant breeding leads to the plant breeding-induced yield growth rate in EU arable farming. The results of this algebraic transformation are displayed in figure 2.23.

Figure 2.23: Annual plant breeding-induced yield growth rates of arable farming in the EU and selected member states between 2000 and 2019 (in percent)

Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	0.95	0.61	0.69	1.04	0.57	0.86
Corn	1.43	1.10	1.06	0.64	1.09	1.03
Other cereals	1.07	1.01	0.78	0.80	0.36	0.94
OSR	0.98	0.82	1.47	3.58	1.66	1.77
Sunflower seeds	2.38	1.10	1.29	0.87	0.84	N.A.
Other oilseeds	0.84	2.46	1.13	0.28	0.85	3.05
Sugar beets	1.51	1.39	1.57	1.35	1.30	1.68
Potatoes	1.33	0.66	0.65	0.70	0.77	0.84
Pulses	0.76	0.91	0.99	1.14	1.23	0.84
Green maize	1.39	0.73	1.36	0.30	1.63	1.52

Source: Own calculations and figure.

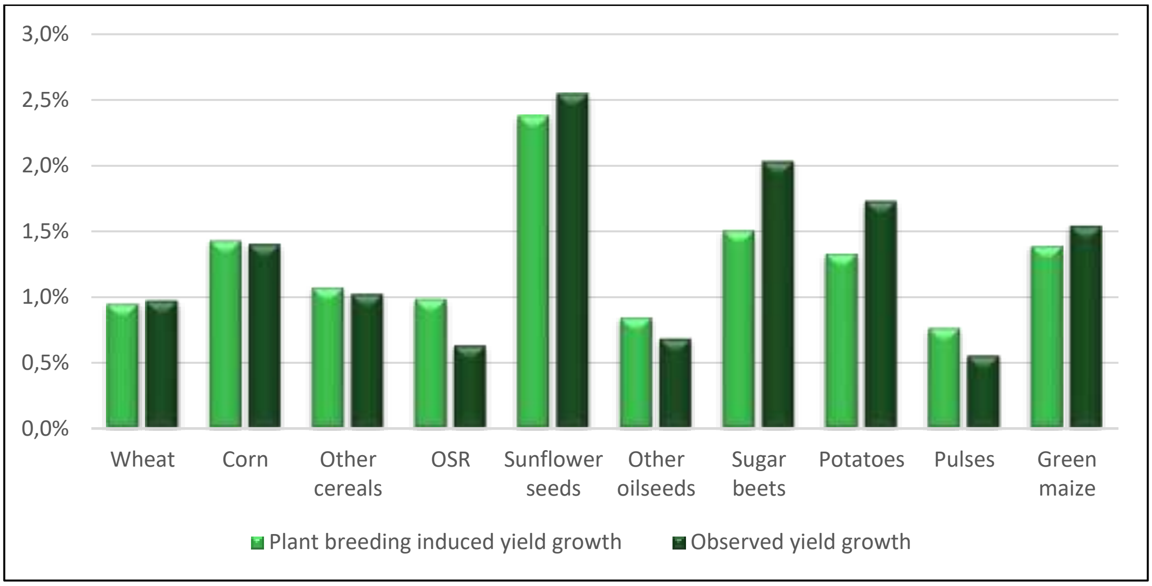
Analysis for the level of the EU in total

Figure 2.24 compares these impacts with the observed annual yield growth per crop for arable farming in the EU in total. It turns out that in all cases plant breeding has an enormous impact that is often like or even larger than statistically measurable yield progress[21]. On average, weighted by

21 At first glance, it might be counter-intuitive that the yield impact of innovations from plant breeding could be higher than the statistically observable trend in yield development. In this respect, it shall be repeated that observable yield is a multifactorial outcome. Some factors such as new seed varieties turn out to increase yields. Other factors, however, tend to decrease yields. A lower overall input use in arable farming, as displayed in figure 2.11, is one important and essential determinant in this regard. Other drivers are (or can be) a higher share of organic farming, a thinning of the spectrum of available PPP, more frequent weather disasters, etc. Analysing the importance of such factors and summing up the embedded partial positive or negative yield impacts makes sense but are beyond the scope of this research.

hectare, it accounts for an annual yield growth of 1.16 percent[22] between 2000 and 2019, what is slightly higher than the observed average yield growth (1.15 percent, see figure 2.2).

Figure 2.24: Annual plant breeding-induced yield growth and annual observed yield growth of arable farming in the EU between 2000 and 2019



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Germany

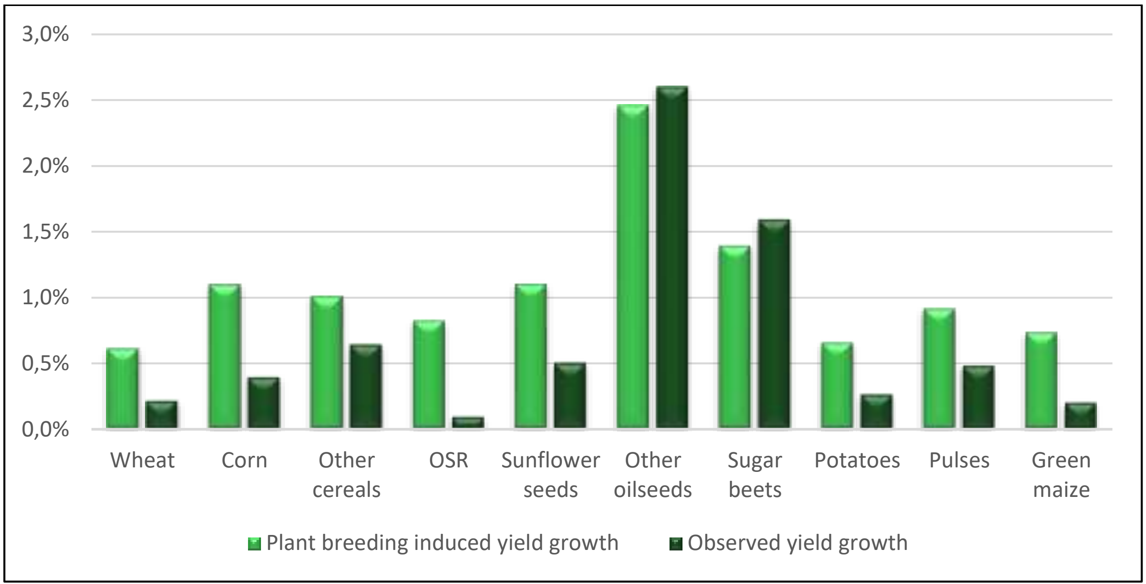
A similar graph can be drawn for arable farming in Germany. It is displayed in figure 2.25 and leads to the conclusion that, on average and weighted by hectare, plant breeding alone has generated an annual yield growth of 0.87 percent between 2000 and 2019, what is considerably higher than the observable yield growth of 0.44 percent in Germany (see figure 2.3).

Analysis for the level of EU member states – the case of France

The plant breeding-induced yield growth per annum since the turn of the millennium is also much higher than the observable annual yield growth in arable farming of France as figure 2.26 visualizes. In this EU member state, on average and weighted by hectare, plant breeding has contributed 0.96 percent to yield increases. This contribution is, as in the case of, for instance, Germany, considerably higher than the observable yield growth (0.29 percent, see figure 2.4).

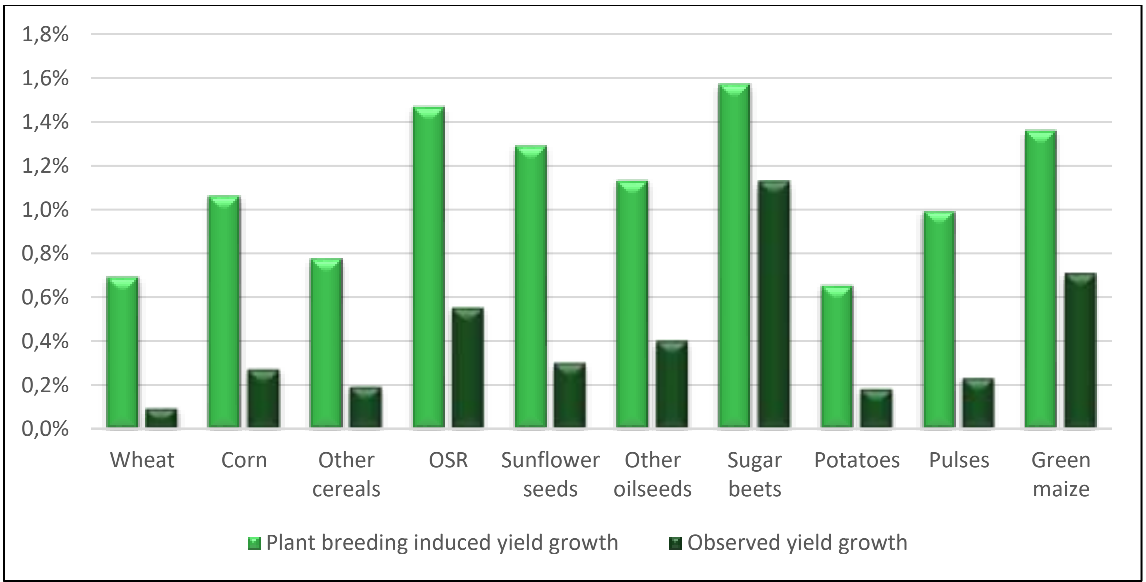
22 This is in an almost similar range as the 1.10 percent postulated by HFFA Research (2016). Thus, the "best guesses" used to assess the importance of plant breeding then can now be substituted by concrete calculations, which by and large confirm but in detail accentuate and substantiate the findings of HFFA Research (2016).

Figure 2.25: Annual plant breeding-induced yield growth and annual observed yield growth of arable farming in Germany between 2000 and 2019



Source: Own calculations and figure.

Figure 2.26: Annual plant breeding-induced yield growth and annual observed yield growth of arable farming in France between 2000 and 2019

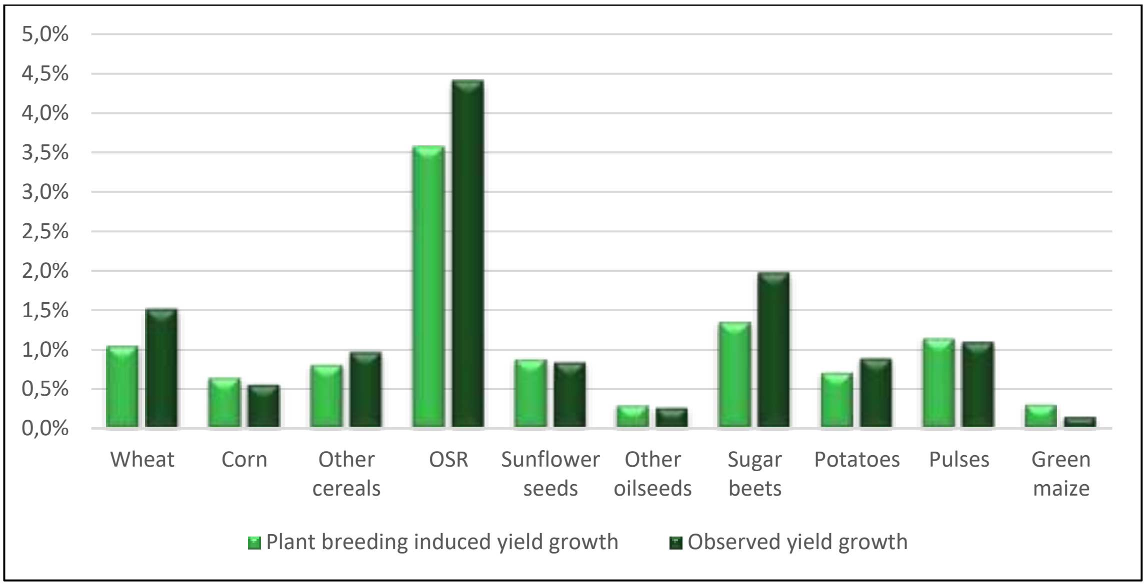


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Italy

The Italian example is an interesting case study insofar as here the crop-specific plant breeding-induced yield growth is rather often smaller than the observable yield growth. Figure 2.27 shows this for five of the ten (groups of) crops. This leads to an average hectare-weighted annual plant breeding yield growth of 0.82 percent, which is slightly lower than the observable yield growth of 1.03 percent between 2000 and 2019 (see figure 2.5).

Figure 2.27: Annual plant breeding-induced yield growth and annual observed yield growth of arable farming in Italy between 2000 and 2019



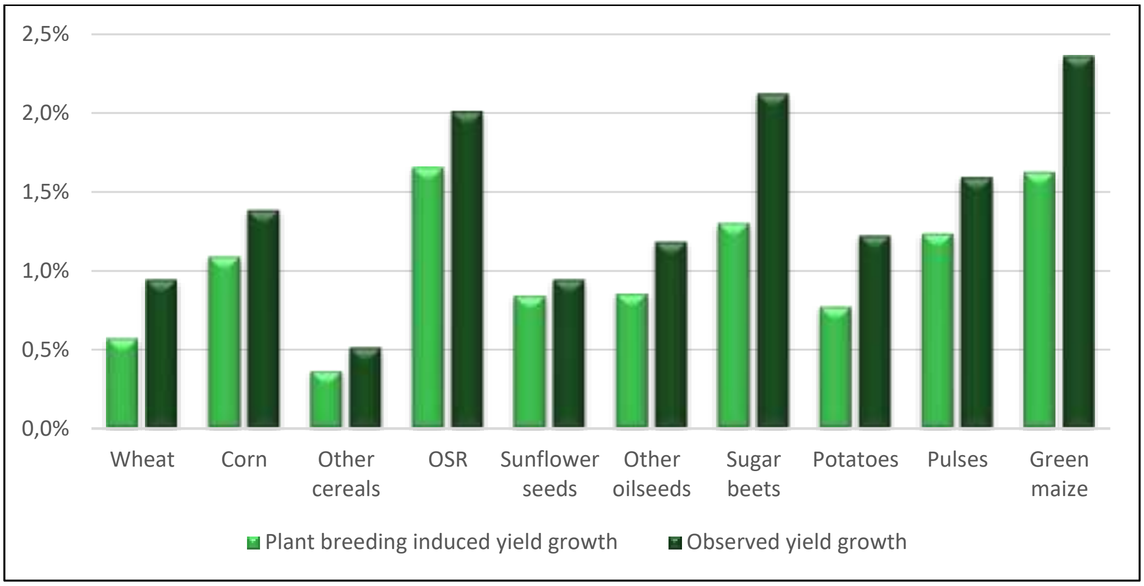
Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Spain

Looking at arable farming in Spain, it turns out that, on average and weighted by hectare, plant breeding alone has generated an annual yield growth of 0.59 percent between 2000 and 2019, which is lower than the observable yield growth of 0.83 percent (see figure 2.6). As figure 2.28 shows, in this EU member state all crop-specific values for plant breeding-induced yield growth are smaller than the correspondingly observed yield increase[23].

[23] In Spain, the overall input use in arable farming has not decreased since the turn of the millennium but remained rather stable (see figure 2.11). Decreasing input use, however, tends to increase the importance of innovation. In this respect, it shall also be highlighted that especially the use of PPP in Spain has increased (see figure 2.9) and the growth rate of capital use is higher than in any other EU member state analysed here (see figure 2.10). It can therefore be assumed that innovations embedded in PPP and capital, e.g., in irrigation technologies, play a pronounced role for increasing yields in Spain.

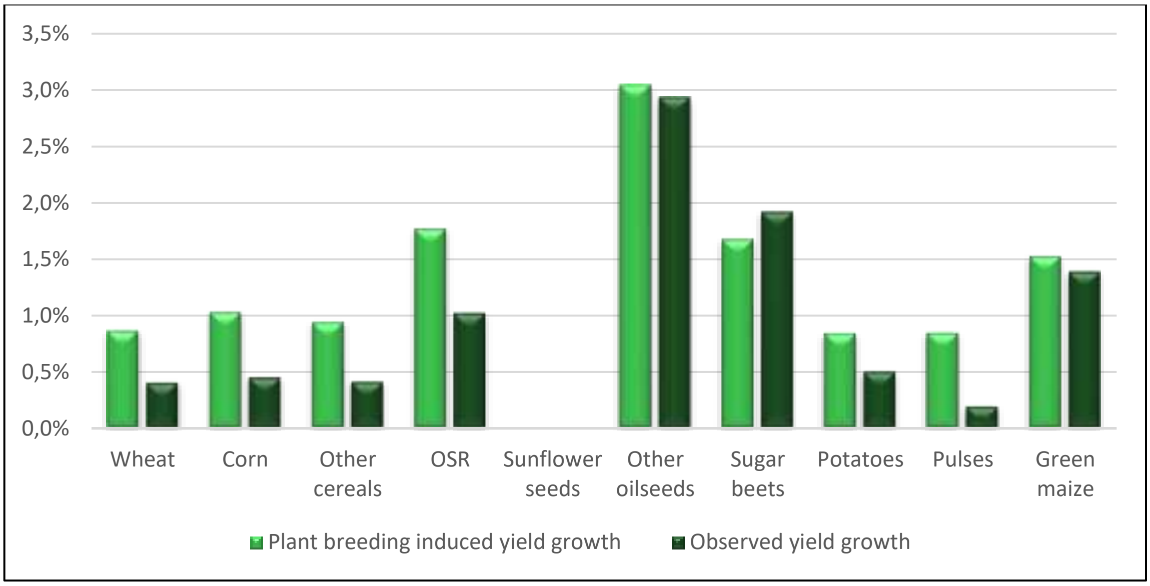
Figure 2.28: Annual plant breeding-induced yield growth and annual observed yield growth of arable farming in Spain between 2000 and 2019



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of the UK

Figure 2.29: Annual plant breeding-induced yield growth and annual observed yield growth of arable farming in the UK between 2000 and 2019



Source: Own calculations and figure.

The plant breeding-induced yield growth per annum is again much higher than the observable annual yield growth in arable farming of the UK between 2000 and 2019 as figure 2.29 visualizes. In this EU member state, on average and weighted by hectare, plant breeding has contributed 1.06 percent to yield increases. The observable yield growth was just 0.57 percent (see figure 2.7).

2.2 Secondary socio-economic consequences

Definition of shift factors to derive plant breeding impacts via proper scenario technique

Analysing the values plant breeding in and for the EU and its member states has had since the turn of the millennium requires to specify a scenario on the status quo in arable farming without yield increases induced by plant breeding efforts in these years. More particularly, the scenario definition must supply a shift factor which various models of agricultural (and later also environmental) economics will be shocked with to derive plant breeding-related impacts on certain indicators. The methodology particularly uses the models and tools of agricultural economics described in annex D.

Overview on defined shift factors by EU region and crop

These models must be shocked with an impulse describing yields in today's arable farming without plant breeding-induced yield growth since the year 2000. More particularly, this shock parameter simulates a relative yield change per region and crop expressed as the percentage to be calculated by accumulating the average annual plant breeding-induced yield growth rates (see figure 2.23) for the entire time horizon between 2000 and 2019 using the compound interest approach. Consequently, figure 2.30 displays the simulated currently experienced yield loss without plant breeding in the EU and selected member states in the last two decades for the chosen major arable crops.

Figure 2.30: Simulated yield loss for major arable crops in 2020 without plant breeding progress between 2000 and 2019 in the EU and selected member states

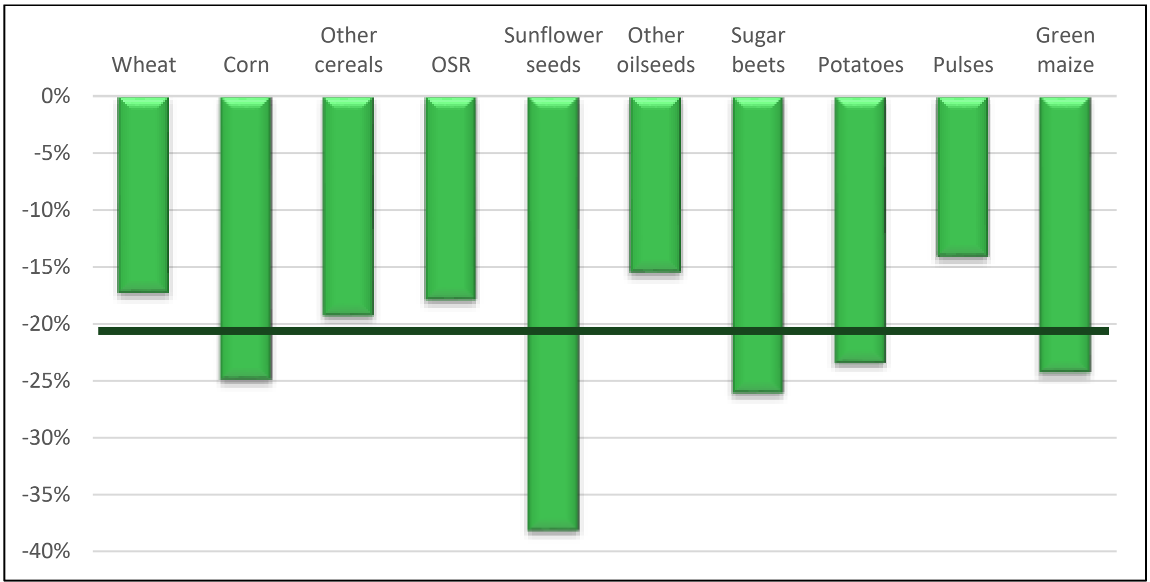
Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	-17.3	-11.5	-12.9	-18.9	-10.8	-15.9
Corn	-25.0	-19.8	-19.3	-12.0	-19.7	-18.7
Other cereals	-19.3	-18.4	-14.4	-14.9	-7.0	-17.2
OSR	-17.9	-15.2	-25.6	-51.7	-28.4	-30.0
Sunflower seeds	-38.2	-19.9	-22.9	-16.1	-15.5	N.A.
Other oilseeds	-15.5	-39.3	-20.4	-5.5	-15.7	-46.2
Sugar beets	-26.2	-24.5	-27.2	-23.7	-23.1	-28.7
Potatoes	-23.5	-12.3	-12.3	-13.1	-14.3	-15.5
Pulses	-14.1	-16.8	-18.1	-20.4	-22.0	-15.6
Green maize	-24.4	-13.7	-24.0	-5.8	-28.0	-26.5

Source: Own calculations and figure.

Analysis for the level of the EU in total

A remarkable drop in arable yield would currently have to be envisaged[24] across all crops without genetic crop improvements, as figure 2.31 indicates. One sixth of current EU wheat production would be missing, for instance. And in the case of sugar beets (sunflower seeds) the loss would be more than a quarter (a third). Inversely rated, EU arable farming today produces much more on arable land than without the plant breeding successes of the last 20 years. Weighted by current acreage, the yield loss in 2020 that can be associated with missing plant breeding progress between 2000 and 2019 would account for 20.6 percent of overall arable production in the EU (see the bold dark green line in figure 2.31).

Figure 2.31: Simulated yield loss for major arable crops in 2020 without plant breeding progress between 2000 and 2019 in the EU



Source: Own calculations and figure.

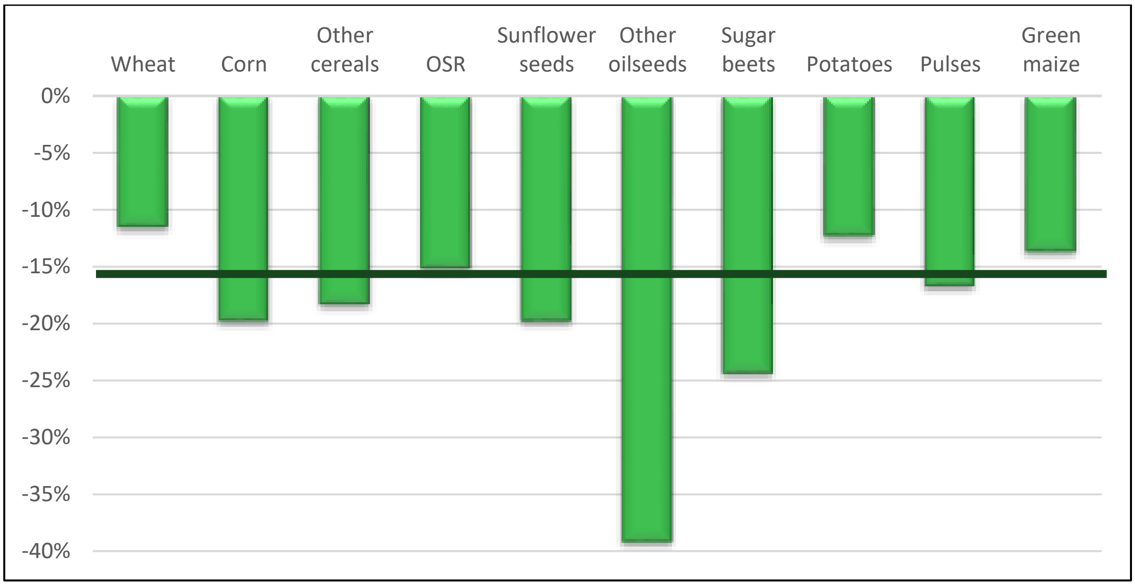
Analysis for the level of EU member states – the case of Germany

In Germany, also a considerable drop in arable yield would have occurred today without progress in plant breeding since 2000 as figure 2.32 indicates. It would have been highest in the cases of other oilseeds (almost 40 percent) and sugar beets (almost 25 percent). All other major arable crops would have shown yields being 10 to 20 percent lower as they currently are. Weighted by hectare, the

24 To abstract from short-term particularities, such as bad weather events or ad hoc policy distortions, it is standard in agricultural economics to use a mean of most recent years to display a specific time-related situation. In this regard, "current" always refers to the year 2020 statistically described as the mean of data for the past three years available.

yield loss in 2020 that can be related to missing plant breeding since the turn of the millennium would account for 15.9 percent of German arable production (see the bold dark green line in figure 2.32).

Figure 2.32: Simulated yield loss for major arable crops in 2020 without plant breeding progress between 2000 and 2019 in Germany



Source: Own calculations and figure.

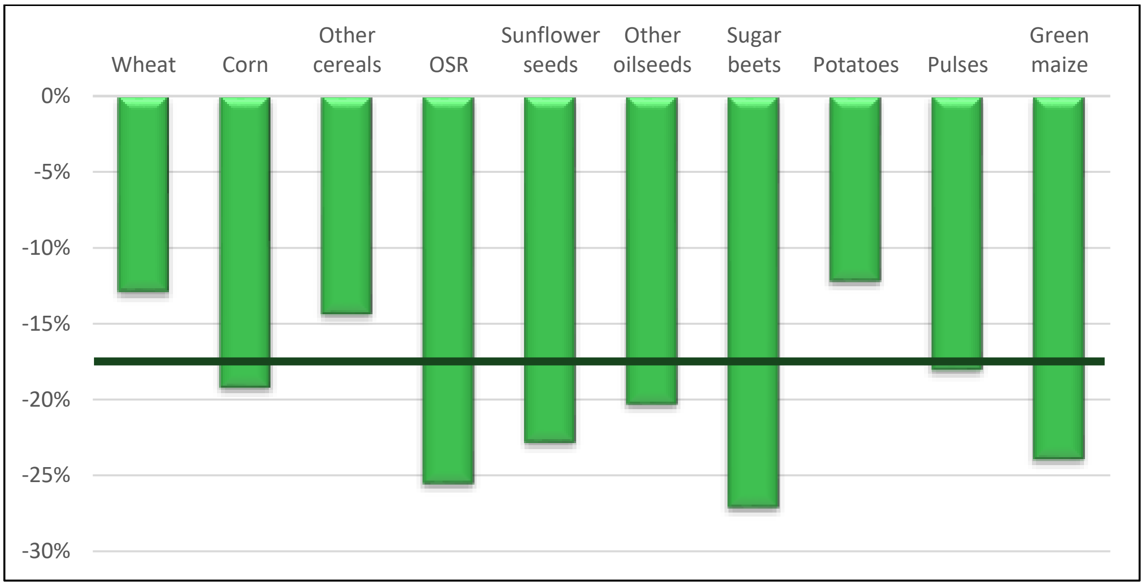
Analysis for the level of EU member states – the case of France

The hectare-weighted average of yield losses in 2020 due to missing plant breeding progress since 2000 would be 17.4 percent in the case of arable farming in France as the bold dark green line in figure 2.33 indicates. In this EU member state, the current yield loss would be around 25 percent in the cases of four crops, namely OSR, sunflower seeds, sugar beets, and green maize, and it would still be well above 10 percent in the cases of wheat, other cereals, and potatoes. Corn and other oilseeds would have shown a yield depression of around 20 percent.

Analysis for the level of EU member states – the case of Italy

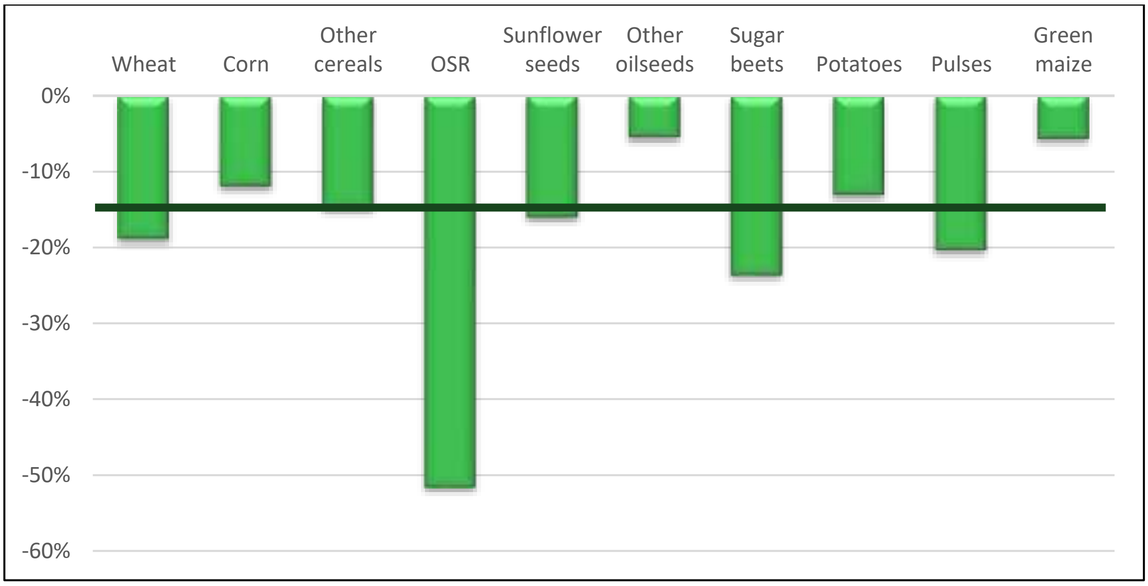
In this EU member state, the current yield loss would be rather high in the case of OSR (more than 50 percent). In various other cases it would be between 10 and 20 percent as figure 2.34 visualizes. This, for instance, applies to all the cereals crops. Only in the cases of other oilseeds and green maize, the yield loss that can be associated with a non-existence of plant breeding progress since 2000 would be lower than 10 percent. Weighted by acreage, the yield loss in 2020 that can be attributed to missing plant breeding efforts since the turn of the millennium would account for 15.1 percent of overall arable production in Italy (see the bold dark green line in figure 2.34).

Figure 2.33: Simulated yield loss for major arable crops in 2020 without plant breeding progress between 2000 and 2019 in France



Source: Own calculations and figure.

Figure 2.34: Simulated yield loss for major arable crops in 2020 without plant breeding progress between 2000 and 2019 in Italy

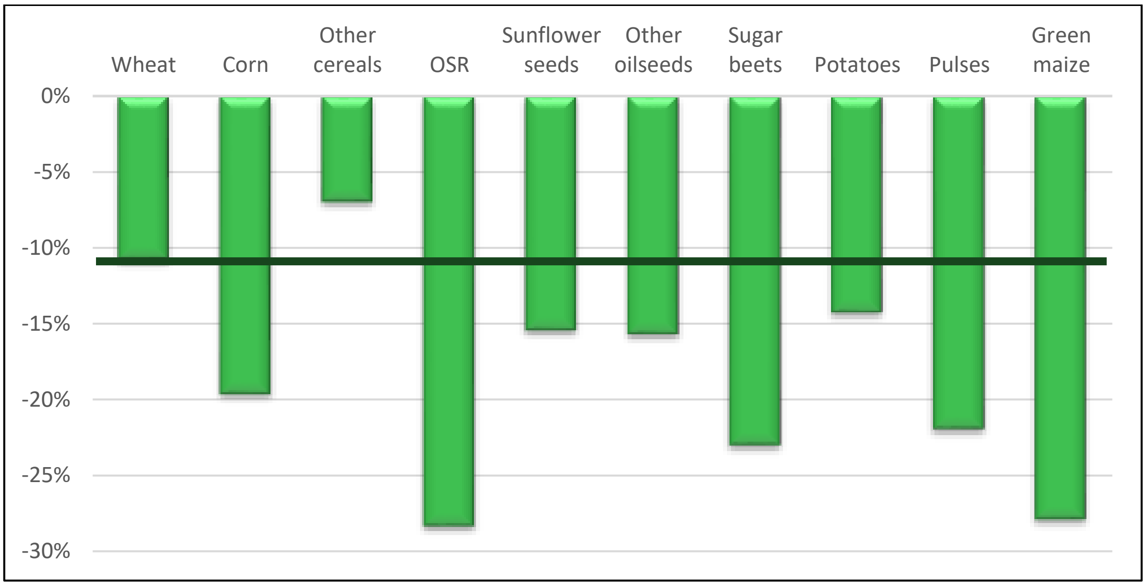


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Spain

Looking at arable farming in Spain, it turns out that every ninth unit to be harvested today would be missing in the absence of plant breeding progress since 2000. This is indicated by the bold dark green line in figure 2.35. The corresponding yield loss in 2020 would be the greatest in the case of OSR and green maize (almost 30 percent) and the lowest in the case of other cereals (7.0 percent).

Figure 2.35: Simulated yield loss for major arable crops in 2020 without plant breeding progress between 2000 and 2019 in Spain



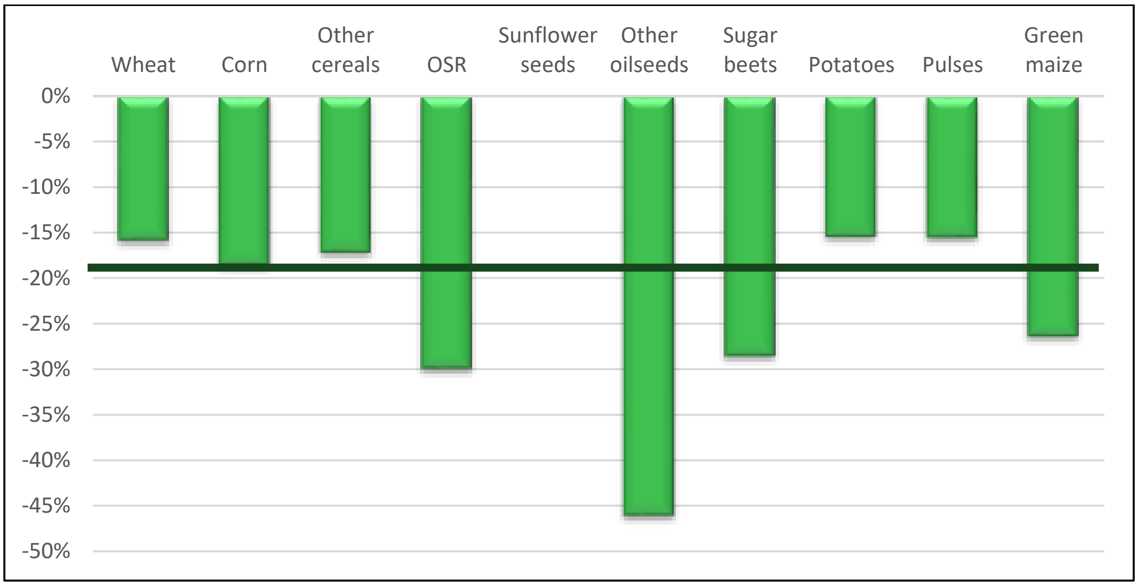
Source: Own calculations and figure.

Analysis for the level of EU member states – the case of the UK

In the UK, also a considerable drop in arable yield would have occurred today without progress in plant breeding since 2000 as figure 2.36 indicates. It would have been highest in the cases of oilseeds and sugar beets (above 25 and even 45 percent). All other major arable crops would have shown yields being more than 15 percent lower as they currently are. Weighted by hectare, the yield loss in 2020 that can be related to missing plant breeding since the turn of the millennium would account for 19.1 percent of arable production in the UK (see the bold dark green line in figure 2.36).

Such initial yield losses would certainly have affected markets. Supply and trade volumes, as well as international commodity prices would have changed. Subsequently, the monetary outcomes of market actors and especially farmers, but also the broader society would have been affected. Against this background, the following discussion is mainly arguing in positive terms. This means, it discusses effects that can be related to plant breeding in the past 20 years as benefits since genetic improvements have allowed to increase (and did not prove to decrease) yields in arable farming of the EU.

Figure 2.36: Simulated yield loss for major arable crops in 2020 without plant breeding progress between 2000 and 2019 in the UK



Source: Own calculations and figure.

Impacts of plant breeding on market supply

Overview on the impacts by EU region and crop

Figure 2.37 shows the impacts of plant breeding in the EU since 2000 on current market supply.

Figure 2.37: Extra market supply for major arable crops in 2020 with plant breeding progress between 2000 and 2019 in the EU and selected member states (in million tons)

Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	22.382	2.432	4.403	0.891	0.551	2.141
Corn	16.121	0.793	2.663	0.814	0.858	0.006
Other cereals	14.436	2.223	1.684	0.511	0.504	0.998
OSR	3.461	0.609	1.186	0.017	0.041	0.632
Sunflower seeds	3.874	0.008	0.330	0.046	0.142	N.A.
Other oilseeds	0.463	0.015	0.059	0.065	0.008	0.011
Raw sugar	5.780	1.232	1.960	0.098	0.149	0.391
Potatoes	12.276	1.225	0.903	0.169	0.305	0.824
Pulses	0.687	0.109	0.158	0.034	0.092	0.136
Green maize	19.160	4.058	2.281	0.325	0.425	0.602

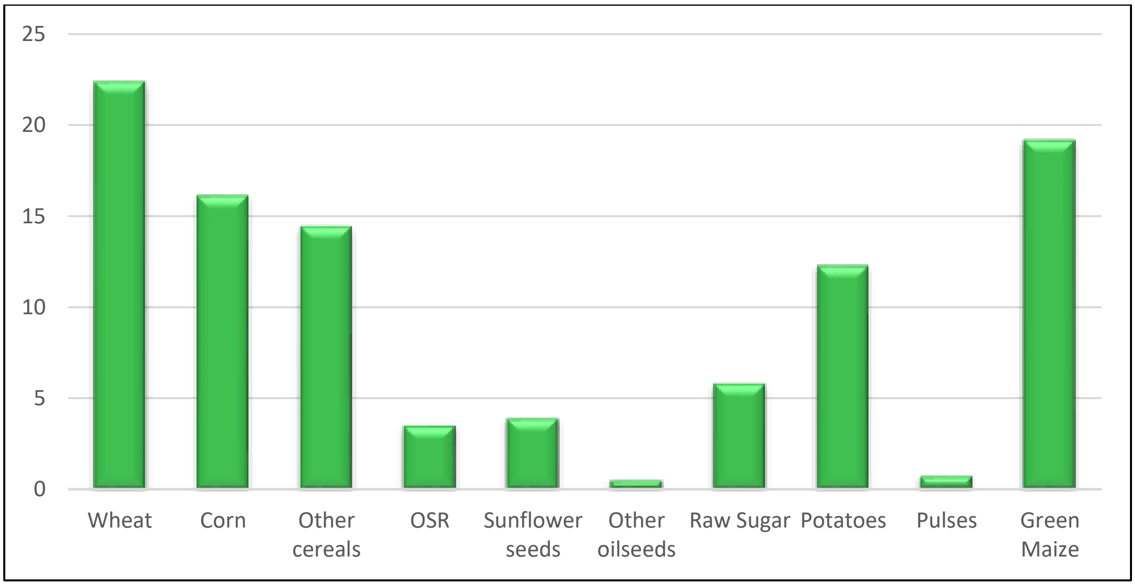
Source: Own calculations and figure.

Analysis for the level of the EU in total

From the modelling exercise it can be concluded that plant breeding since the year 2000 has allowed the EU in total to supply additional market volumes in 2020 as depicted in figure 2.38. In this respect, the following can be highlighted:

- For cereals in total, the supply effect is almost 53 million tons, and wheat alone accounts for additional 22 million tons.
- Oilseeds aggregate to additional 7.8 million tons almost equally shared between sunflower seeds and other oilseeds (including OSR).
- Raw sugar produced from sugar beets[25] and potatoes add 5.8 and 12.1 million tons, respectively.
- The supply of pulses has increased by less than 0.7 million tons.
- And in terms of dry matter[26], almost 20 million tons of green maize gains are additionally available.

Figure 2.38: Extra market supply for major arable crops in 2020 with plant breeding progress between 2000 and 2019 in the EU (in million tons)



Source: Own calculations and figure.

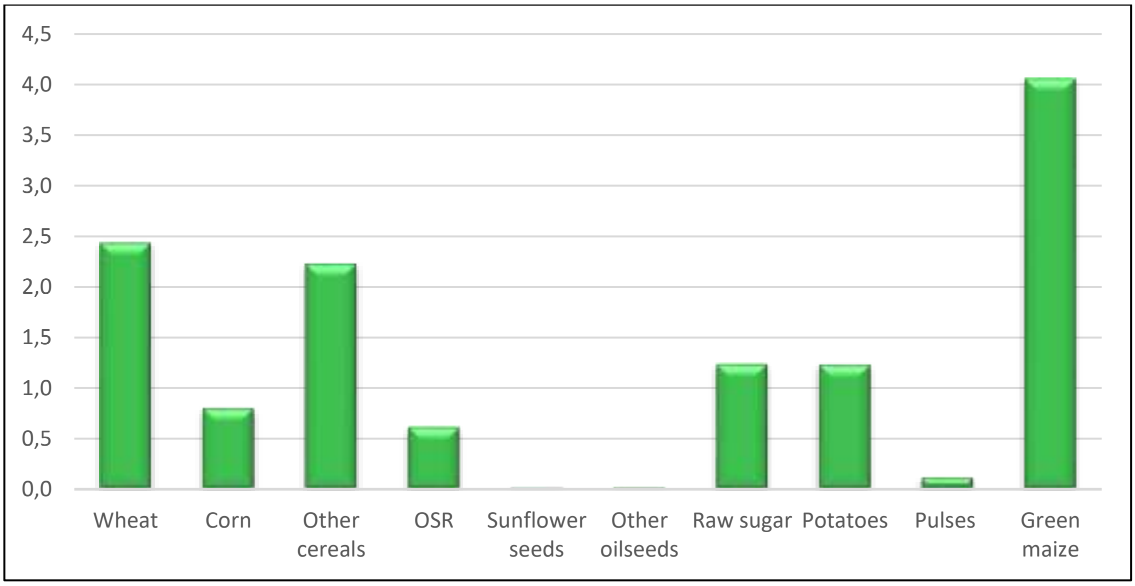
25 In accordance with Krenn (2016), a raw sugar content of 18.5 percent is used here.
26 Following KTBL (2021), dry matter content was set at 35 percent.

Analysis for the level of EU member states – the case of Germany

Looking at Germany, plant breeding since the year 2000 has allowed the country to additionally supply market volumes in 2020 as depicted in figure 2.39. The following can particularly be stated:

- For cereals in total, the supply effect is almost 5.5 million tons, and wheat alone accounts for additional 2.5 million tons.
- OSR supply has increased by more than 0.6 million tons.
- Both, raw sugar produced from sugar beets and potatoes add more than 1.2 million tons each.
- Pulses play a minor part and are additionally supplied in a range of 0.1 million tons.
- And more than 4 million tons of green maize (dry matter) are additionally available.

Figure 2.39: Extra market supply for major arable crops in 2020 with plant breeding progress between 2000 and 2019 in Germany (in million tons)



Source: Own calculations and figure.

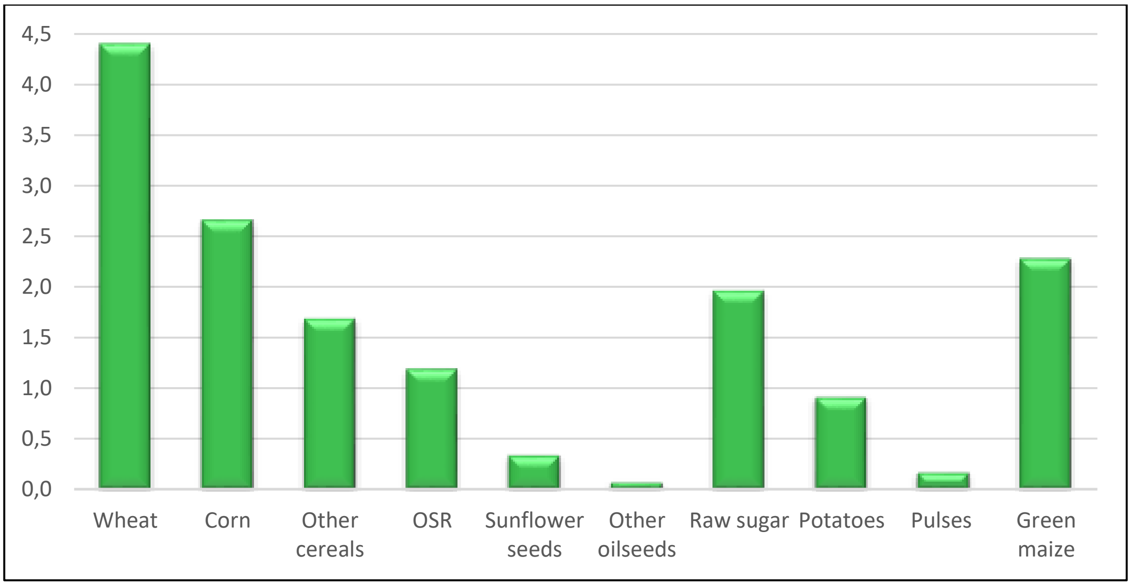
Analysis for the level of EU member states – the case of France

In the case of France, plant breeding since the year 2000 has contributed to the additional market volumes in 2020 shown in figure 2.40. The following can be highlighted:

- For cereals in total, an additional supply of more than 8.7 million tons can be noted. Wheat alone accounts for almost 4.5 million additional tons.

- Oilseeds aggregate to almost 1.6 million tons. The majority comes from OSR (1.2 million tons).
- Almost 2.0 million tons of raw sugar and 0.9 million tons of potatoes are additionally produced.
- Pulses play a minor part, and less than 0.2 million tons are additionally supplied.
- Green maize supply has increased by 2.3 million tons dry matter content.

Figure 2.40: Extra market supply for major arable crops in 2020 with plant breeding progress between 2000 and 2019 in France (in million tons)



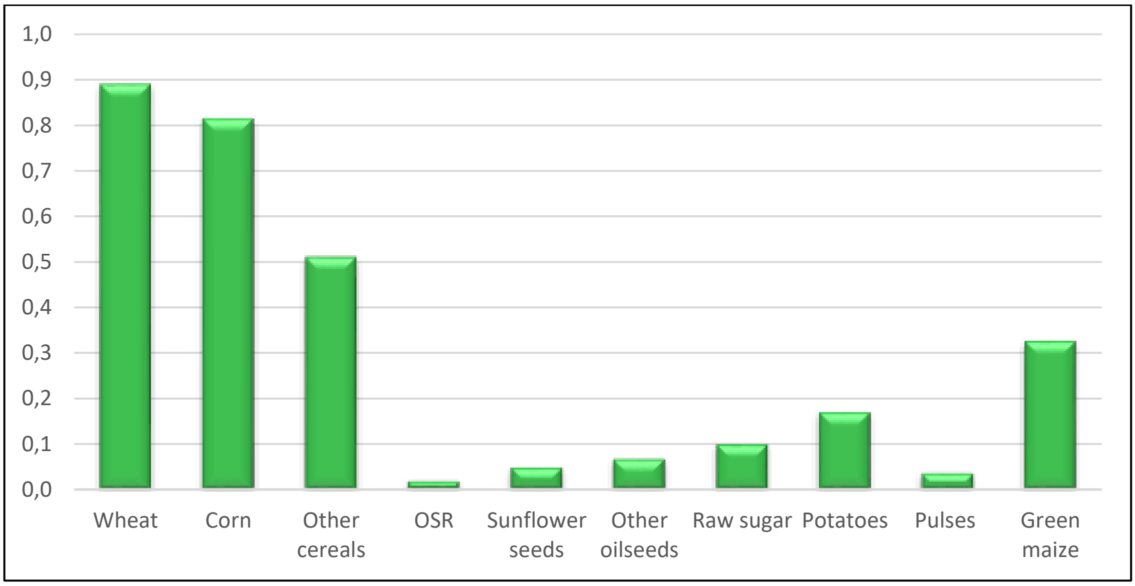
Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Italy

Figure 2.41 displays the market supply impacts in 2020 of plant breeding for Italy since the turn of the millennium. The following applies:

- For cereals in total, an additional supply of more than 2.2 million tons can be noted. Both wheat and corn contribute more than 0.8 million tons each to improved market volume.
- Oilseed supply increases as well. However, on aggregate it is less than 0.2 million tons.
- Raw sugar and potatoes supply also increases by less than 0.2 million tons each.
- And the additional supply of pulses is, although given, almost neglectable.
- Green maize supply has increased by 0.3 million tons dry matter content.

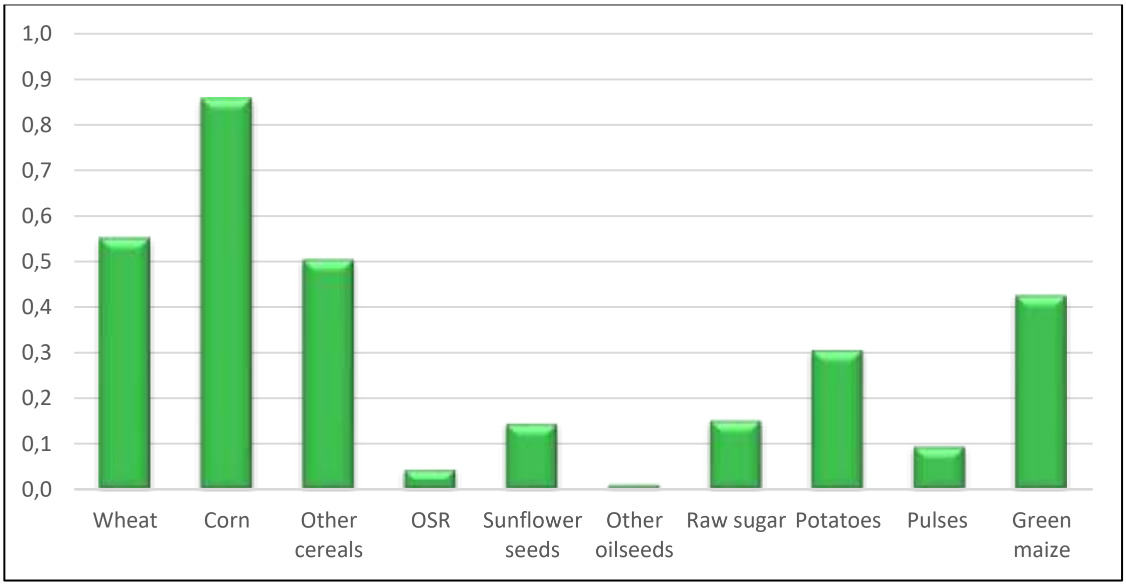
Figure 2.41: Extra market supply for major arable crops in 2020 with plant breeding progress between 2000 and 2019 in Italy (in million tons)



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Spain

Figure 2.42: Extra market supply for major arable crops in 2020 with plant breeding progress between 2000 and 2019 in Spain (in million tons)



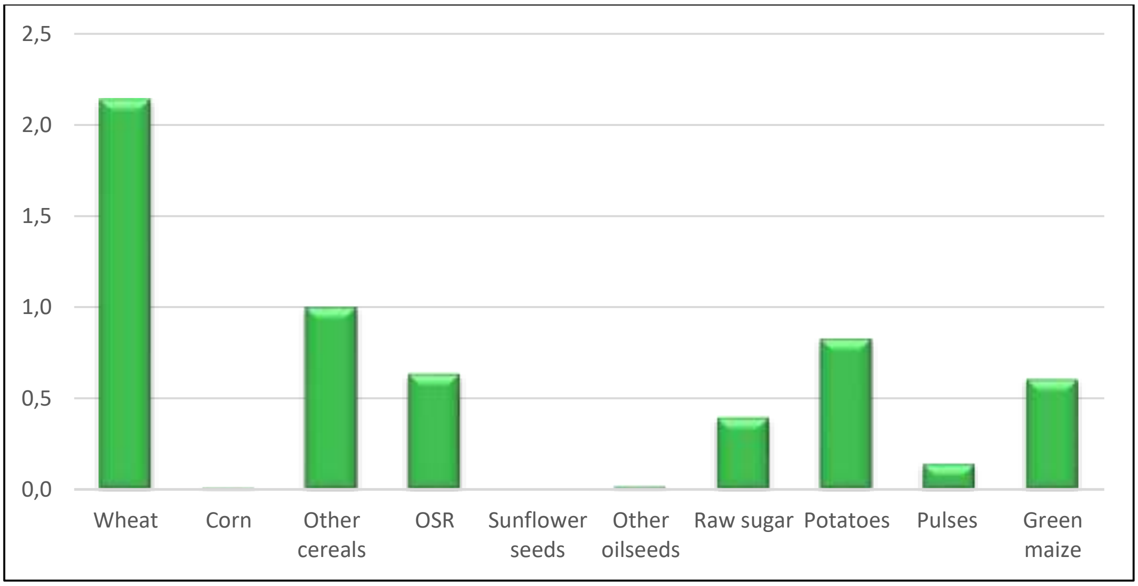
Source: Own calculations and figure.

Figure 2.42 provides the details on additional market supply with respect to Spain. In this EU member state, plant breeding since the year 2000 has contributed to the following additional market volumes in 2020:

- For cereals in total, an additional supply of almost 2.0 million tons can be noted. Corn alone accounts for almost 0.9 million additional tons.
- Oilseeds aggregate to almost 0.2 million tons. The majority comes from sunflower seeds.
- More than 0.1 million tons of raw sugar and approximately 0.3 million tons of potatoes are additionally produced.
- Pulses, again, play a minor part, and less than 0.1 million tons are additionally supplied.
- Green maize supply has increased by 0.4 million tons dry matter content.

Analysis for the level of EU member states – the case of the UK

Figure 2.43: Extra market supply for major arable crops in 2020 with plant breeding progress between 2000 and 2019 in the UK (in million tons)



Source: Own calculations and figure.

Plant breeding since the year 2000 has allowed the UK to additionally supply market volumes in 2020 as depicted in figure 2.43. In this respect, the following can be highlighted:

- For cereals in total, the supply effect is more than 3.1 million tons, and wheat alone accounts for additional 2.1 million tons.

- OSR supply has increased by more than 0.6 million tons.
- Raw sugar produced from sugar beets adds 0.4 million tons, and potatoes supply has increased by more than 0.8 million tons.
- Pulses play a minor part and are additionally supplied in a range of 0.1 million tons.
- And more than 0.6 million tons of green maize (dry matter) are additionally available.

Impacts of plant breeding on net trade volumes

Overview on the impacts by EU region and crop

The EU acts as a single market. For the EU in total, this means that trade can only be measured in terms of trade between the EU and other countries outside the EU. This is different from the perspective when looking at a particular member state. An EU member state is usually confronted with EU-extra trade (with countries outside the EU) and EU-intra trade (with other EU member states). Therefore, aggregated trade data and information for the EU in total and its member states cannot properly be contrasted. A comparable overview, thus, cannot be given. The analysis must always focus on the specific regional level.

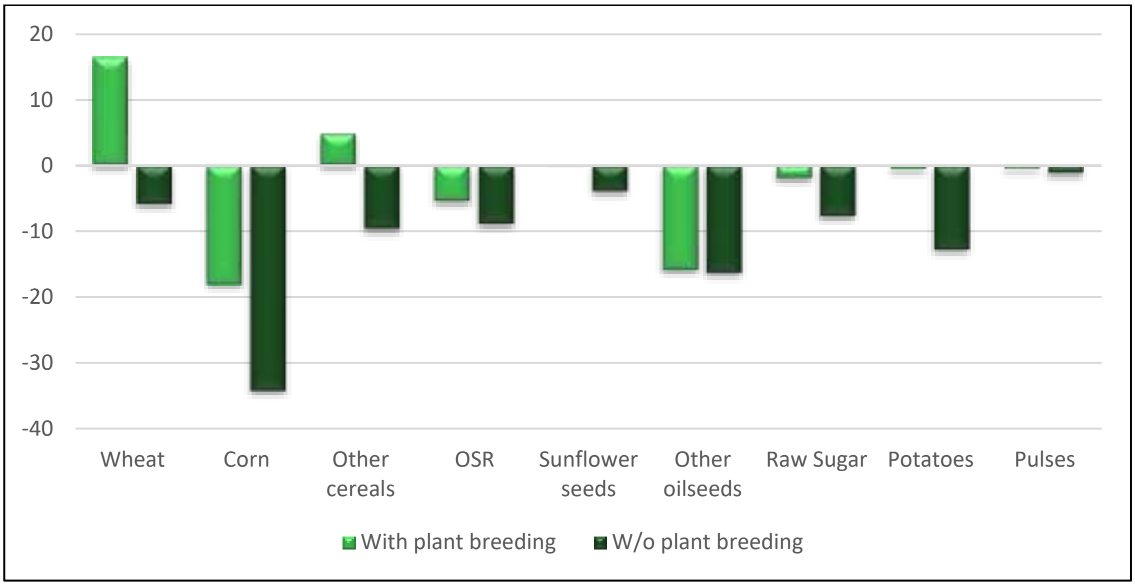
Analysis for the level of the EU in total

Changing market supply does affect trade volumes. The resulting changes – in terms of current EU-extra trade – in the case of missing plant breeding progress since 2000 for the EU in total are depicted in figure 2.44. Thereby, the situation with plant breeding describes the status quo in terms of net trade, that is exports minus imports, as statistically provided by FAO (2021)[27]. The following can be highlighted:

- The figure reveals that plant breeding in the past two decades allows the EU today to still be an exporter in the case of major arable crops such as wheat and other cereals. All other commodities already have a net import balance in agricultural commodity trade – and this despite plant breeding and other innovations in the past.
- If progress in crop genetics had not occurred in the past two decades, the EU would have been a net importer of all arable crops including wheat and other cereals today. Hence, EU agricultural trade would considerably have deteriorated without the efforts of European plant breeders. In the case of corn, for instance, the net import would have approximately doubled; and it would have been considerably enlarged also in the cases of raw sugar, potatoes, and oilseeds.

27 Green maize is assumed not to be traded between countries. In fact, FAO (2021) data show no remarkable volumes internationally traded for the commodity.

Figure 2.44: Net trade volumes of the EU for major arable crops in 2020 with and without plant breeding progress between 2000 and 2019 (in million tons)



Source: Own calculations and figure.

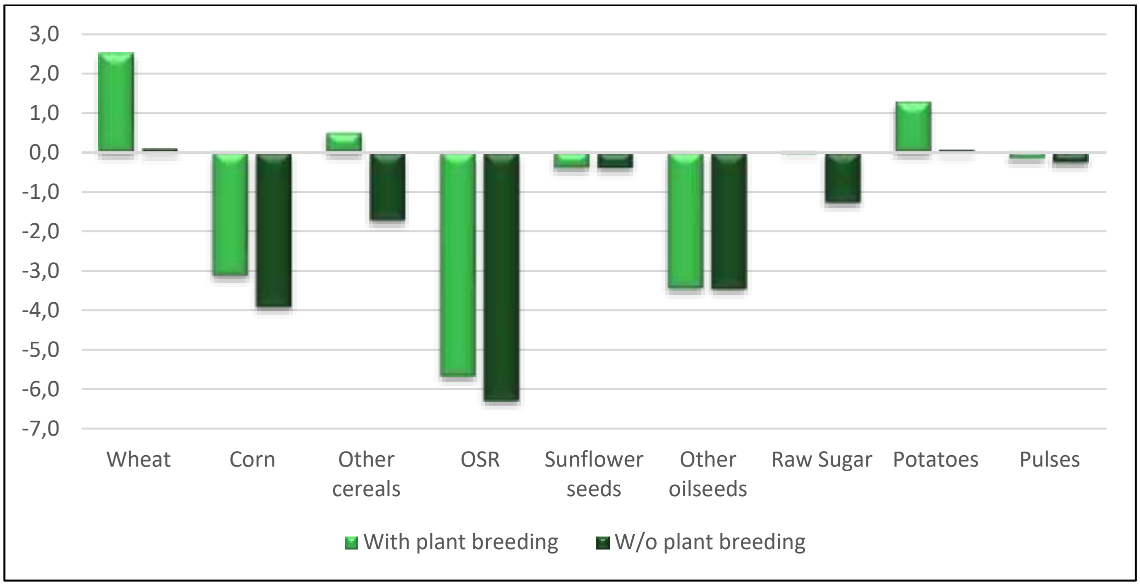
Analysis for the level of EU member states – the case of Germany

The resulting net trade changes in the case of missing plant breeding progress since 2000 for Germany can be obtained from figure 2.45. It becomes obvious that plant breeding in the past two decades still allows Germany to be in a net export situation in 2020 with respect to wheat, other cereals, and potatoes. All other commodities already have a net import balance in international trade. Without plant breeding progresses in the past two decades, Germany would be a net importer today also as regards other cereals, and the positive trade balance with respect to wheat and potatoes would be almost zero. International trade with the other commodities would considerably have deteriorated without plant breeding in the past two decades as well.

Analysis for the level of EU member states – the case of France

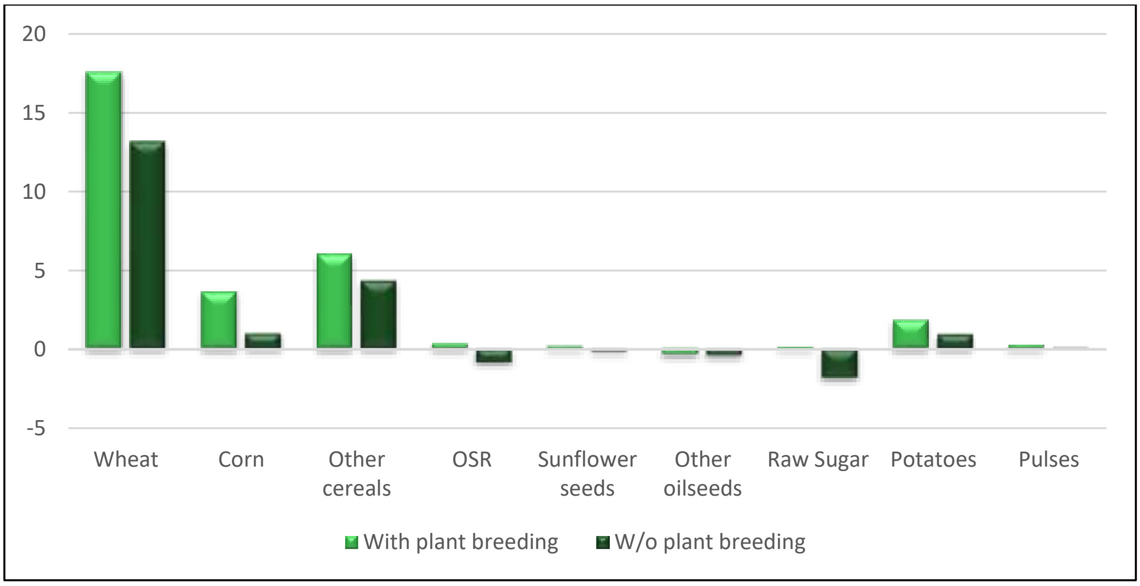
France can be considered a leading net exporter at global scale. Also, thanks to plant breeding, the trade balance today is positive as regards nine of the here included (groups of) arable crops. Just in the case of other oilseeds, the current trade balance is already negative. Not too much would have changed without genetic crop improvements in the past two decades – at first glance. However, wheat (other cereals) exports would have been 25 (30) percent lower, for instance. And the positive trade balance would switch to a negative situation in the cases of OSR and sunflower seeds. All this would, thus, have weakened the international trade position of France for major agricultural commodities without genetic improvements as figure 2.46 visualizes.

Figure 2.45: Net trade volumes of Germany for major arable crops in 2020 with and without plant breeding progress between 2000 and 2019 (in million tons)



Source: Own calculations and figure.

Figure 2.46: Net trade volumes of France for major arable crops in 2020 with and without plant breeding progress between 2000 and 2019 (in million tons)

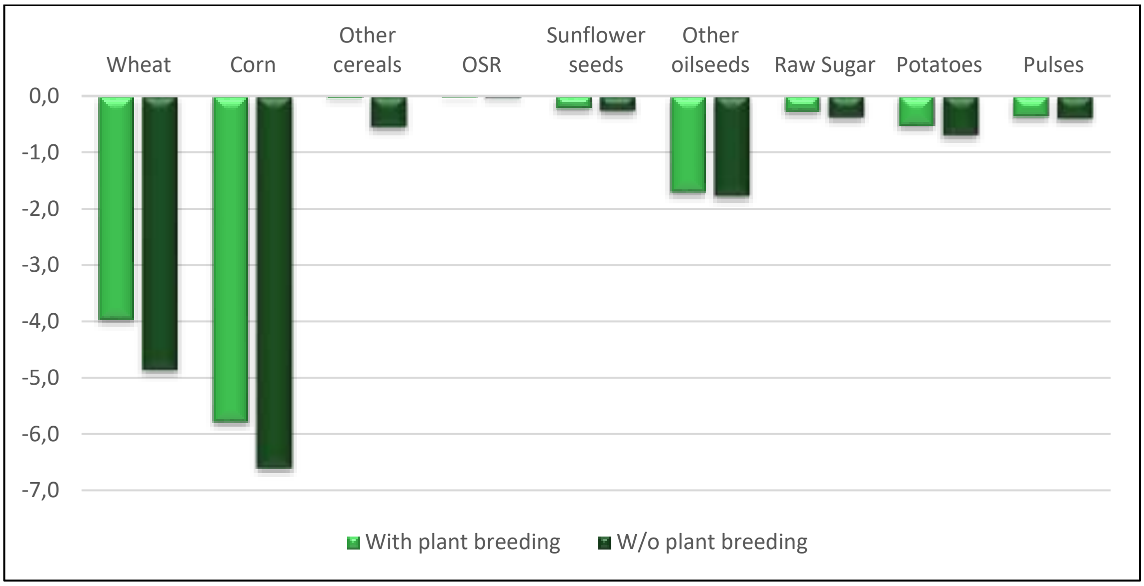


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Italy

Italy is currently in a net import situation with respect to nine of the here included ten (groups of) crops as figure 2.47 shows. Only in the case of other cereals, a rather small net export is still realized. Without plant breeding in the past two decades, all commodities would today face a net import situation.

Figure 2.47: Net trade volumes of Italy for major arable crops in 2020 with and without plant breeding progress between 2000 and 2019 (in million tons)



Source: Own calculations and figure.

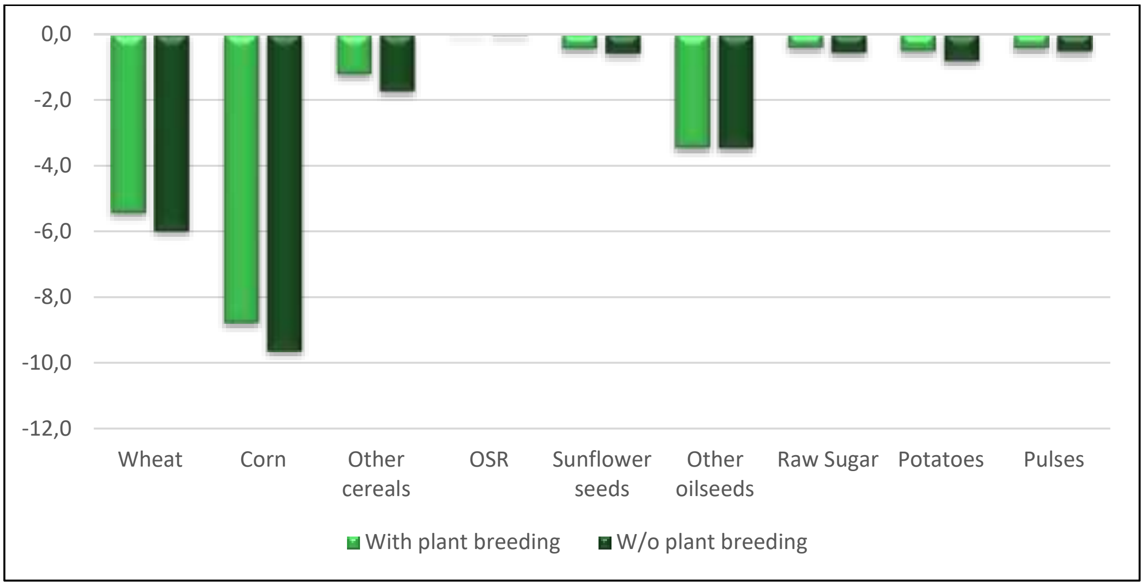
Analysis for the level of EU member states – the case of Spain

What has been stated with respect to Italy can basically be repeated for Spain as figure 2.48 displays. The country is currently in a net import situation with respect to all major arable crops being in the focus of this study. Without plant breeding progress since 2000, this net import position would be even more pronounced.

Analysis for the level of EU member states – the case of the UK

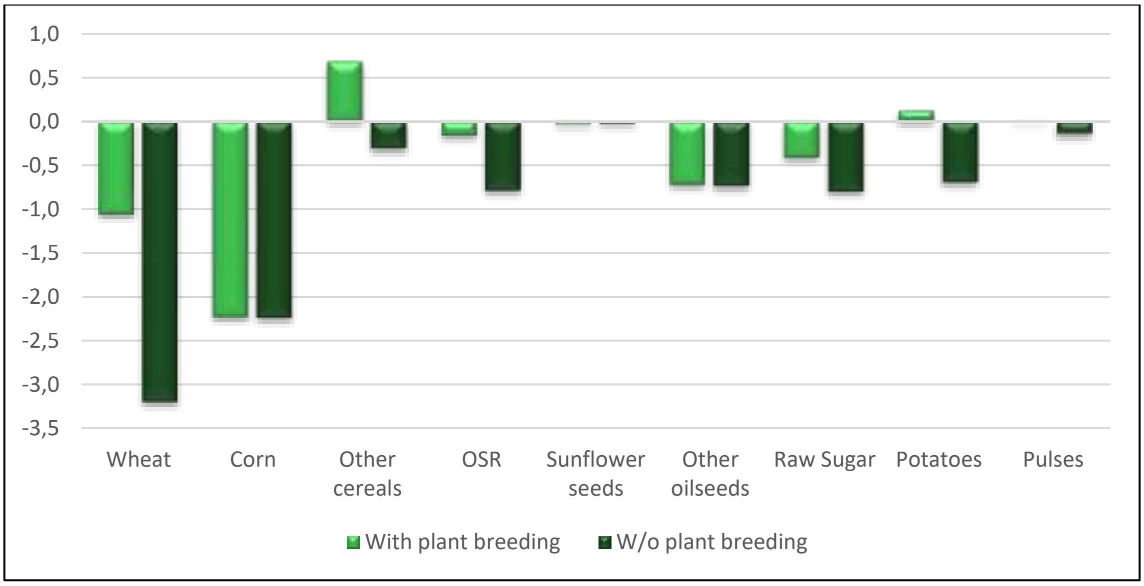
The resulting net trade changes in the case of missing plant breeding progress since 2000 for the UK can finally be obtained from figure 2.49. It becomes obvious that the UK is currently still in a net export position in the cases of other cereals and potatoes, whereas it is a net importer with respect to all the other eight cases. Without plant breeding in the past two decades, it would always have been in a net import situation. The net import volume for wheat, for instance, would today be three times as large as it currently is with plant breeding since 2000.

Figure 2.48: Net trade volumes of Spain for major arable crops in 2020 with and without plant breeding progress between 2000 and 2019 (in million tons)



Source: Own calculations and figure.

Figure 2.49: Net trade volumes of the UK for major arable crops in 2020 with and without plant breeding progress between 2000 and 2019 (in million tons)



Source: Own calculations and figure.

Food availability

Overview on the impacts by EU region

Plant breeding in the EU proves to increase production. A part of this production via market supply is used as food. Hence, plant breeding also tends to increase food availability and with that food security. In the following the increase of food availability (or security) as of today that can be attributed to plant breeding progress between 2000 and 2019 shall be analysed. Therefore, a food basket is constructed which is filled with an average amount of food from the nine relevant (groups of) crops[28] that is consumed per capita and year at EU level and global scale. FAO (2021) data is used for it. FAO (2021) is also used to determine the share of food in total market supply per (group of) crop. Consequently, figure 2.50 displays the number of people that can additionally be provided with a full food basket in 2020 due to plant breeding progress between 2000 and 2019.

Figure 2.50: Additionally available food in 2020 with plant breeding progress between 2000 and 2019 in the EU and selected member states (in food for million people)

Food basket of ...	EU	DE	FR	IT	ES	UK
EU citizens	114.1	14.8	21.1	3.1	3.1	8.8
Global population	168.8	21.6	28.7	5.3	5.0	12.9

Source: Own calculations and figure.

Analysis for the level of the EU in total

As figure 2.51 visualizes, plant breeding progress in the EU in total since the turn of the millennium has remarkably increased global food availability. In 2020, food baskets filled with produce from the nine relevant (groups of) crops for an additional almost 170 million people became available worldwide. Alternatively, more than 110 million additional Europeans could be provided with food.

Analysis for the level of EU member states – the case of Germany

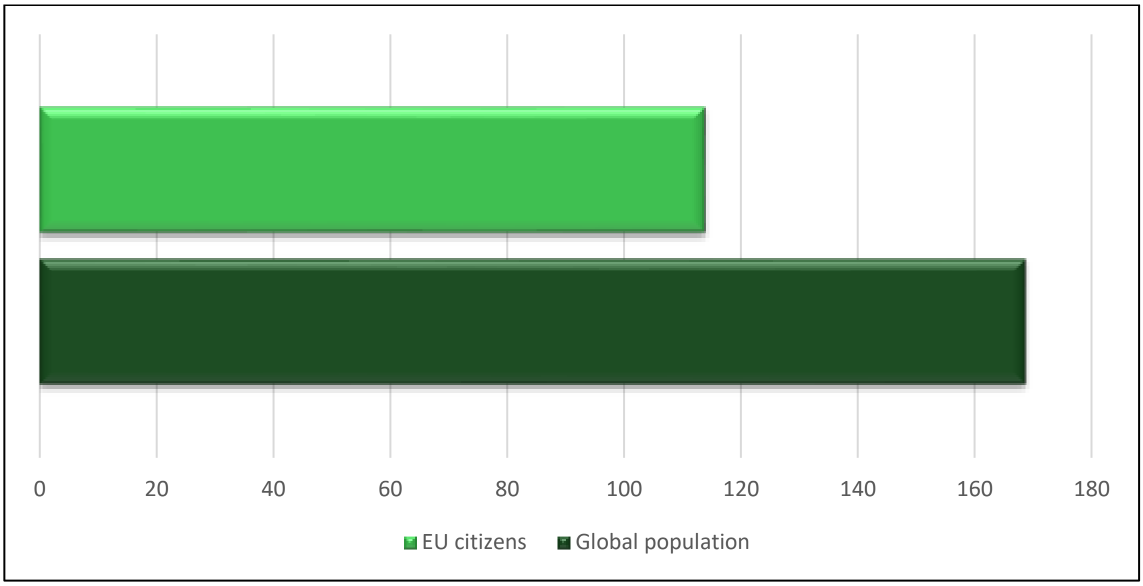
Plant breeding progress in Germany since 2000 has also contributed to an increased food availability as figure 2.52 depicts. In 2020, food baskets for an additional more than 20 (almost 15) million people at global scale (at EU scale) became available.

Analysis for the level of EU member states – the case of France

In the case of France, food baskets for an additional almost 30 (more than 20) million people at global scale (at EU scale) became available in 2020 due to plant breeding progress since 2000 as figure 2.53 shows.

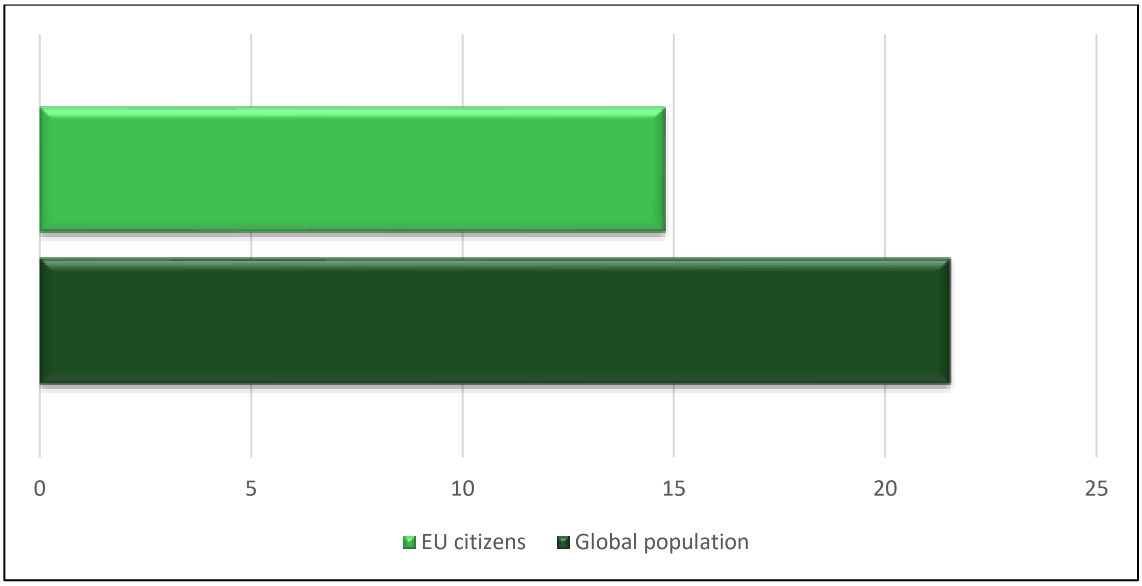
28 Green maize is not relevant.

Figure 2.51: Additionally available food in 2020 with plant breeding progress between 2000 and 2019 in the EU (in food for million people)



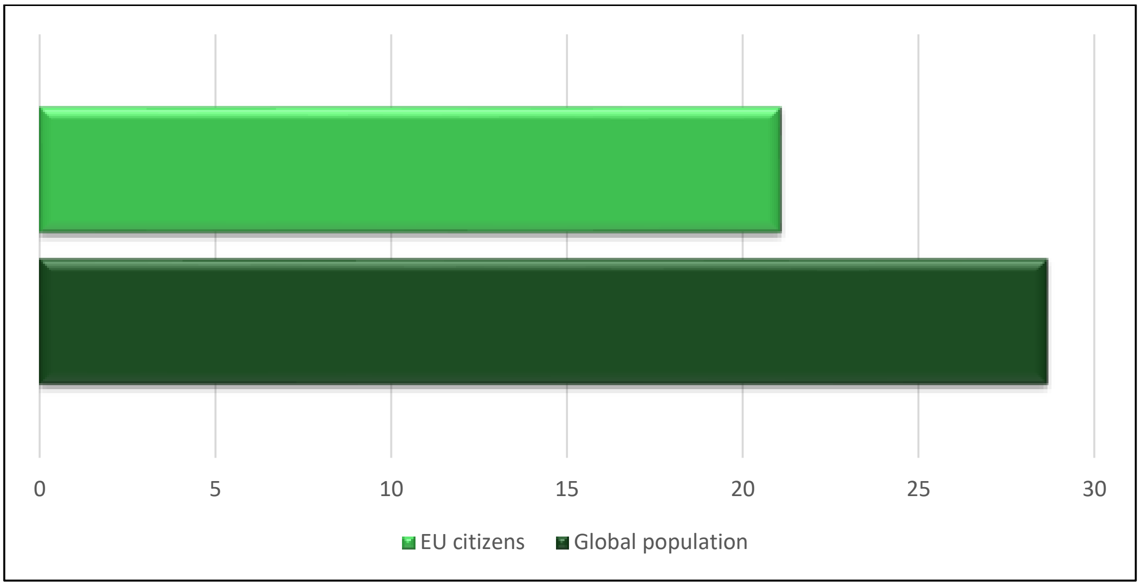
Source: Own calculations and figure.

Figure 2.52: Additionally available food in 2020 with plant breeding progress between 2000 and 2019 in Germany (in food for million people)



Source: Own calculations and figure.

Figure 2.53: Additionally available food in 2020 with plant breeding progress between 2000 and 2019 in France (in food for million people)



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Italy

As figure 2.54 visualizes, plant breeding progress in Italy since the turn of the millennium has also remarkably contributed to an increased food availability. In 2020, food baskets filled with produce from the nine relevant (groups of) crops for an additional more than 5 million people globally became available. Alternatively, more than 3 million additional Europeans could be provided with food baskets.

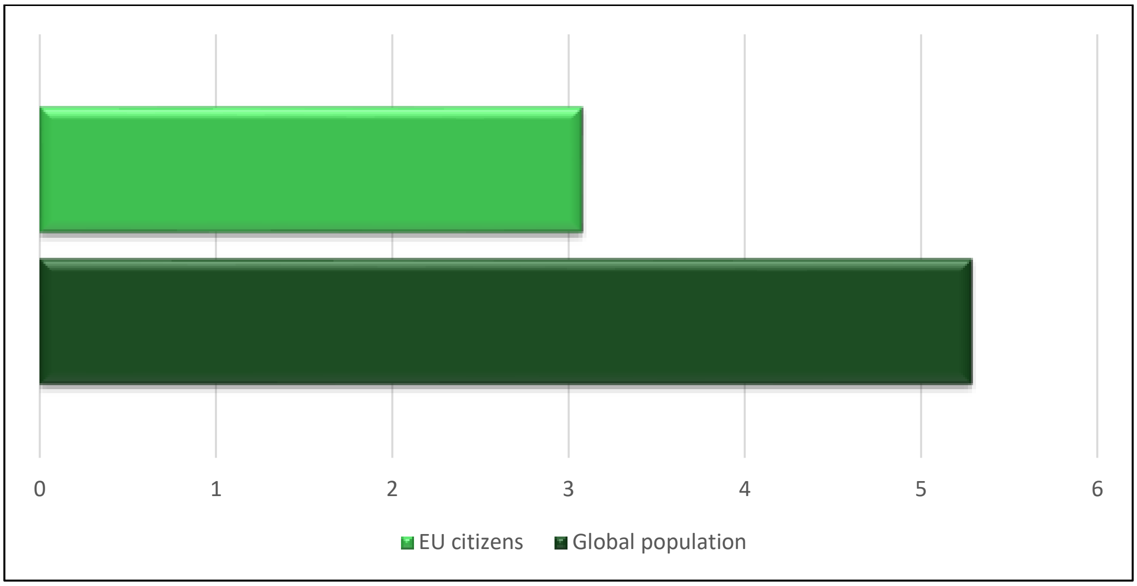
Analysis for the level of EU member states – the case of Spain

Plant breeding progress in Spain between 2000 and 2019 has also contributed to an increased food availability as figure 2.55 depicts. In 2020, food baskets for an additional 5 million people at global scale became available this way. And at EU scale it was enough food to fill baskets for more than 3 million people.

Analysis for the level of EU member states – the case of the UK

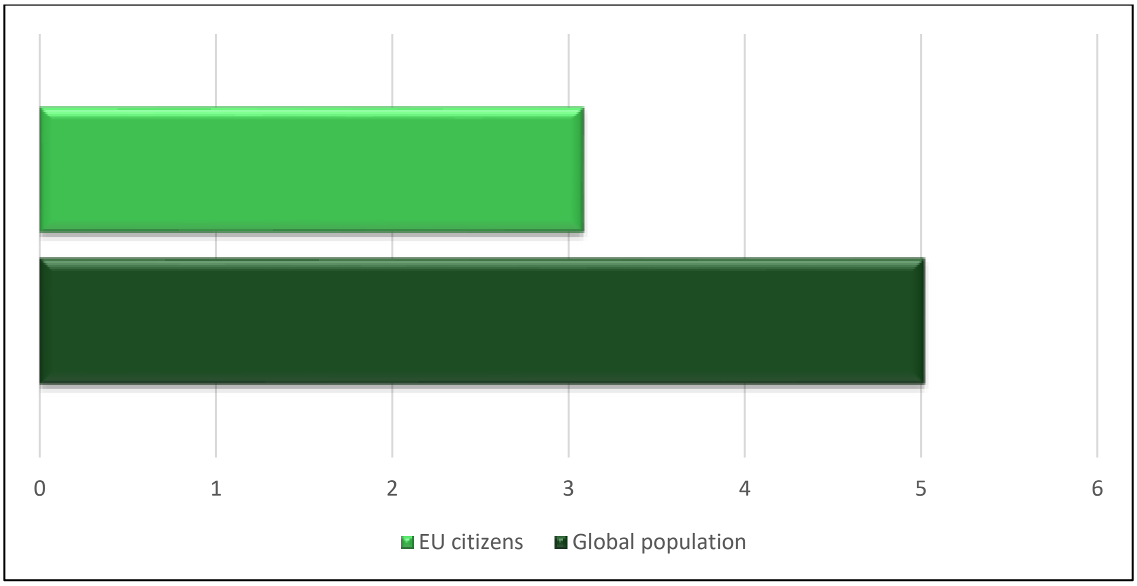
Finally, the specific impact of plant breeding progress between 2000 and 2019 for the UK shall be discussed. As can be seen by looking at figure 2.56, food baskets for an additional more than 12 million people at global scale became available. And at EU scale it is today enough food to fill baskets for almost 9 million people.

Figure 2.54: Additionally available food in 2020 with plant breeding progress between 2000 and 2019 in Italy (in food for million people)



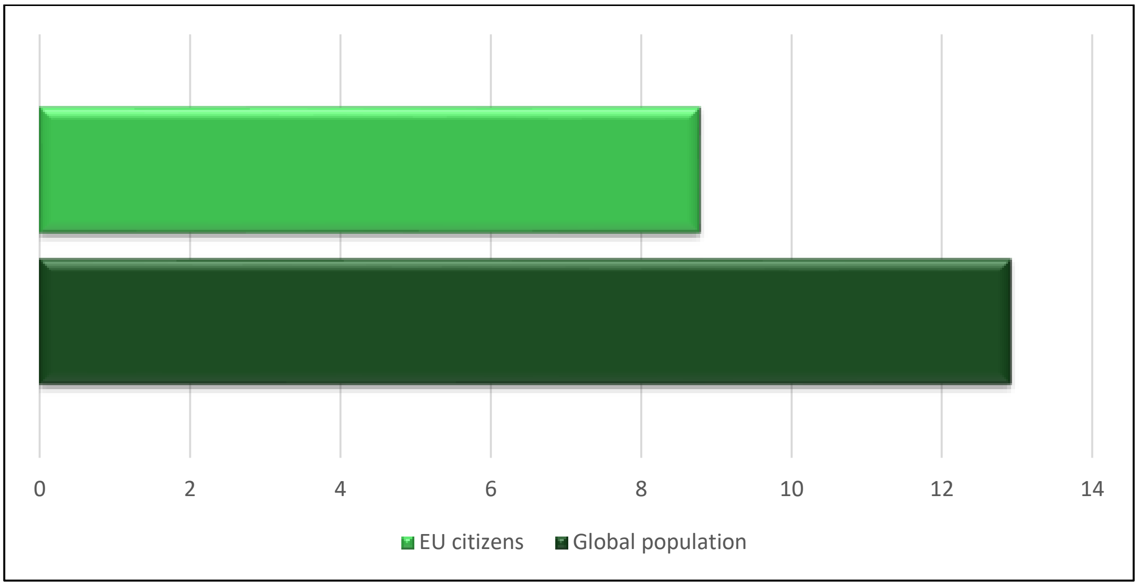
Source: Own calculations and figure.

Figure 2.55: Additionally available food in 2020 with plant breeding progress between 2000 and 2019 in Spain (in food for million people)



Source: Own calculations and figure.

Figure 2.56: Additionally available food in 2020 with plant breeding progress between 2000 and 2019 in the UK (in food for million people)



Source: Own calculations and figure.

Market prices

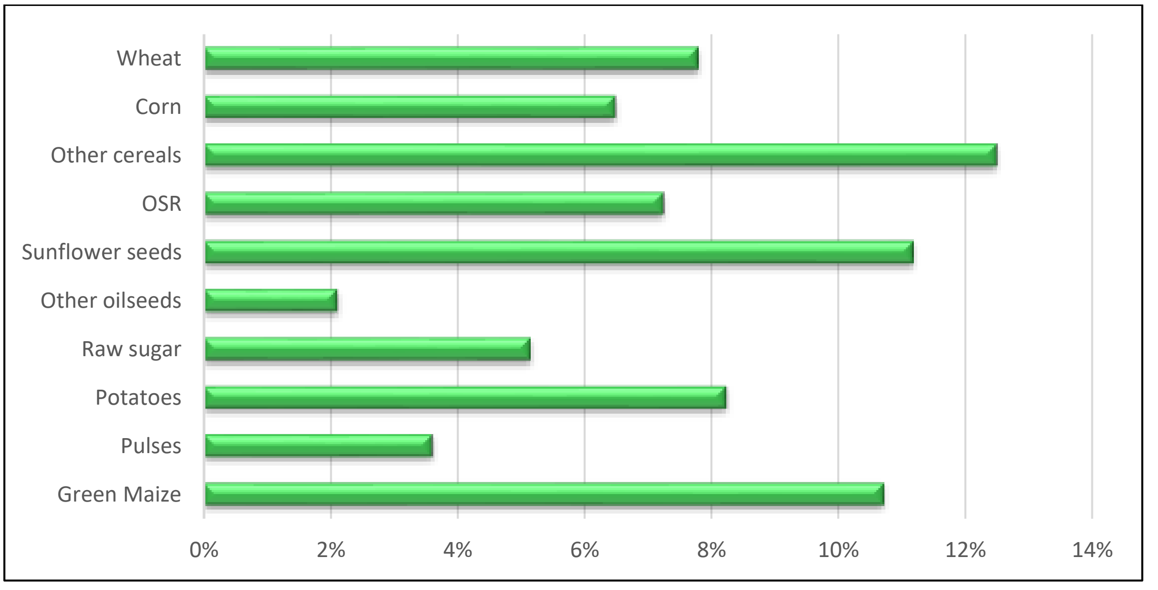
Overview on the impacts by EU region and crop

It has already been stated above: The EU has a single market, and market prices therefore reflect complex interlinkages within individual EU member states as well as between EU member states. In addition, it must be noted that the scenario defined here assumes that no plant breeding progress post the turn of the millennium would have occurred in the EU as a whole – and not only in the one or other EU member state. Therefore, market price impact due to plant breeding can only be assessed at the EU level. The following analysis, thus, does not distinguish an EU level from a member state level.

A rather high market supply volume with plant breeding does not only create a benefit in terms of the trade balance as already discussed, but additionally enables consumers in the EU and around the globe to buy food and agricultural raw materials at affordable prices. Against this background, figure 2.57 depicts the market price effect of plant breeding in the EU since the turn of the millennium, i.e., the avoided price increases. Accordingly, it turns out that prices at internationally linked agricultural commodity markets would have been 2 to 12 percent higher without plant breeding in the EU during the last two decades than they are at present. Except for green maize, which is not traded, the avoided (global) market price increase is highest (12 percent) in other cereals, a rather narrow world market with the EU as a major player involved (keyword: barley); and it is lowest

(2 percent) in other oilseeds (mainly soybeans), which should be considered a rather huge market in terms of globally traded volumes with comparably little affected supply coming from the EU.

Figure 2.57: Avoided price increases for major arable commodity markets in 2020 with plant breeding progress between 2000 and 2019 in the EU in total



Source: Own calculations and figure.

Apart from this (vice versa) basic price decreasing effect of genetic improvements, it shall additionally be stated that plant breeding also contributes to price stabilization. Larger tradeable volumes (with plant breeding in the EU in the last two decades) tend to lower market volatility. In fact, agricultural commodity prices tend to be rather volatile for several reasons such as inelastic markets, weather if not to say climate change phenomena, emerging plant diseases, ad-hoc policy decisions such as export stops and import bans, input use restrictions, etc. In such a rather unfavourable environment for commodity markets, genetic improvements and, thus, higher marketable volumes help keep price volatility low (see, e.g., Santeramo and Lamonaca, 2019).

Sectoral income

Overview on the impacts by EU region and crop

From an income perspective, changes in so-called societal welfare[29] may serve as a proxy for discussing changes of sector-borne (here: agriculture-related) income. The current social welfare effect

[29] The methodological concept since long has been standard in agricultural economics (see, e.g., Houck, 1986; Jechlitschka et al., 2007) and has often been successfully applied (see, e.g., Saunders and Driver, 2016; Blandford, 2015).

– from an analytical and modelling perspective the sum of so-called producer surpluses (producer income) and consumer surpluses (consumer savings)[30] – of plant breeding progress in the EU between 2000 and 2019 for the arable crops and regions included in the analysis is listed in figure 2.58[31].

Figure 2.58: Additional sectoral income for major arable crops in 2020 with plant breeding progress between 2000 and 2019 in the EU and selected member states (in billion EUR)

Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	3.783	0.411	0.744	0.151	0.093	0.362
Corn	2.338	0.115	0.386	0.118	0.124	0.001
Other cereals	2.093	0.322	0.244	0.074	0.073	0.145
OSR	1.211	0.213	0.415	0.006	0.014	0.221
Sunflower seeds	1.395	0.003	0.119	0.017	0.051	N.A.
Other oilseeds	0.130	0.004	0.017	0.018	0.002	0.003
Raw sugar	0.937	0.200	0.318	0.016	0.024	0.063
Potatoes	0.675	0.067	0.050	0.009	0.017	0.045
Pulses	0.206	0.033	0.047	0.010	0.028	0.041
Green maize	1.542	0.327	0.184	0.026	0.034	0.048

Source: Own calculations and figure.

Analysis for the level of the EU in total

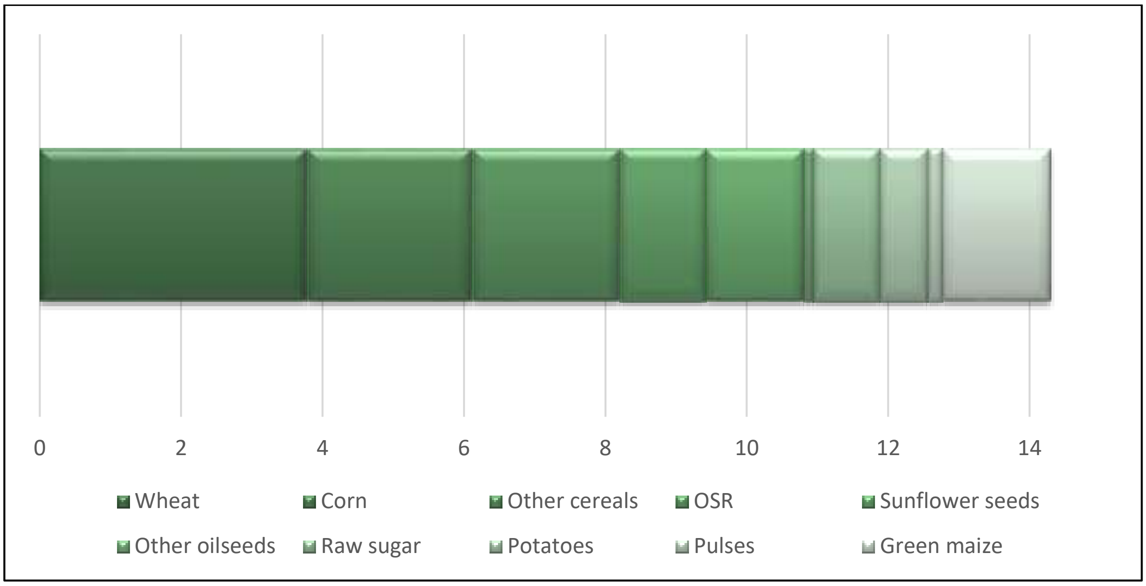
The total social welfare gain of plant breeding progress since 2000 for the analysed crops in the EU amounts to more than EUR 14 billion in 2020 as figure 2.59 displays. According to latest available information, the current gross value added in the agriculture sector (including forestry and fishery) of the EU – a statistical proxy for the sectoral income – totals approximately EUR 239 billion (Eurostat, 2021d). It implies that this number would have been 6.0 percent lower without plant breeding just for major arable crops in the EU since the turn of the millennium. The apparent current loss

30 The entire present discussion focuses on the market level for agricultural raw materials. Consumers in this sense, are – to a large extent – farmers using the crop output as an input for feeding animals and/or bioenergy facilities. Not only but especially against this specific background, it makes sense to also include consumer savings into what is considered hereafter a sectoral income effect of plant breeding.

31 Since there is neither an EU-wide nor a broader international market for green maize, modelling societal welfare for the crop is a challenge. The challenge is even greater since green maize is often used internally within a farm and opportunity costs must be taken into consideration. In accordance with Cornelius (2017), a "value price" of 230 EUR per ton (fresh matter) is assumed and consequently used hereafter.

without plant breeding in the past two decades, thus, is more than the gross value added in the Netherlands' sector comprising agriculture, forestry, and fishery (Eurostat, 2021d).

Figure 2.59: Additional sectoral income for major arable crops in 2020 with plant breeding progress between 2000 and 2019 in the EU (in billion EUR)



Source: Own calculations and figure.

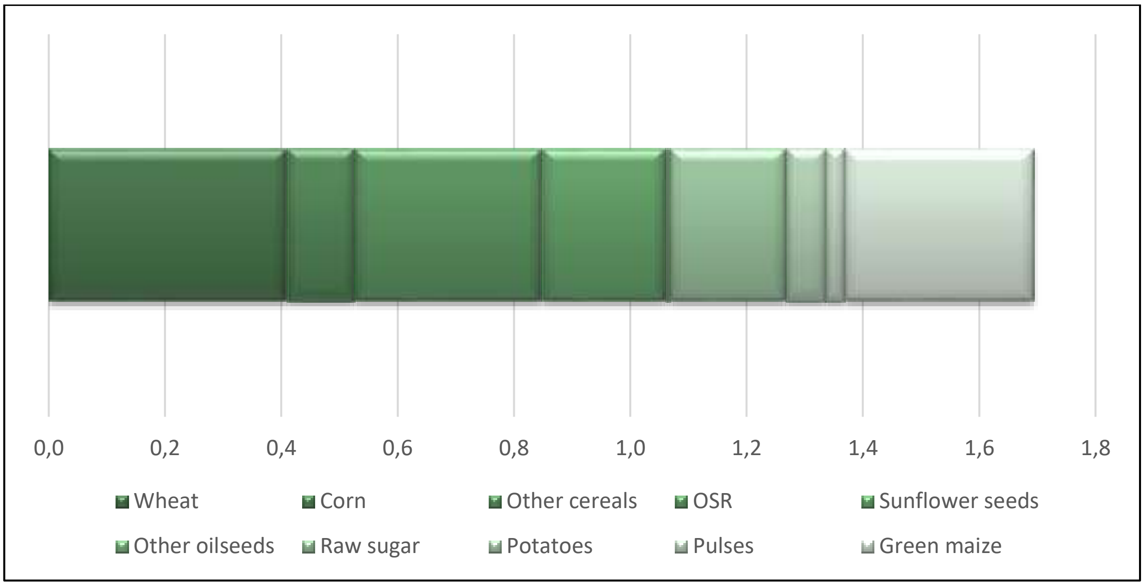
Analysis for the level of EU member states – the case of Germany

Figure 2.60 depicts the outcome of this specific analysis for Germany. Accordingly, it can be stated that plant breeding progress since 2000 has enabled the country to currently generate an extra sectoral income of almost EUR 1.7 billion. According to Eurostat (2021d), the current gross value added in the agriculture sector (including forestry and fishery) of Germany is EUR 22.1 billion implying that this number would have been 7.7 percent lower without plant breeding progress just for major arable crops in the country since the year 2000. The apparent current loss without corresponding genetic improvements, thus, is more than the gross value added in Croatia's sector comprising agriculture, forestry, and fishery (Eurostat, 2021d).

Analysis for the level of EU member states – the case of France

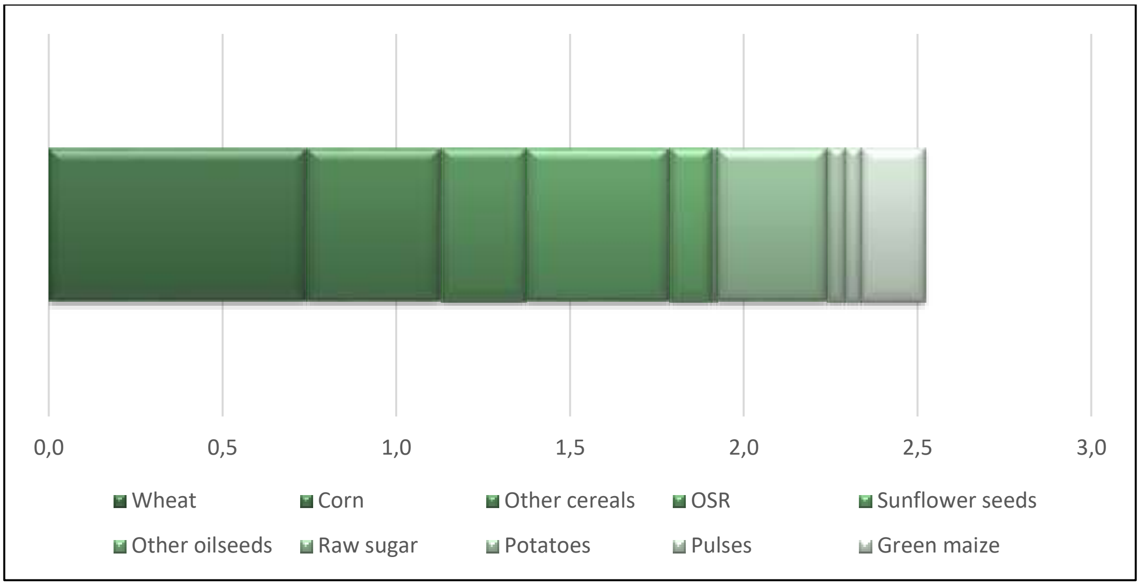
According to figure 2.61, it can be argued that plant breeding improvements since the turn of the millennium have enabled France to currently add an extra sectoral income of more than EUR 2.5 billion. According to Eurostat (2021d), the current gross value added in the agriculture sector (including forestry and fishery) of France is EUR 39.2 billion implying that this number would have been 6.4 percent lower without plant breeding progress just for major arable crops in the country since the year 2000. The apparent current loss without corresponding genetic improvements, thus, is more than the gross value added in Slovakia's sector comprising agriculture, forestry, and fishery (Eurostat, 2021d).

Figure 2.60: Additional sectoral income for major arable crops in 2020 with plant breeding progress between 2000 and 2019 in Germany (in billion EUR)



Source: Own calculations and figure.

Figure 2.61: Additional sectoral income for major arable crops in 2020 with plant breeding progress between 2000 and 2019 in France (in billion EUR)

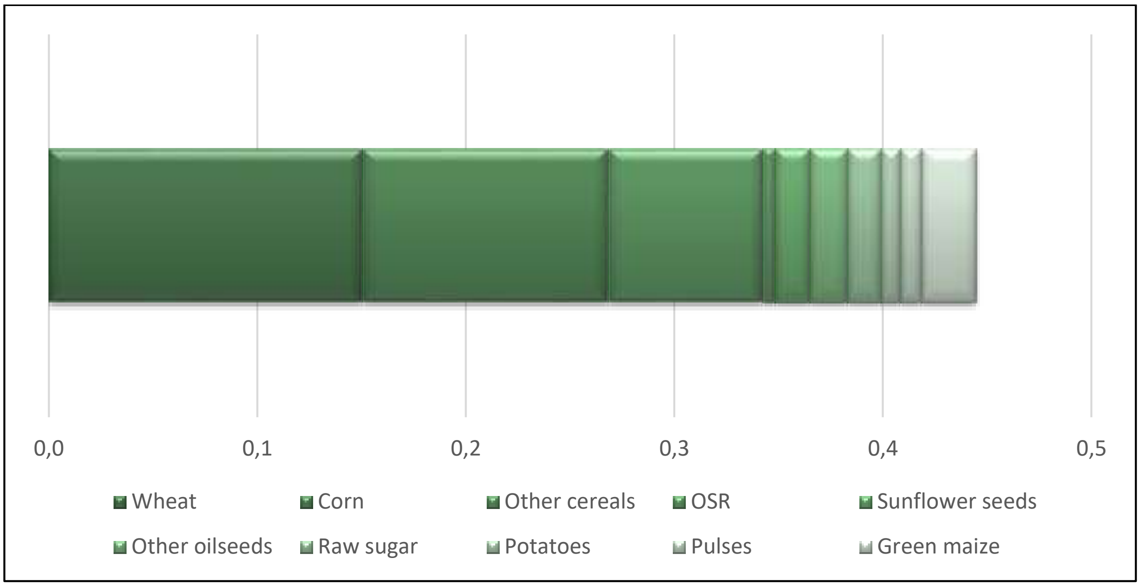


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Italy

Looking at the results for Italy, as displayed in figure 2.62, it can be highlighted that progress in plant breeding since 2000 has contributed to a sectoral income that is currently more than EUR 0.4 billion higher than without the progress made. According to Eurostat (2021d), the current gross value added in the agriculture sector (including forestry and fishery) of Italy is EUR 32.8 billion implying that this number would have been 1.4 percent lower without plant breeding progress just for the here selected arable crops in the country since the turn of the millennium. The apparent current loss, thus, is approximately as large as the gross value added in Estonia's sector comprising agriculture, forestry, and fishery (Eurostat, 2021d).

Figure 2.62: Additional sectoral income for major arable crops in 2020 with plant breeding progress between 2000 and 2019 in Italy (in billion EUR)

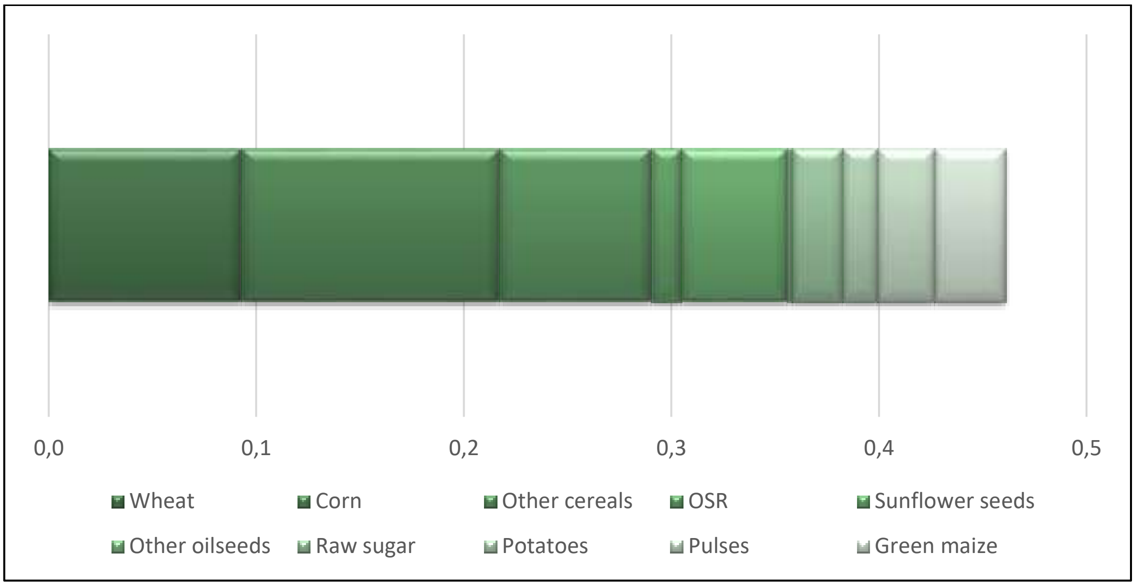


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Spain

Figure 2.63 displays the outcome of this specific analysis for Spain. Accordingly, it can be stated that plant breeding progress since 2000 has enabled the country to currently generate an extra sectoral income below EUR 0.5 billion. According to Eurostat (2021d), the current gross value added in the agriculture sector (including forestry and fishery) of Spain is EUR 35.2 billion implying that this number would have been 1.3 percent lower without plant breeding progress just for the selected arable crops in the country since the year 2000. The apparent current loss without corresponding genetic improvements, thus, is three times more than the gross value added in Luxembourg's sector comprising agriculture, forestry, and fishery (Eurostat, 2021d).

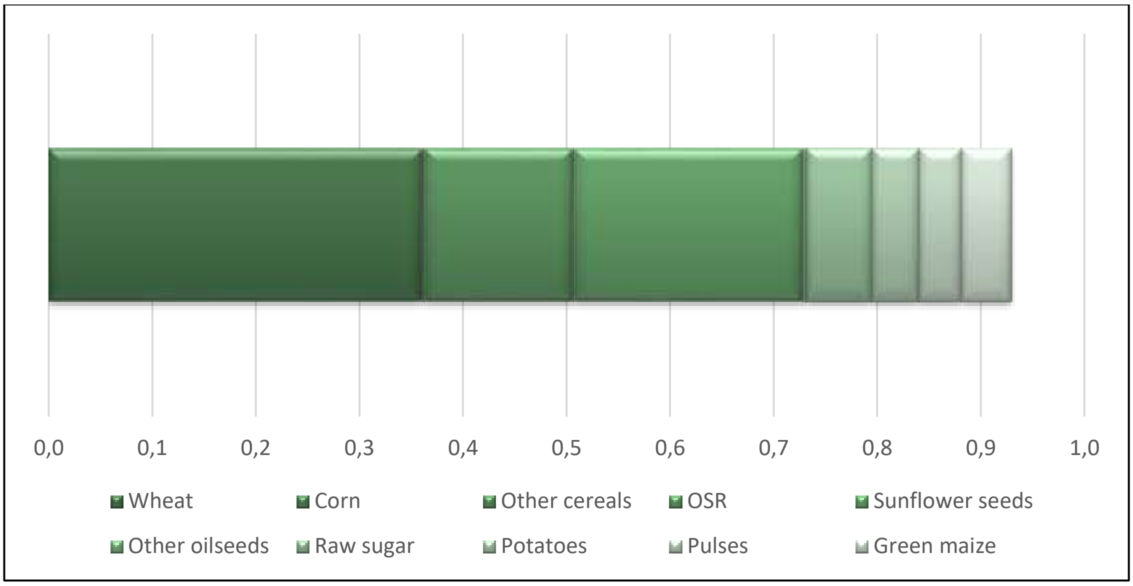
Figure 2.63: Additional sectoral income for major arable crops in 2020 with plant breeding progress between 2000 and 2019 in Spain (in billion EUR)



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of the UK

Figure 2.64: Additional sectoral income for major arable crops in 2020 with plant breeding progress between 2000 and 2019 in the UK (in billion EUR)



Source: Own calculations and figure.

The total social welfare gain of plant breeding since 2000 for the analysed crops in the UK amounts to more than EUR 0.9 billion, as figure 2.64 displays. According to latest available information, the current gross value added in the agriculture sector (including forestry and fishery) of the UK totals approximately EUR 14.9 billion (Eurostat, 2021d) implying that this number would have been 6.3 percent lower without plant breeding just for major arable crops in the UK since the turn of the millennium. The apparent current loss without plant breeding in the past two decades, thus, is more than the gross value added in Lithuania's sector comprising agriculture, forestry, and fishery (Eurostat, 2021d).

GDP contributions

Overview on the impacts by EU region and crop

It becomes clear that genetic crop improvements have a strong sectoral economic impact in the EU and its member states what is also supported by conclusions of other scientists (Lenaerts et al., 2016). Accordingly, investments into plant breeding activities pay off in economic terms. Plant breeding activities particularly offer (very) high returns on investments not only from a private but also from a societal perspective (Lotze-Campen et al., 2015; Cobb et al., 2019). This is also supported and confirmed by the following analysis.

In fact, plant breeding does not only benefit the primary agricultural sector but the society in total. It particularly creates an economic value not only for farmers but for (mainly rural) citizens upstream and downstream the value chain because the additionally produced agricultural raw material must be transported, processed, traded, retailed etc. This tends to increase the generation of income in other sectors.

Accordingly, the producer surplus additionally generated through plant breeding being a substantial part of the societal welfare effect displayed in figure 2.58[32] must be linked to GDP multipliers as described in annex D. Figure 2.65 gives an overview on the results for the EU and its selected member states.

Analysis for the level of the EU in total

According to this exercise, the overall GDP impact should be valued more than EUR 26 billion in 2020 for the EU in total. Its composition – consisting of the sectoral (agricultural) effect and the effect belonging to sectors upstream and downstream the agricultural value chain – is subsequently presented with figure 2.66. It becomes apparent that GDP contributions of plant breeding in the EU since 2000 are almost equally shared by the agricultural sector (52 percent) on the one hand and other sectors linked to the primary sector (48 percent) on the other hand. The entire monetary value of above EUR 26 billion, thereby, approximately equals the GDP of Estonia (IMF, 2020).

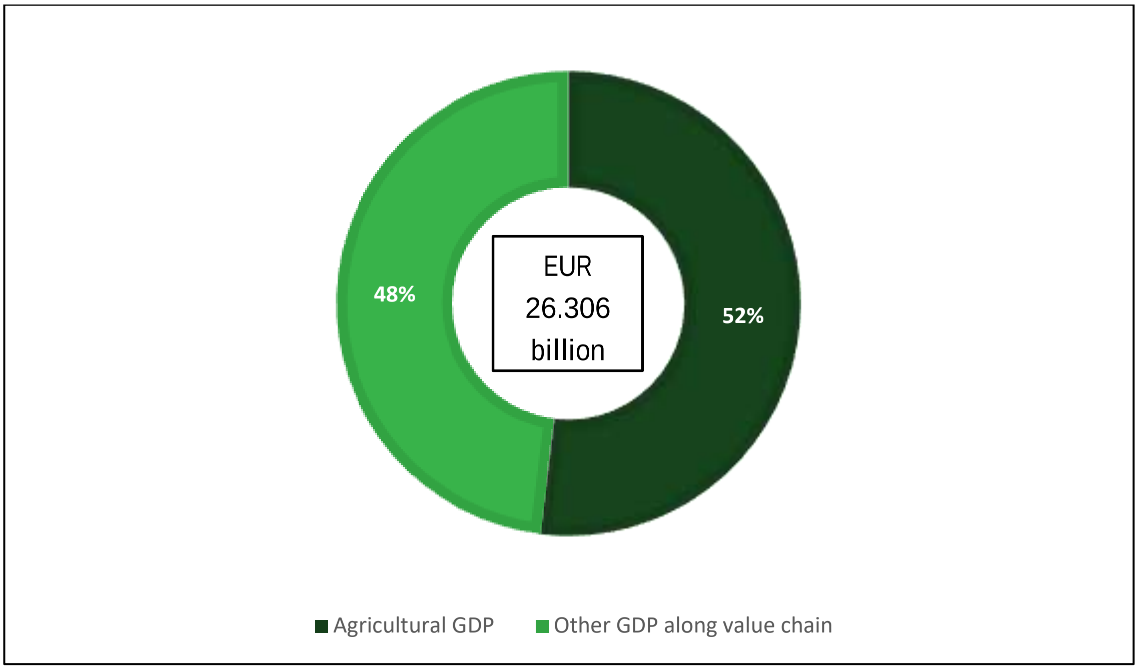
32 To be methodologically consistent, this surplus is considered an approximation of the agricultural GDP and accounts – on average – for 95.5 percent of the just calculated societal welfare gain.

Figure 2.65: Additional GDP attributable to major arable crops in 2020 with plant breeding progress between 2000 and 2019 in the EU and selected member states (in billion EUR)

Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	6.900	0.726	1.521	0.331	0.207	0.663
Corn	4.264	0.203	0.789	0.259	0.277	0.002
Other cereals	3.818	0.570	0.499	0.163	0.163	0.265
OSR	1.967	0.335	0.755	0.011	0.028	0.361
Sunflower seeds	2.264	0.005	0.216	0.033	0.102	N.A.
Other oilseeds	0.210	0.007	0.030	0.035	0.004	0.005
Raw sugar	2.113	0.436	0.803	0.043	0.067	0.144
Potatoes	1.522	0.147	0.125	0.025	0.046	0.103
Pulses	0.465	0.072	0.120	0.028	0.076	0.093
Green maize	2.784	0.571	0.371	0.057	0.075	0.088

Source: Own calculations and figure.

Figure 2.66: Level and composition of the additional GDP attributable to major arable crops in 2020 with plant breeding progress between 2000 and 2021 in the EU

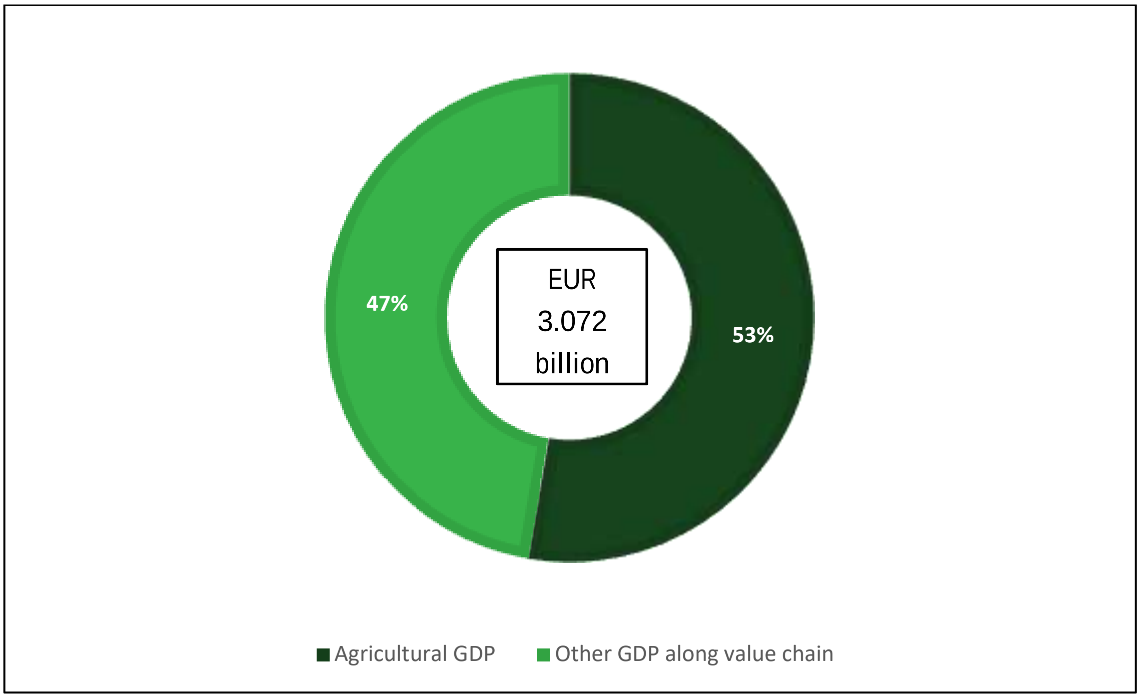


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Germany

For Germany, the impact of plant breeding progress since 2000 on current GDP should be seen in the range of EUR 3.1 billion as figure 2.67 describes. It becomes obvious, that GDP contributions of plant breeding progress in the country between 2000 and 2019 are also almost equally shared by the agricultural sector (53 percent) and other sectors linked to the primary sector (47 percent).

Figure 2.67: Level and composition of the additional GDP attributable to major arable crops in 2020 with plant breeding progress between 2000 and 2019 in Germany



Source: Own calculations and figure.

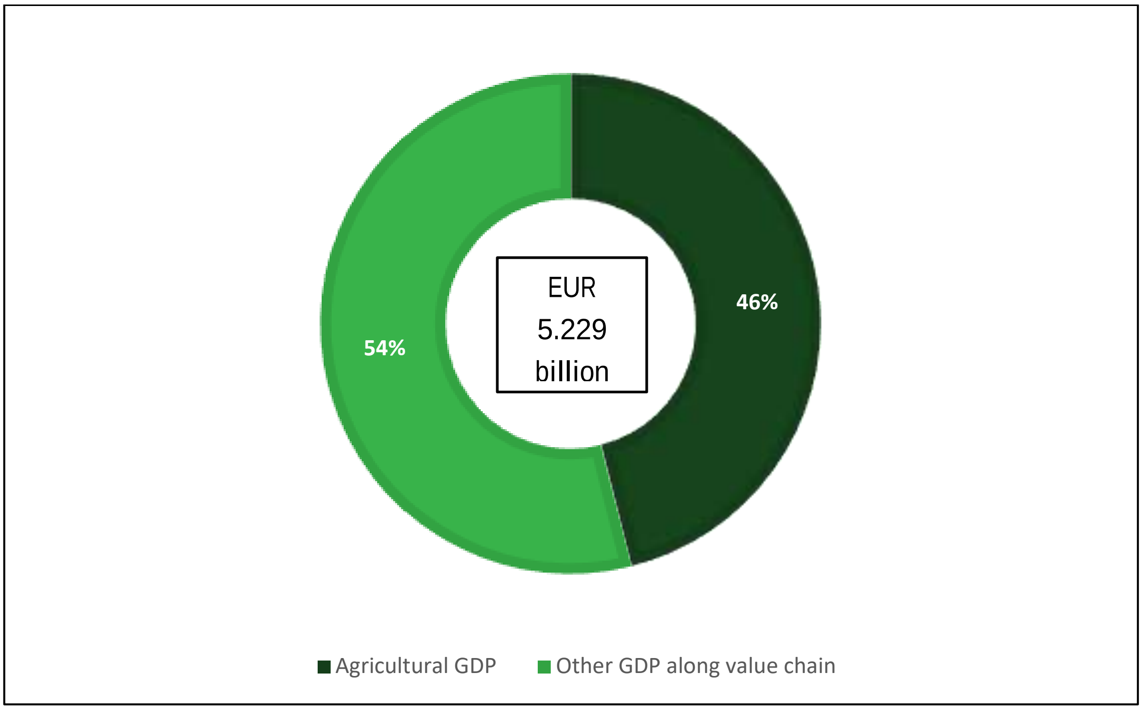
Analysis for the level of EU member states – the case of France

The overall impact of plant breeding progress since the turn of the millennium on current GDP in France should be seen in the range of EUR 5.2 billion as figure 2.68 visualizes. Apparently, GDP contributions of plant breeding in the EU member state since 2000 are slightly lower in the agricultural sector (46 percent) than in total of other sectors linked to the primary sector (54 percent).

Analysis for the level of EU member states – the case of Italy

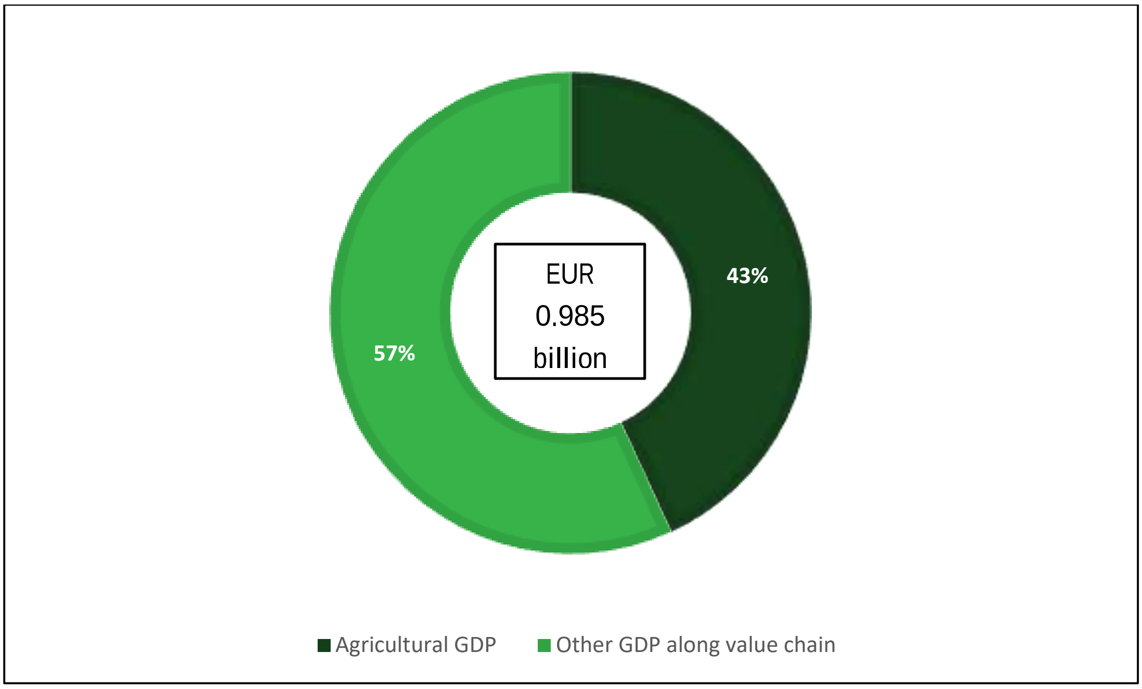
In Italy, the overall impact of plant breeding progress since 2000 on current GDP is around EUR 1.0 billion as figure 2.69 depicts. GDP contributions of plant breeding in the EU member state since 2000 seem to be lower in the agricultural sector (43 percent) than in total of other sectors linked to the primary sector (57 percent).

Figure 2.68: Level and composition of the additional GDP attributable to major arable crops in 2020 with plant breeding progress between 2000 and 2019 in France



Source: Own calculations and figure.

Figure 2.69: Level and composition of the additional GDP attributable to major arable crops in 2020 with plant breeding progress between 2000 and 2019 in Italy

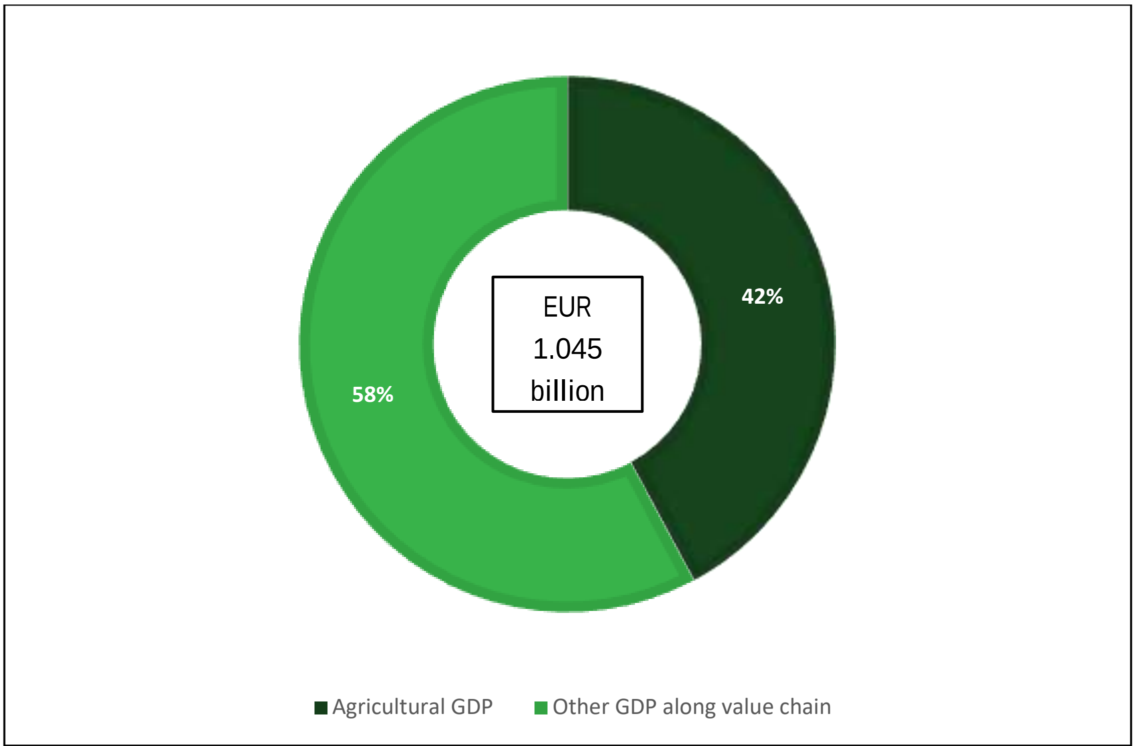


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Spain

The overall impact of plant breeding progress since the turn of the millennium on current GDP in Spain should be seen in the range of slightly more than EUR 1.0 billion as figure 2.70 visualizes. Apparently, GDP contributions of plant breeding progress in the EU member state since 2000 are remarkably lower in the agricultural sector (42 percent) than in total of other sectors linked to the primary sector (58 percent) pointing at a considerably high share of value added along the various agricultural and food value chains.

Figure 2.70: Level and composition of the additional GDP attributable to major arable crops in 2020 with plant breeding progress between 2000 and 2019 in Spain

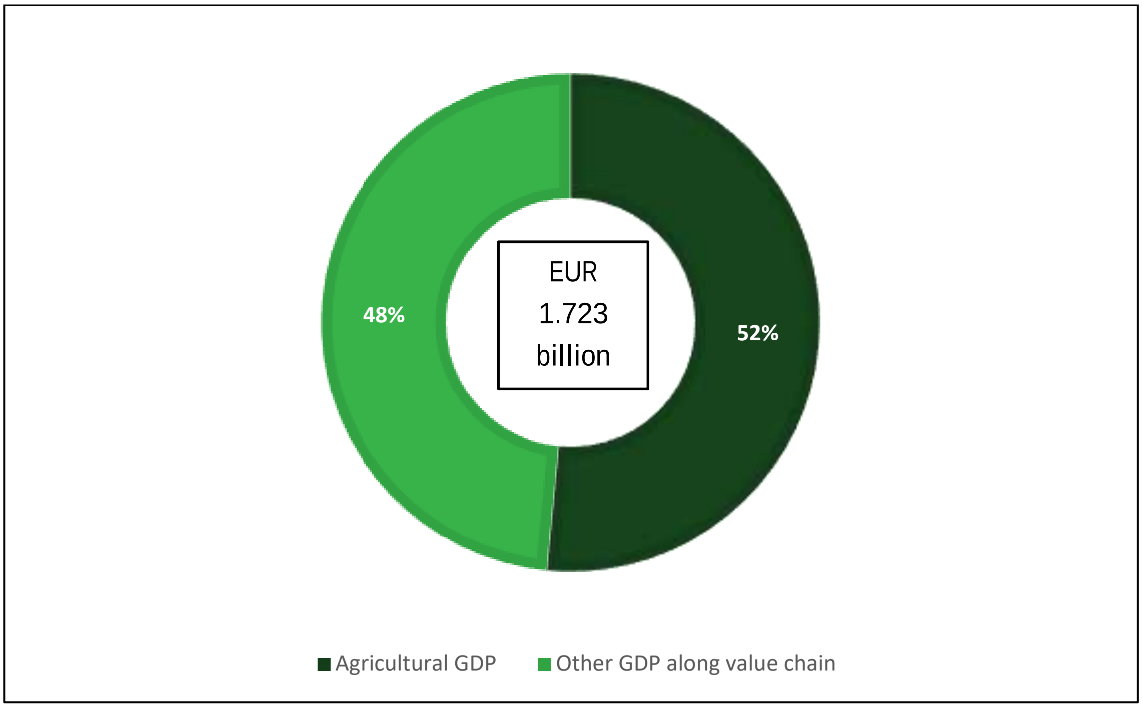


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of the UK

For the UK, the impact of plant breeding progress between 2000 and 2019 on current GDP should be seen in the range of EUR 1.7 billion as figure 2.71 finally describes. It becomes obvious, that GDP contributions of plant breeding in the UK since the turn of the millennium are almost equally shared by the agricultural sector (52 percent) and the other sectors linked via value chains to the primary sector (48 percent).

Figure 2.71: Level and composition of the additional GDP attributable to major arable crops in 2020 with plant breeding progress between 2000 and 2019 in the UK



Source: Own calculations and figure.

Farm income

Overview on the impacts by EU region and crop

In the context of socio-economic effects, the farm income effect of genetic crop improvements shall be analysed for labour directly engaged in arable farming and cultivating the crops under consideration. Such crop-specific activities include, for instance, tillage, sowing and drilling, applying fertilizers, pest management, harvesting, and transport, as well as other area-related management. For calculating the effect, data from EC (2019b) is used. The results are as displayed in figure 2.72.

Figure 2.72: Farm income of arable farms and income induced by plant breeding progress between 2000 and 2019 in the EU and selected member states (in EUR/AWU)

Indicator/Region	EU	DE	FR	IT	ES	UK
Farm income	17 100	41 167	25 300	19 667	20 067	39 200
Income induced by plant breeding	6 105	9 072	11 557	2 437	1 249	19 508
Other farm income	10 995	32 095	13 743	17 229	18 817	19 692

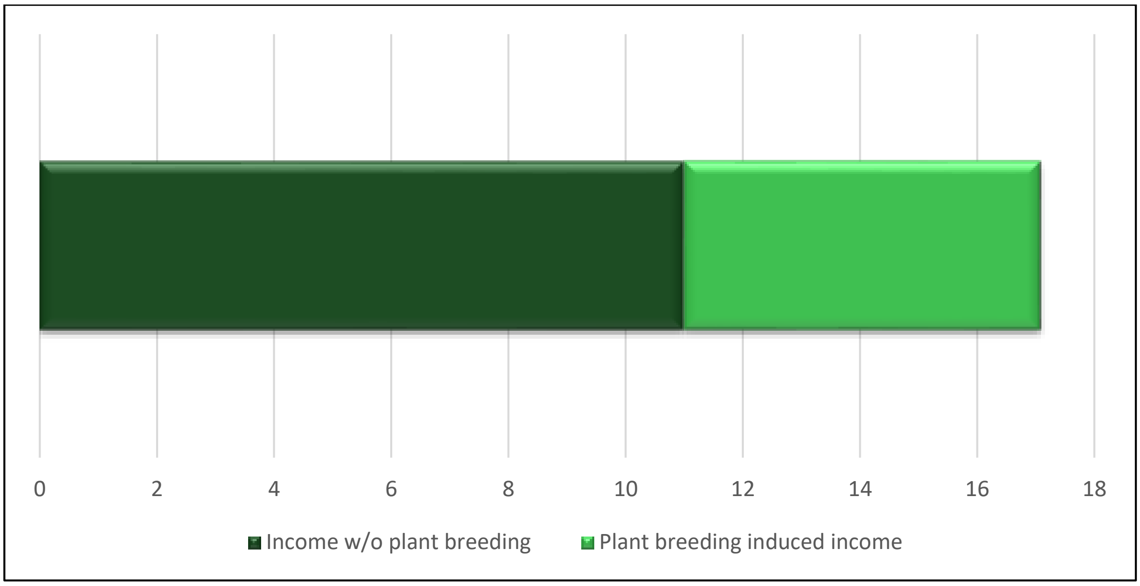
Source: Own calculations and figure.

Analysis for the level of the EU in total

Accordingly, an annual working unit (AWU) in EU arable farming has most recently generated an income – expressed in terms of farm net value added (FNVA)[33] – of around EUR 17 100. Without the market revenue currently earned due to plant breeding progress since 2000, this income would shrink by approximately EUR 6 100. In other words: The current income of an average arable farm in the EU would have decreased by one third as figure 2.73 depicts.

The interesting part here is that the current EU farm income of around EUR 17 100 is still larger than the amount received from subsidies minus taxes. In fact, the current governmental spending is around 12 900 EUR/AWU what equals 75 percent of the entire farm income (see again EC, 2019b). Without plant breeding since 2000, the current farm income per AWU would, thus, be less than the subsidies received. In other words: From a purely economic point of view, it would have been better to pay the subsidies and close the farm business without plant breeding progress since 2000.

Figure 2.73: Farm income of arable farms and income induced by plant breeding progress between 2000 and 2019 in the EU (in thousand EUR/AWU)



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Germany

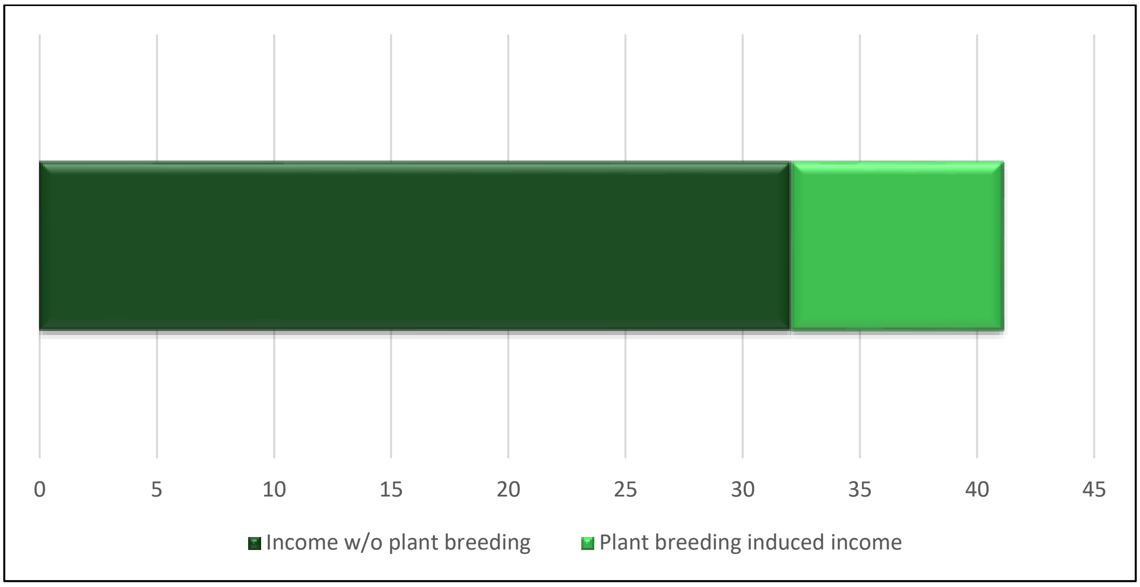
Figure 2.74 depicts the situation for Germany. Accordingly, it can be stated that an AWU engaged in arable farming of Germany currently generates an income of more than EUR 41 000. Without the

33 In terms of farm economics, the FNVA equals the market revenue plus subsidies minus taxes minus intermediate consumption minus depreciation.

market revenue earned due to plant breeding progress since 2000, this income would shrink by approximately EUR 9 000. In other words: The current income of an average arable farm in Germany – without plant breeding progress since the turn of the millennium – would shrink by almost a quarter.

Since subsidies currently amount to approximately 75 percent of the farm income in the country (see again EC, 2019b) this means that a German arable farmer would have to be fully dependent on governmental transfers.

Figure 2.74: Farm income of arable farms and income induced by plant breeding progress between 2000 and 2019 in Germany (in thousand EUR/AWU)



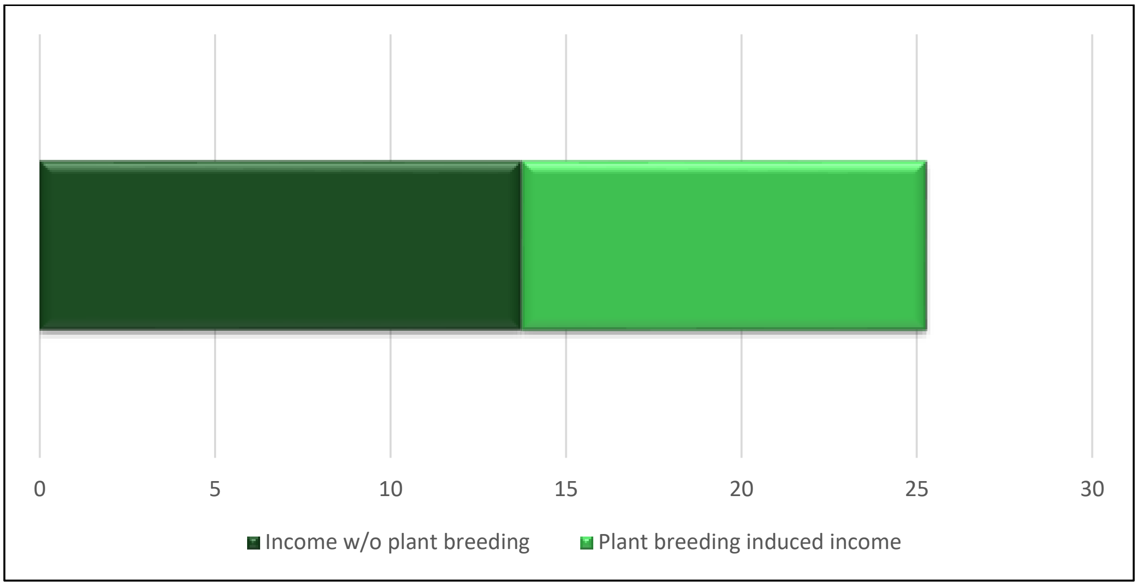
Source: Own calculations and figure.

Analysis for the level of EU member states – the case of France

Looking at the case of France, it can be highlighted with figure 2.75 that an AWU engaged in arable farming of the country currently generates an income of slightly more than EUR 25 000. Without the market revenue generated because plant breeding since 2000 has contributed progress, this income would shrink by approximately EUR 11 500. In other words: The income of an average arable farm in France – without plant breeding achievements since 2000 – would shrink almost by a half.

Subsidies paid to arable farmers are at around EUR 26 500 (see again, EC 2019b) and, thus, already today higher than the generated income in France. Thus, a French arable farmer would face an even greater calamity and dependency on state transfers without plant breeding.

Figure 2.75: Farm income of arable farms and income induced by plant breeding progress between 2000 and 2019 in France (in thousand EUR/AWU)



Source: Own calculations and figure.

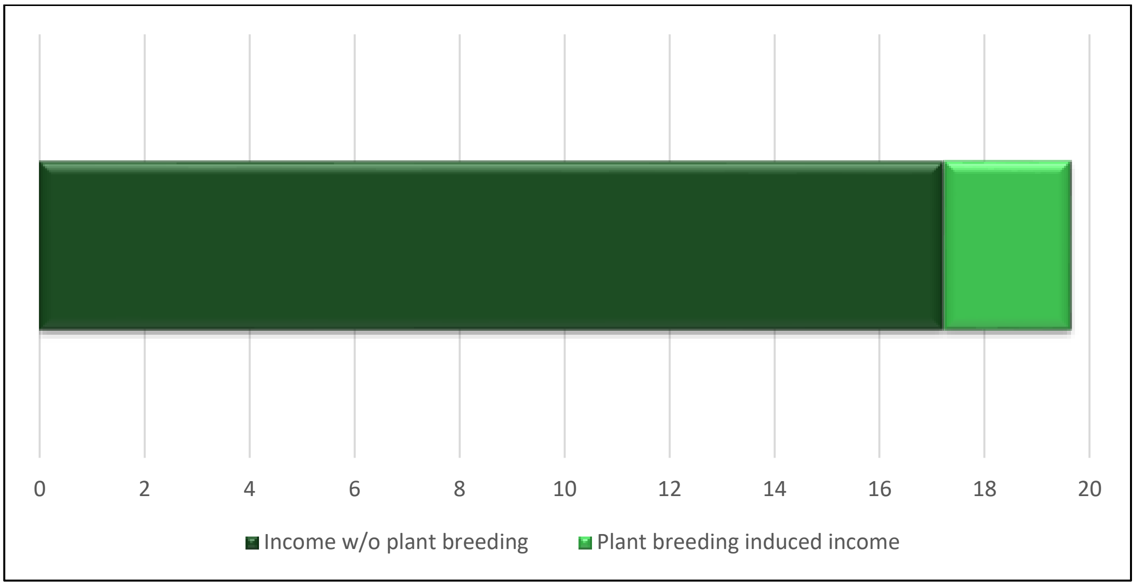
Analysis for the level of EU member states – the case of Italy

Figure 2.76 displays the situation for Italy. Accordingly, it can be stated that an AWU engaged in arable farming of Italy generates an income of almost EUR 20 000. Without the market revenue currently earned due to plant breeding progress since 2000, this income would shrink by approximately EUR 2 500. In other words: The income of an average arable farm in Italy – without plant breeding progress for the here selected arable crops since the turn of the millennium – would shrink by more than 10 percent. Subsidies currently amount to approximately 45 percent of the farm income in the country (see again EC, 2019b). This means that an Italian arable farmer would become considerably more state dependent in the absence of plant breeding achievements.

Analysis for the level of EU member states – the case of Spain

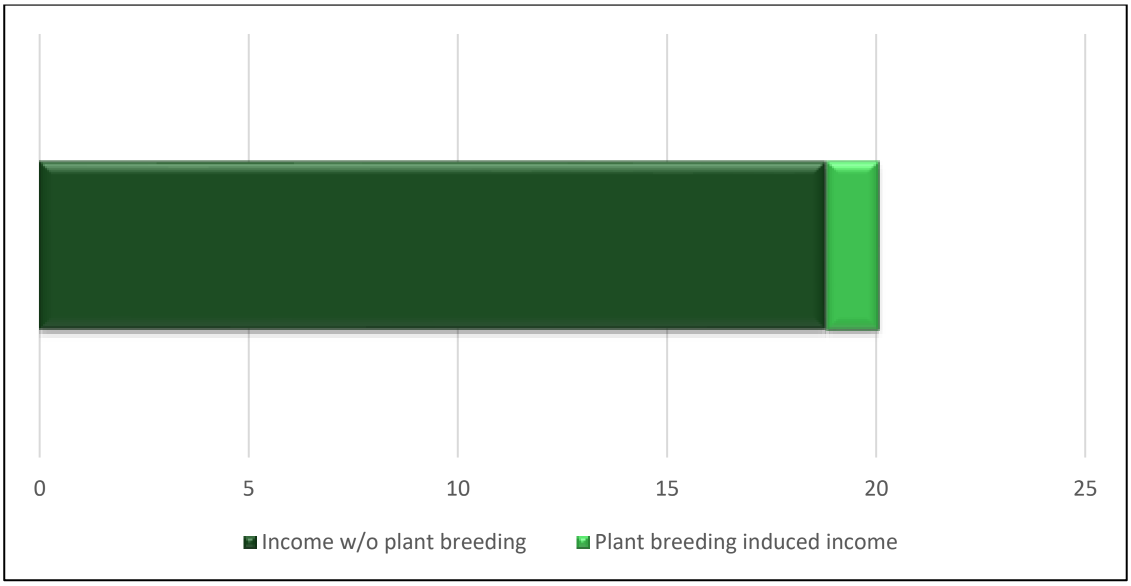
Looking at the case of Spain, it can be highlighted with figure 2.77 that an AWU engaged in arable farming of the country currently generates an income of slightly more than EUR 20 000. Without the market revenue generated because plant breeding since 2000 has contributed progress, this income would shrink by approximately EUR 1 250. In other words: The income of an average arable farm in Spain – without plant breeding achievements since 2000 – would shrink by more than 6 percent. Subsidies paid to arable farmers in the country are at around EUR 14 600 (see again EC, 2019b). These are already more than 70 percent of the entire income. The share without plant breeding progress of the past two decades would be close to 80 percent indicating greater dependency on governmental transfers.

Figure 2.76: Farm income of arable farms and income induced by plant breeding progress between 2000 and 2019 in Italy (in thousand EUR/AWU)



Source: Own calculations and figure.

Figure 2.77: Farm income of arable farms and income induced by plant breeding progress between 2000 and 2019 in Spain (in thousand EUR/AWU)



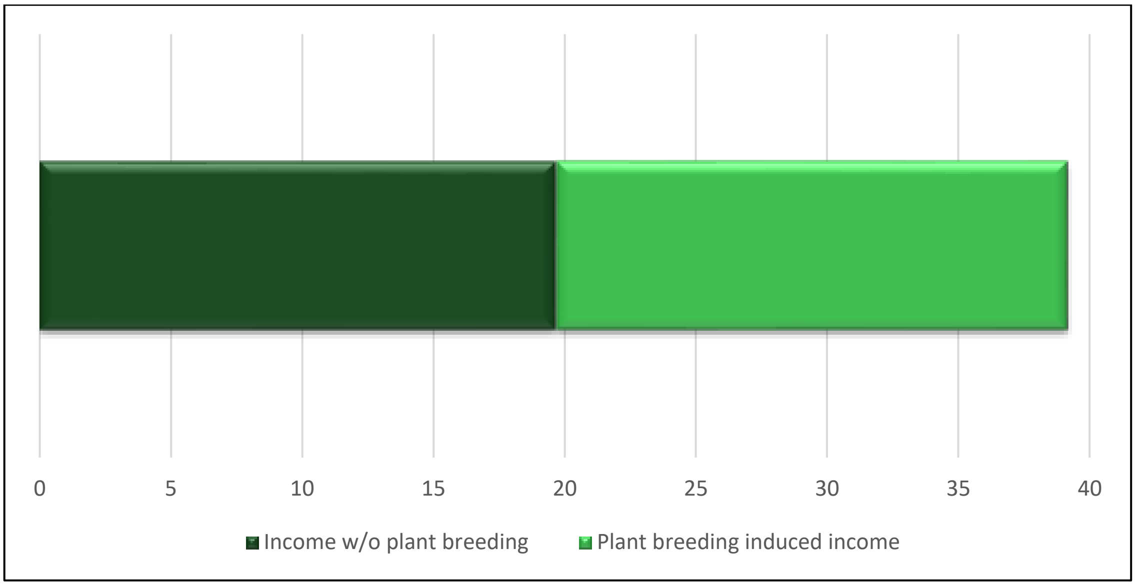
Source: Own calculations and figure.

Analysis for the level of EU member states – the case of the UK

Figure 2.78 depicts the situation for the UK. Accordingly, it can be stated that an AWU engaged in arable farming of the UK generates an income of more than EUR 39 000. Without the market revenue currently earned due to plant breeding since 2000, this income would shrink by approximately EUR 19 500, i.e., it would basically be half.

Subsidies paid to arable farmers in the UK are at around EUR 40 000 (see again EC, 2019b) and, thus, already today higher than the generated income in the country. Thus, an arable farmer in the UK would face an even greater calamity – or state dependency – without plant breeding.

Figure 2.78: Farm income of arable farms and income induced by plant breeding progress between 2000 and 2019 in the UK (in thousand EUR/AWU)



Source: Own calculations and figure.

Farm and other labour

Overview on the impacts by EU region and crop

Of course, farmers would try to adapt to this worsening income situation. Some would stop working, others would partly move to other income generating options and/or switch to part-time working in arable farming. The underlying reason is that the absence of plant breeding would additionally imply that a lower amount of work force not only for cultivating (some fields) but also for harvesting, transporting, and storing activities on-farm would be necessary. Using EC (2019b) and additionally KTBL (2021) data, the resulting labour effect can be calculated. It is displayed in figure 2.79 per crop and region.

Figure 2.79: Farm labour losses attributable to major arable crops in 2020 without plant breeding progress between 2000 and 2019 in the EU and selected member states (in percent)

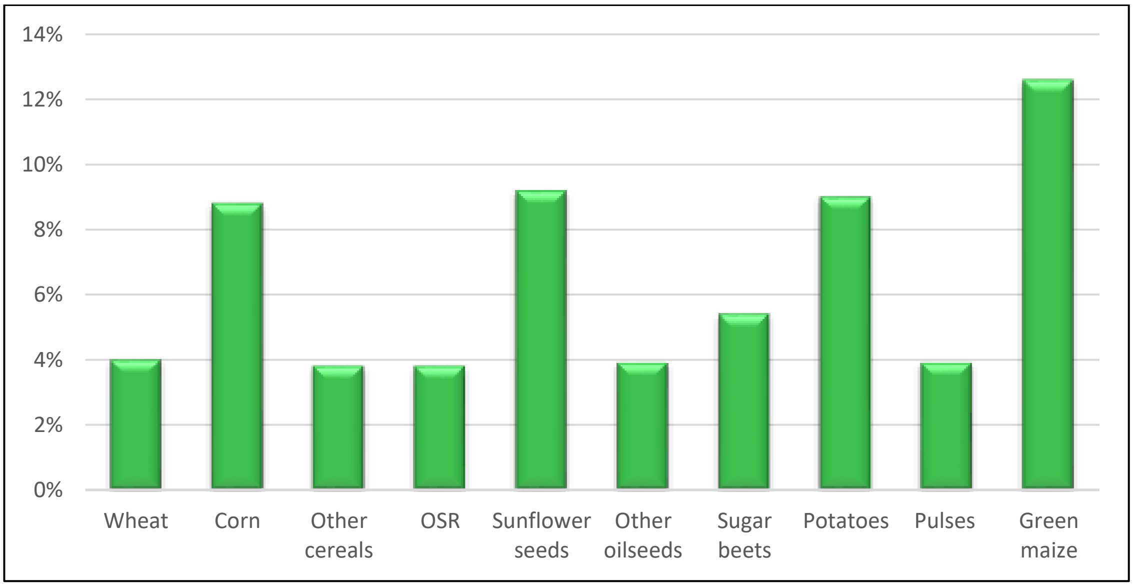
Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	4.0	2.7	3.0	4.4	2.5	3.7
Corn	8.8	7.0	6.8	4.2	6.9	6.6
Other cereals	3.8	3.6	2.8	2.9	1.4	3.4
OSR	3.8	3.2	5.4	11.0	6.0	6.4
Sunflower seeds	9.2	4.8	5.5	3.9	3.7	N.A.
Other oilseeds	3.9	9.9	5.1	1.4	4.0	11.6
Raw sugar	5.4	5.0	5.6	4.9	4.8	5.9
Potatoes	9.0	4.7	4.7	5.0	5.5	6.0
Pulses	3.9	4.6	5.0	5.6	6.1	4.3
Green maize	12.6	7.1	12.4	3.0	14.5	13.7

Source: Own calculations and figure.

Analysis for the level of the EU in total

Figure 2.80 displays the effects on labour currently engaged in arable farming for the case of missing plant breeding innovation since 2000 in the EU in total.

Figure 2.80: Farm labour losses attributable to major arable crops in 2020 without plant breeding progress between 2000 and 2019 in the EU



Source: Own calculations and figure.

As can be seen, the percentage of AWU not needed today in EU arable farming in the case of missing plant breeding in the last two decades is comparably low in wheat and other cereals, OSR and other oilseeds as well as pulses, but rather high in corn, potatoes, sugar beets, and especially green maize as these are crops where a lot of working time needs to be devoted to harvest and transport activities in relation to other field-based efforts such as fertilizing, applying PPP etc.

Weighting by acreage, the total effect amounts to 5.5 percent of all labour yet employed in EU arable farming. This percentage of AWU would not have been needed today if plant breeding activities had been stopped in 2000. From EC (2019b), it can be concluded that 2.02 AWU are employed per 100 hectares of (arable) land. The crops being in the focus of this study are cultivated on approximately 80.3 million hectares across the EU (Eurostat, 2021b; FAO, 2021). This means, more than 1.6 million AWU are currently engaged in arable farming. Subsequently almost 90 000 AWU, i.e., an equal amount of paid or unpaid labour force in arable farming of the EU, would be endangered to lose their jobs without plant breeding since the turn of the millennium.

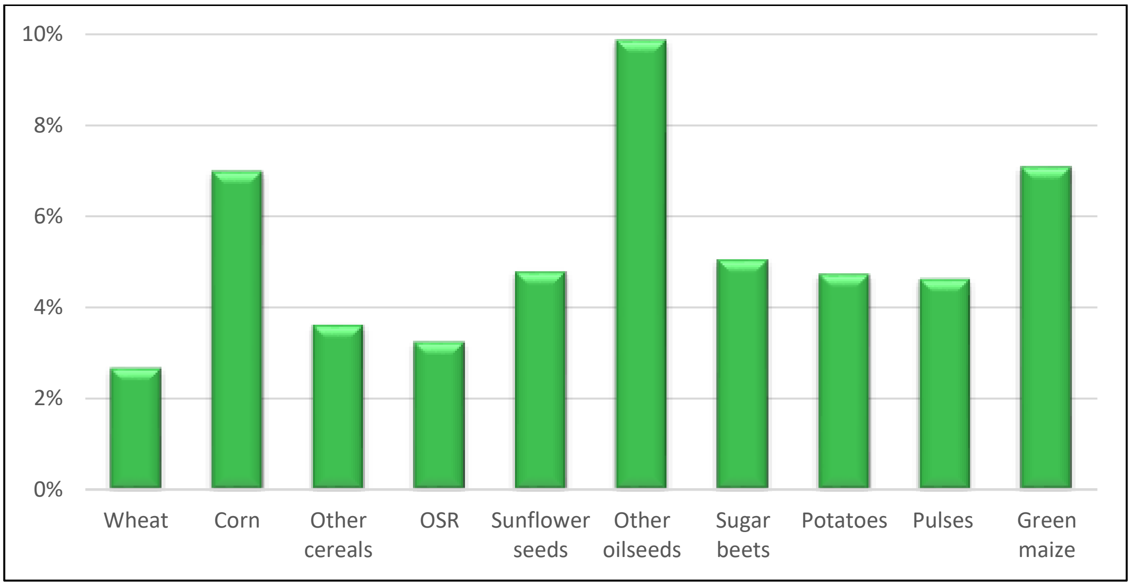
The decrease in production without plant breeding progress since 2000 also causes less purchasing of inputs, as well as less processing, trading, and retailing of the primary agricultural commodities. This would additionally cause some labour market turbulences upstream and downstream the agricultural value chain. Using again sophisticated multiplier analysis (see again annex D) allows to calculate the overall labour effect. This leads to the conclusion that more than 850 000 jobs in storing, processing, and packaging, internationally trading and retailing the missing crop volumes caused by absent plant breeding since 2000 in the EU would have at least partially been endangered, i.e., would currently suffer from income losses or even unemployment in the EU in total.

Analysis for the level of EU member states – the case of Germany

Figure 2.81 displays the impacts of plant breeding on labour for German arable farming and basically mirrors what has already been stated for the EU in total: Labour engagement in crops with a particularly high labour share devoted to harvesting and on-farm storage of harvest would suffer the most from the absence of plant breeding progress since the turn of the millennium. However, in Germany the hectare-weighted average impact would be lower than in the EU in total and amount to a decrease in labour need of 4.4 percent.

From EC (2019b) it can be concluded that 1.25 AWU are employed per 100 hectares of (arable) land in Germany. The crops being in the focus of this study are cultivated on approximately 10.4 million hectares across the country (Eurostat, 2021b; FAO, 2021). This means, more than 130 000 AWU are currently engaged in German arable farming. Subsequently more than 5 700 AWU currently engaged in arable farming in Germany would be endangered to lose their jobs without plant breeding since 2000. Due to less purchasing of inputs as well as less processing, trading, and retailing of the forgone primary agricultural commodity volume, missing plant breeding innovations post the millennium would additionally have endangered more than 42 000 jobs along the various agricultural and food value chains in Germany today.

Figure 2.81: Farm labour losses attributable to major arable crops in 2020 without plant breeding progress between 2000 and 2019 in Germany



Source: Own calculations and figure.

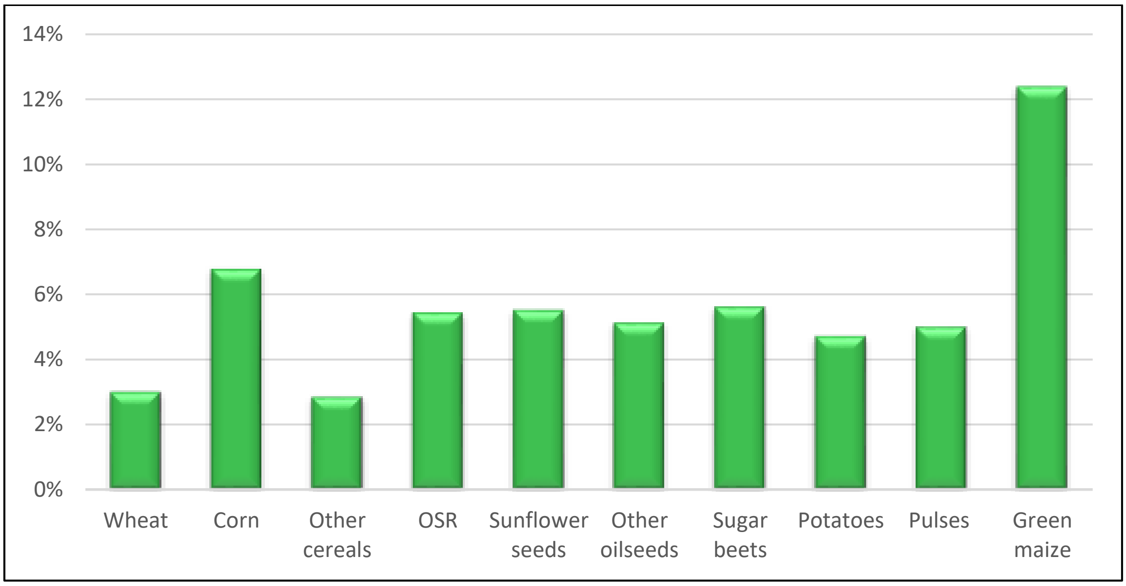
Analysis for the level of EU member states – the case of France

Looking at figure 2.82, it turns out that in France especially labour force engaged in maize (corn and green maize) production would today have been endangered if plant breeding progress had stopped in 2000. In France, the hectare-weighted average – labour decreasing – impact would be around 4.9 percent. From EC (2019b) it can be concluded that 1.15 AWU are employed per 100 hectares of (arable) land in the country. The crops being in the focus of this study are cultivated on 13.8 million hectares across the country (Eurostat, 2021b; FAO, 2021). This means, almost 160 000 AWU are currently engaged in French arable farming. Subsequently more than 7 700 AWU currently engaged in arable farming in France would be endangered to lose their jobs without plant breeding since 2000. Due to less purchasing of inputs as well as less processing, trading, and retailing of the forgone primary agricultural commodity volume, missing plant breeding innovations since 2000 would additionally have endangered more than 58 000 jobs along the value chains in France today.

Analysis for the level of EU member states – the case of Italy

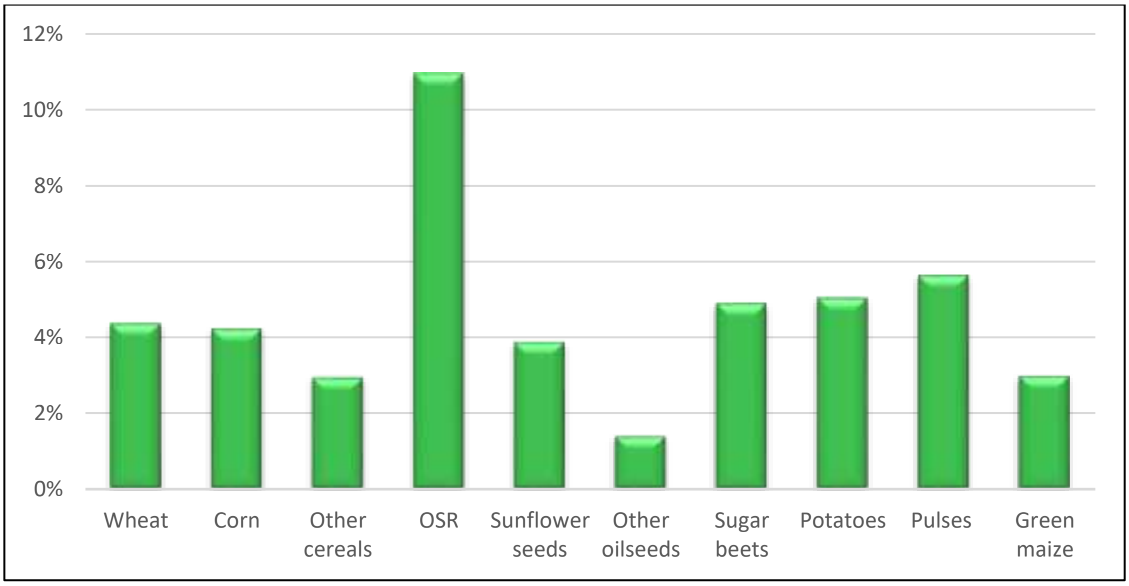
Figure 2.83 displays the impacts of plant breeding on labour for arable farming in Italy and indicates that, by and large, the losses that would have occurred today in the absence of plant breeding progress since 2000 are less pronounced than in the already discussed country cases. Here, jobs related to OSR and pulses would most be affected. In Italy, the hectare-weighted average impact would thus be considerably lower than in the EU in total and amount to a decrease in labour need for arable farming of 3.8 percent.

Figure 2.82: Farm labour losses attributable to major arable crops in 2020 without plant breeding progress between 2000 and 2019 in France



Source: Own calculations and figure.

Figure 2.83: Farm labour losses attributable to major arable crops in 2020 without plant breeding progress between 2000 and 2019 in Italy



Source: Own calculations and figure.

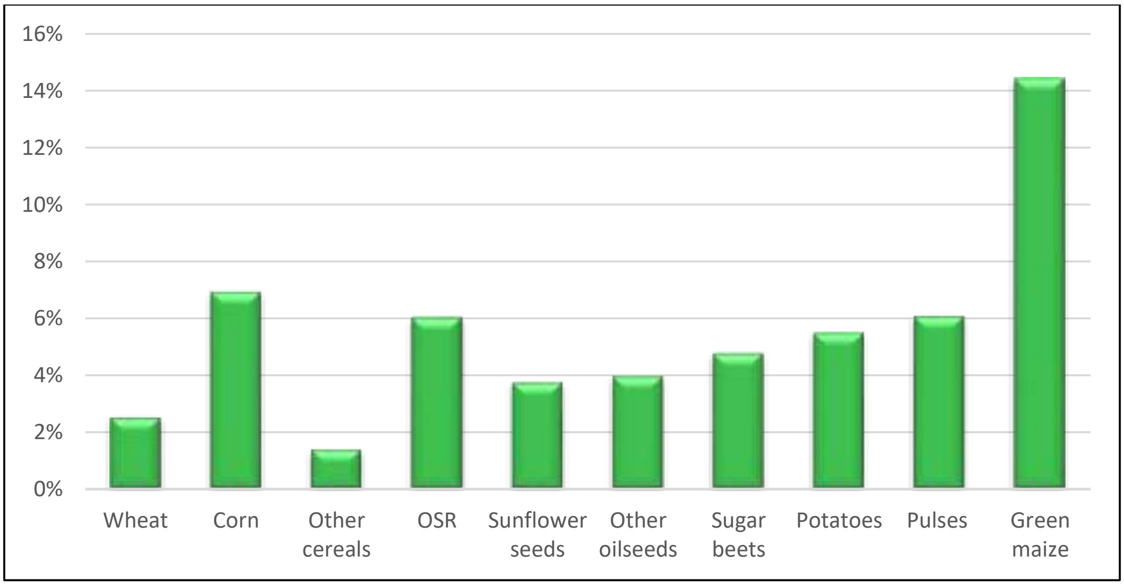
From EC (2019b) it can be concluded that 3.29 AWU are employed per 100 hectares of (arable) land in Italy. The crops being in the focus of this study are cultivated on approximately 4.1 million hectares across the county (Eurostat, 2021b; FAO, 2021). This means, more than 130 000 AWU are currently engaged in Italian arable farming. Subsequently more than 5 100 AWU currently engaged in arable farming in Italy would be endangered to lose their jobs without plant breeding since the turn of the millennium. Due to less purchasing of inputs as well as less processing, trading, and retailing of the forgone primary agricultural commodity volume, missing plant breeding innovations after 2000 would additionally have endangered almost 43 000 jobs along the value chains in Italy today.

Analysis for the level of EU member states – the case of Spain

Figure 2.84 displays the impacts of plant breeding on labour for arable farming in Spain and indicates – as in the case of Italy – that the losses that would have occurred today in the absence of plant breeding progress since 2000 are less pronounced than in the already discussed country cases. Here, workload related to maize (corn and green maize) would most be endangered. In Spain, the hectare-weighted average impact amounts to 2.7 percent.

From EC (2019b) it can be concluded that 1.19 AWU are employed per 100 hectares of (arable) land in Spain. The crops being in the focus of this study are cultivated on approximately 7.5 million hectares across the county (Eurostat, 2021b; FAO, 2021). This means, almost 90 000 AWU are currently engaged in Spanish arable farming. Subsequently almost 2 500 AWU currently engaged in arable farming in Spain would be endangered to lose their jobs without plant breeding since 2000.

Figure 2.84: Farm labour losses attributable to major arable crops in 2020 without plant breeding progress between 2000 and 2019 in Spain



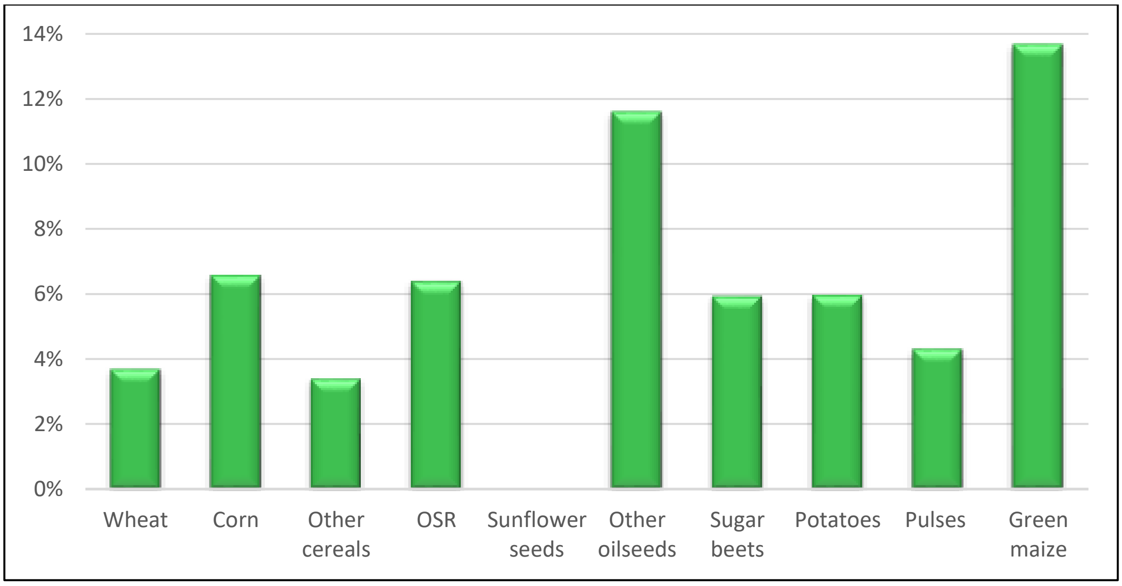
Source: Own calculations and figure.

Due to less purchasing of inputs as well as less processing, trading, and retailing of the forgone primary agricultural commodity volume, missing plant breeding innovations after 2000 would additionally have endangered almost 24 000 jobs along the value chains in Spain today.

Analysis for the level of EU member states – the case of the UK

Figure 2.85 displaying the impacts of plant breeding on labour for arable farming in the UK shows more pronounced effects in the cases of maize (corn and green maize) and other oilseeds and less crucial agricultural labour shocks as regards, for instance, wheat and other cereals. However, the hectare-weighted average impact is comparable to the effect in Germany and France and would amount to a decrease in labour need (due to missing plant breeding progress since 2000) of 4.6 percent.

Figure 2.85: Farm labour losses attributable to major arable crops in 2020 without plant breeding progress between 2000 and 2019 in the UK



Source: Own calculations and figure.

From EC (2019b) it can be concluded that 0.95 AWU are employed per 100 hectares of (arable) land in the UK. The crops being in the focus of this study are cultivated on approximately 4.4 million hectares across the country (Eurostat, 2021b; FAO, 2021). This means, almost 42 000 AWU are currently engaged in arable farming in the UK. Subsequently almost 2 000 AWU currently engaged in arable farming of the country would be endangered to lose their jobs without plant breeding since 2000. Due to less purchasing of inputs as well as less processing, trading, and retailing of the forgone primary agricultural commodity volume, missing plant breeding innovations post the millennium would additionally have endangered more than 15 000 jobs along the value chains in the UK today.

2.3 Tertiary environmental effects

Before the tertiary environmental effects are discussed in more detail, it shall be recognized, that the methodology to derive the various results particularly uses the models and tools of environmental economics described in annex E. In fact, changing framework conditions do not only affect production and trade, as well as income and labour, but also the broader environment. The major rationale behind these environmental effects and its analysis is the following:

- Decreasing yields – here due to the absence of plant breeding activities in the EU and its member states for selected arable crops since 2000 – imply a lower market supply of agricultural commodities today while market demand is largely unaffected.
- The resulting market disequilibrium can and will be combated by using more natural resources, here arable land. This can principally happen domestically or abroad. Arable land in the EU, however, is already a limited resource and shrinking.
- Against this background, the cultivation of additional arable land within the EU is considered impossible[34]. In such a situation, changing exports and imports (as already discussed above) compensate for yield losses.

This leads to several resource-based and hence environmental impacts, which will now be discussed. Thereby, the following must be noted: The models described in annex E force the EU to interact with the other world regions via international trade and define the EU as a single market. Trade interactions within the EU are internally compensated and resulting volume changes in EU-intra trade are shifted towards the EU border. This means, the following essentially refers to EU-extra trade effects. Against this background, green maize is defined as a non-tradable good. The land pressure and thus land-use effects resulting from market shortcomings in green maize (and the subsequent other environmental impacts) are transferred into additional land-use changes with respect to other crops assuming that the relative share of arable land use per remaining arable crop in the EU remains unchanged due to this green maize transfer effect.

Virtual land trade

Overview on the impacts by EU region and crop

The obvious reductions in EU-extra exports and the apparent increases in EU-extra imports in case of missing plant breeding activities since 2000 (see, again, figure 2.44) would subsequently change the balance of EU net imports of virtual agricultural land. The resulting avoided net virtual land trade in 2020 that can be attributed to the EU in total as well as the selected member states due to successful plant breeding since the turn of the millennium is visualized in figure 2.86.

34 In fact, the maintenance of grassland and, thus, its non-conversion into and subsequent use as arable land is one of the current greening agricultural practices as defined by EU regulation (EC, 2015).

Figure 2.86: Avoided net virtual land imports attributable to major arable crops in 2020 with plant breeding progress between 2000 and 2019 in the EU and selected member states (in million hectares)

Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	7.730	0.840	1.521	0.308	0.190	0.739
Corn	2.702	0.133	0.446	0.136	0.144	0.001
Other cereals	5.093	0.784	0.594	0.180	0.178	0.352
OSR	3.238	0.570	1.109	0.015	0.038	0.591
Sunflower seeds	1.906	0.004	0.162	0.023	0.070	N.A.
Other oilseeds	0.066	0.002	0.009	0.009	0.001	0.002
Raw sugar	0.361	0.077	0.122	0.006	0.009	0.024
Potatoes	0.171	0.017	0.013	0.002	0.004	0.011
Pulses	0.321	0.051	0.074	0.016	0.043	0.064

Source: Own calculations and figure.

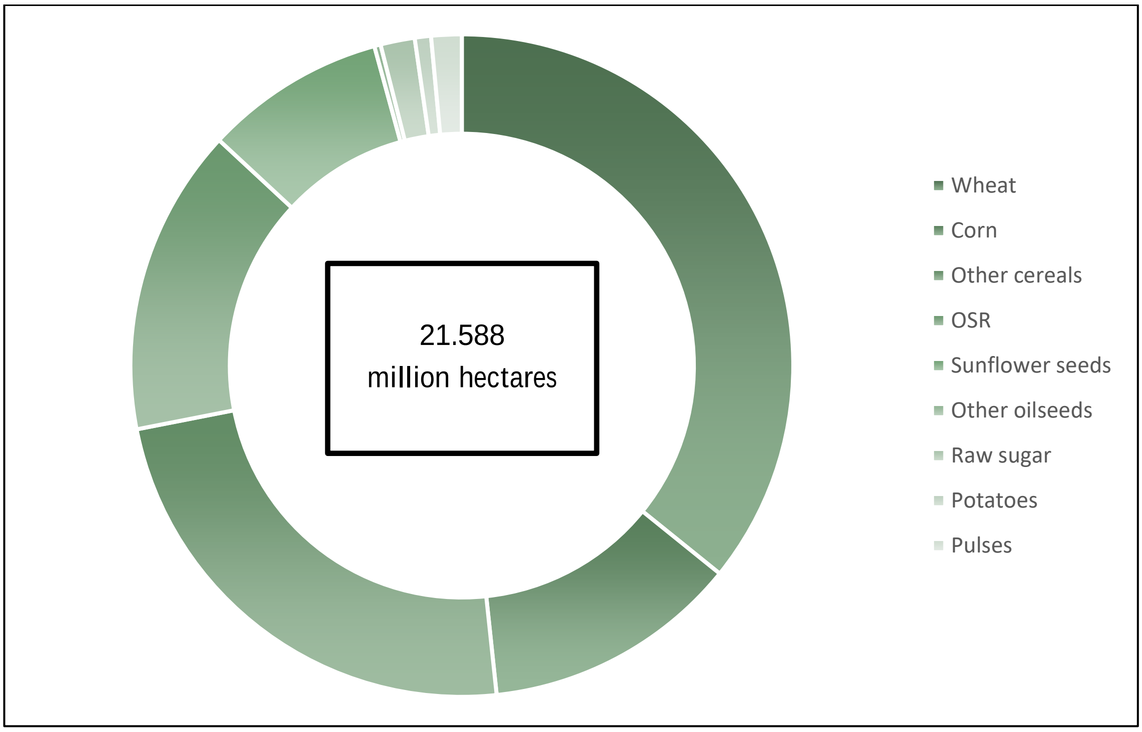
Analysis for the level of the EU in total

Looking at figure 2.87 and considering all other factors than land to be unchanged (e.g., yields in the other world regions), almost 22 million hectares of arable land would globally have been needed in addition to what is already used worldwide in 2020 if plant breeding in the EU had been terminated in 2000. This would have meant an increase of an area almost as large as the entire (land) territory of Romania (Worldometer, 2020). Thereby, the bulk of the potential growth in net land imports would be caused by wheat (7.7 million hectares) and other cereals (5.1 million hectares) followed by OSR (3.2 million hectares), corn (2.7 million hectares) and sunflower seeds (1.9 million hectares).

More interesting, however, is where this yet still natural or nature-like land would have entered agriculture. This regional distribution of the avoided EU net imports of virtual agricultural land around the globe is listed in figure 2.81. Accordingly:

- More than 5.3 million hectares would come from the Commonwealth of Independent States (CIS), and the Middle East/North Africa (MENA) region would contribute almost 3.6 million hectares.
- Almost 2.9 million hectares would need to be additionally occupied in Asia, while around 2.5 million hectares would be located each in North America, Sub-Sahara Africa, and Oceania.
- South America would need to contribute almost 2.0 million additional hectares, and the Rest of the World (RoW) would add close to 0.5 million hectares.

Figure 2.87: Avoided net virtual land imports in 2020 with plant breeding progress between 2000 and 2019 in the EU, by crop



Source: Own calculations and figure.

Figure 2.88: Avoided net virtual land imports in 2020 with plant breeding progress between 2000 and 2019 in the EU, by region (in million hectares)

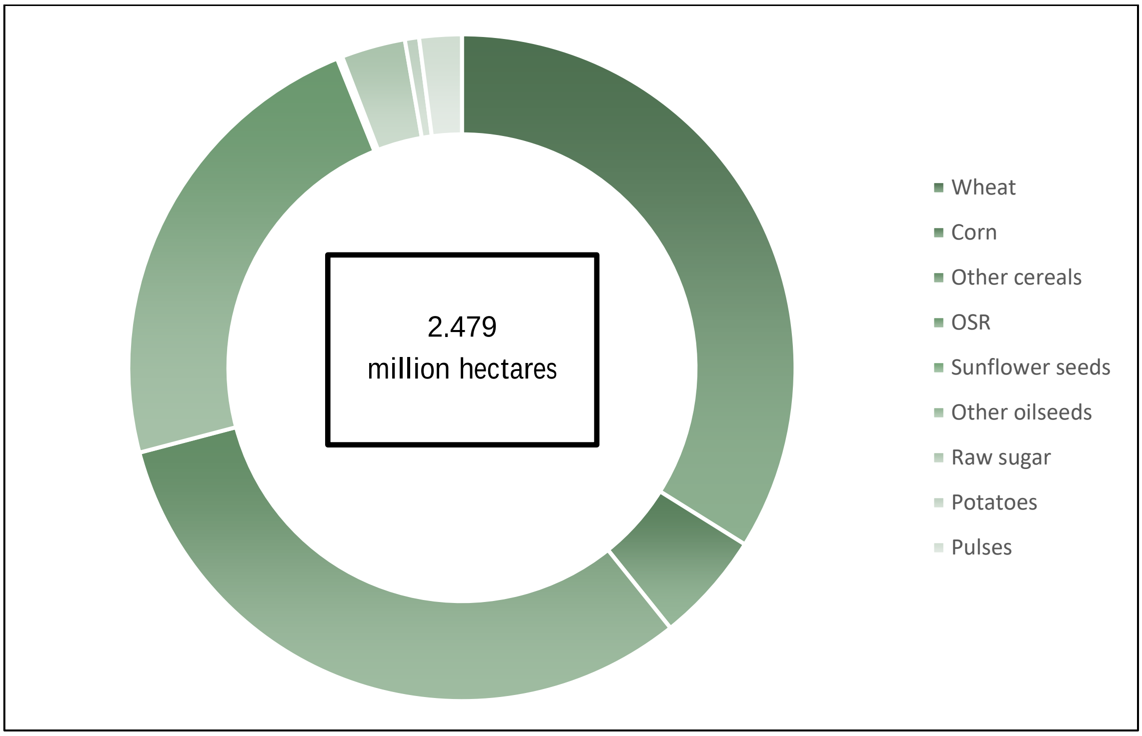
Region	Value	Region	Value
North America	2.442	Sub-Sahara Africa	2.341
South America	1.847	Oceania	2.684
Asia	2.893	CIS	5.318
MENA	3.595	RoW	0.468

Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Germany

Figure 2.89 displays the avoided net virtual land imports in 2020 of Germany due to plant breeding progress since 2000 by crop. Accordingly, it can be stated that almost 2.5 million hectares of natural or nature-like habitats across the globe remain unused today for agricultural purposes.

Figure 2.89: Avoided net virtual land imports in 2020 with plant breeding progress between 2000 and 2019 in Germany, by crop



Source: Own calculations and figure.

The regional distribution of these German avoided net imports of virtual agricultural land around the globe in 2020 is listed in figure 2.90. Accordingly, more than 0.5 million hectares would come from the CIS, and the MENA region as well as Oceania would contribute around 0.4 million hectares each. More than (close to) 0.3 million hectares would need to be additionally occupied in North America (Asia and Sub-Sahara Africa). South America would need to contribute almost 0.2 million additional hectares, and the RoW still would add the remaining less than 0.1 million hectares.

Figure 2.90: Avoided net virtual land imports in 2020 with plant breeding progress between 2000 and 2019 in Germany, by region (in million hectares)

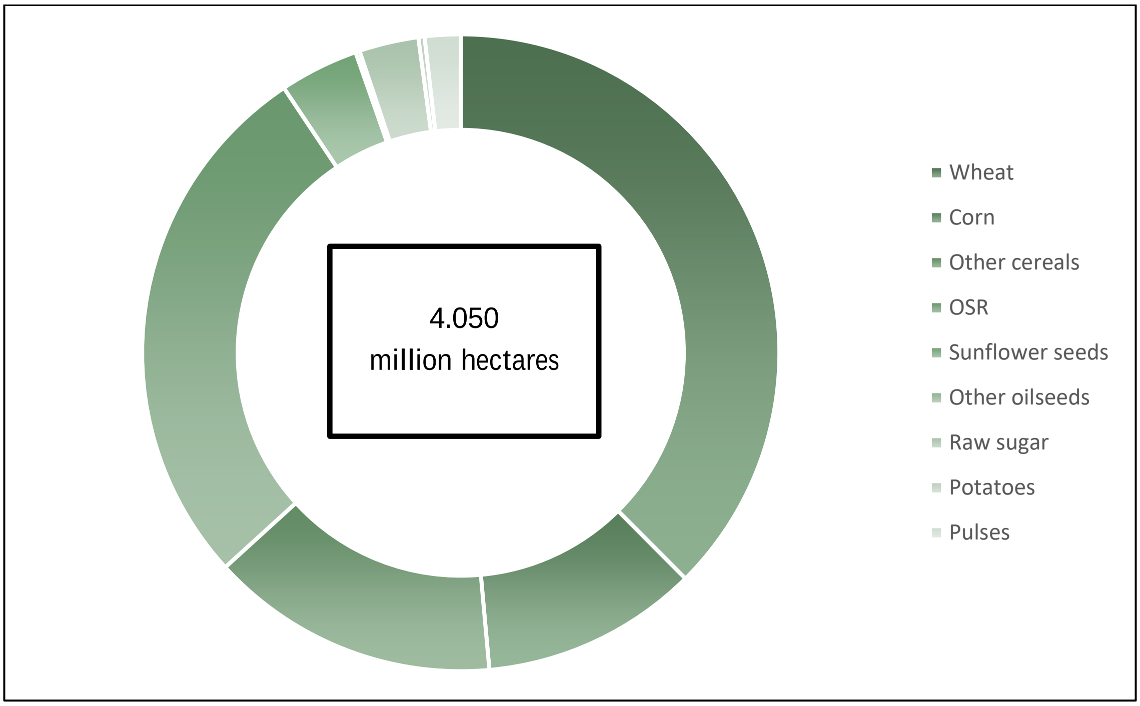
Region	Value	Region	Value
North America	0.343	Sub-Sahara Africa	0.272
South America	0.199	Oceania	0.380
Asia	0.283	CIS	0.512
MENA	0.435	RoW	0.054

Source: Own calculations and figure

Analysis for the level of EU member states – the case of France

Looking at figure 2.91, it can be stated that the avoided net virtual land imports of France today due to plant breeding progress since 2000 are higher than 4.0 million hectares. This is the amount of natural or nature-like habitats across the globe that still is not used for agricultural purposes due to plant breeders' innovations in this EU member state.

Figure 2.91: Avoided net virtual land imports in 2020 with plant breeding progress between 2000 and 2019 in France, by crop



Source: Own calculations and figure.

The regional distribution of these French avoided net imports of virtual agricultural land around the globe is listed in figure 2.92. Accordingly:

- More than 1.0 million hectares would come from the CIS, and the MENA region as well as Oceania would contribute around 0.6 million hectares each.
- More than 0.4 million hectares would need to be additionally occupied in North America, Asia and Sub-Sahara Africa each.
- South America would need to contribute almost 0.3 million additional hectares, and the RoW would need to add the remaining 0.1 million hectares.

Figure 2.92: Avoided net virtual land imports in 2020 with plant breeding progress between 2000 and 2019 in France, by region (in million hectares)

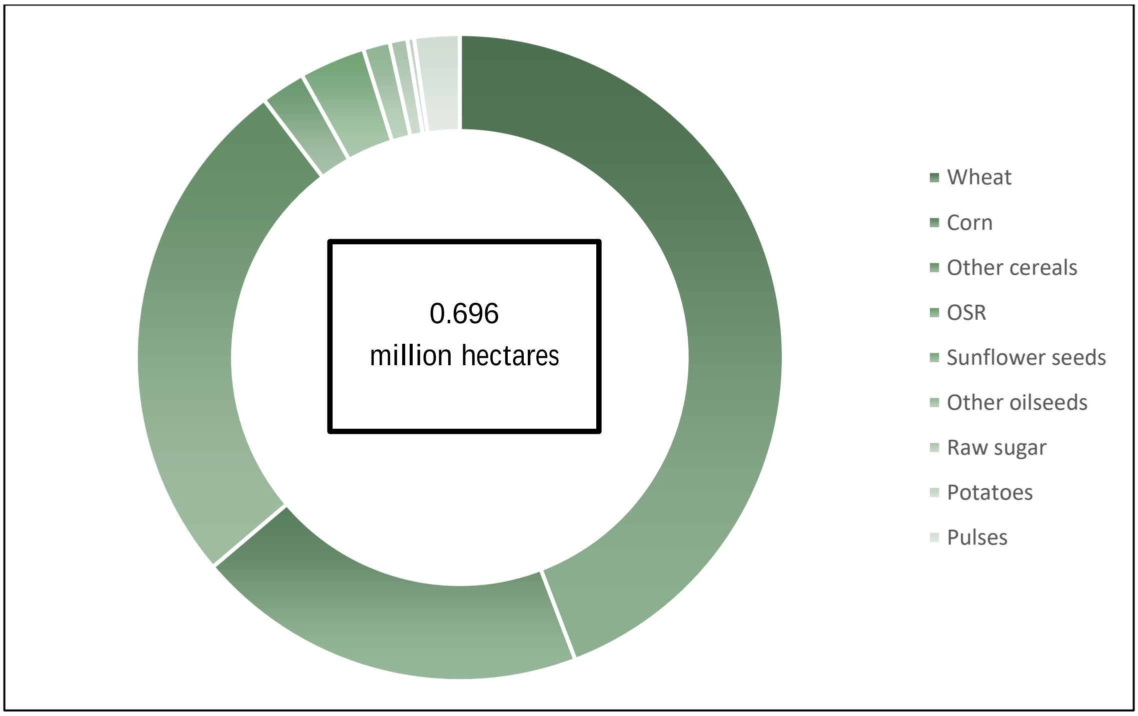
Region	Value	Region	Value
North America	0.549	Sub-Sahara Africa	0.414
South America	0.295	Oceania	0.593
Asia	0.460	CIS	1.048
MENA	0.606	RoW	0.085

Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Italy

Figures 2.93 and 2.94 visualize the results for Italy. Accordingly, it can be stated that the avoided net virtual land imports of Italy due to plant breeding progress since 2000 are around 700 000 hectares. This is the amount of natural or nature-like habitats across the globe that still is not used for agricultural purposes due to plant breeders' innovations in the past two decades in the country.

Figure 2.93: Avoided net virtual land imports in 2020 with plant breeding progress between 2000 and 2019 in Italy, by crop



Source: Own calculations and figure.

Looking at the regional distribution of these Italian avoided net imports of virtual agricultural land around the globe, it can be argued that more than 150 000 hectares would come from the CIS, and the MENA region would contribute more than 130 000 hectares. Close to 100 000 hectares would have to come from Asia and Sub-Sahara Africa each, while around 75 000 hectares would additionally be cultivated for agricultural purposes in both, Oceania and South America. North America would add another 65 000 hectares, while the RoW would need to contribute the remaining 13 000 hectares.

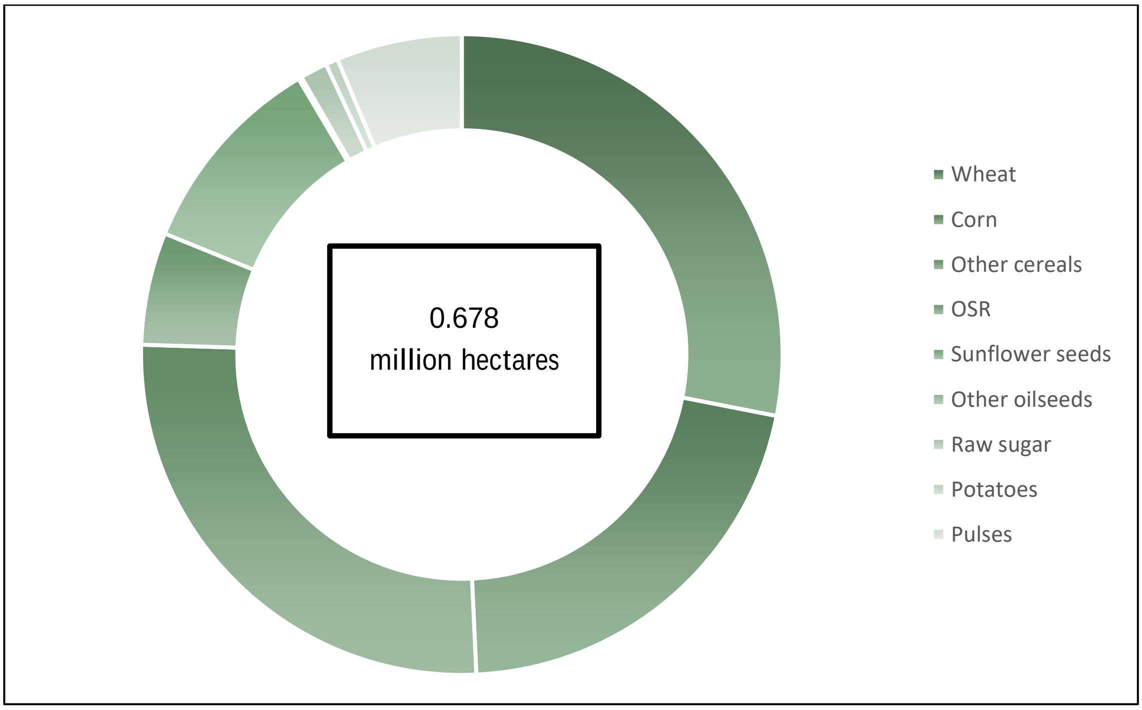
Figure 2.94: Avoided net virtual land imports in 2020 with plant breeding progress between 2000 and 2019 in Italy, by region (in million hectares)

Region	Value	Region	Value
North America	0.065	Sub-Sahara Africa	0.091
South America	0.075	Oceania	0.074
Asia	0.089	CIS	0.153
MENA	0.135	RoW	0.013

Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Spain

Figure 2.95: Avoided net virtual land imports in 2020 with plant breeding progress between 2000 and 2019 in Spain, by crop



Source: Own calculations and figure.

Looking at figure 2.95, it can be stated that the avoided net virtual land imports of Spain due to plant breeding progress since 2000 are also around 700 000 hectares. This is the amount of natural or nature-like habitats across the globe that currently is still not used for agricultural purposes due to plant breeders' innovations in the past two decades in this EU member state.

The regional distribution of these Spanish avoided net imports of virtual agricultural land around the globe is listed in figure 2.96. Accordingly, almost 180 000 hectares would come from the CIS, and the MENA region as well as Asia would contribute around 100 000 hectares each. More than 70 000 hectares would need to be additionally occupied in North America, South America, and Sub-Sahara Africa each. Oceania would add another 65 000 hectares while the RoW would need to add the remaining 15 000 hectares.

Figure 2.96: Avoided net virtual land imports in 2020 with plant breeding progress between 2000 and 2019 in Spain, by region (in million hectares)

Region	Value	Region	Value
North America	0.079	Sub-Sahara Africa	0.072
South America	0.072	Oceania	0.064
Asia	0.092	CIS	0.176
MENA	0.109	RoW	0.015

Source: Own calculations and figure.

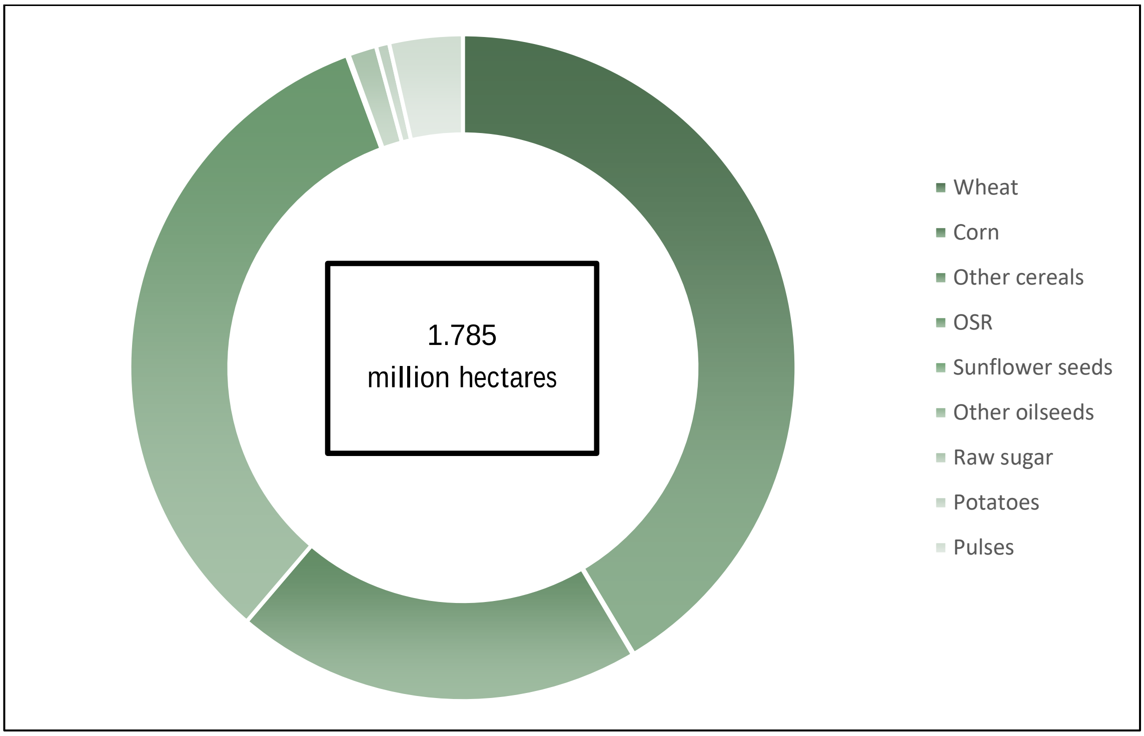
Analysis for the level of EU member states – the case of the UK

Figure 2.97 displays the avoided net virtual land imports of the UK in 2020 due to plant breeding progress since 2000 by crop. Accordingly, it can be stated that almost 1.8 million hectares of natural or nature-like habitats across the globe are today still not used for agricultural purposes by the UK alone.

The regional distribution of these yet avoided net imports of virtual agricultural land around the globe is listed in figure 2.98. Accordingly:

- Almost 0.4 million hectares would come from the CIS, and North America, the MENA region as well as Oceania would contribute around 0.3 million hectares each.
- More than 0.1 million hectares would need to be additionally occupied in South America, Asia, and Sub-Sahara Africa.
- The RoW would add the remaining less than 0.1 million hectares.

Figure 2.97: Avoided net virtual land imports in 2020 with plant breeding progress between 2000 and 2019 in the UK, by crop



Source: Own calculations and figure.

Figure 2.98: Avoided net virtual land imports in 2020 with plant breeding progress between 2000 and 2019 in the UK, by region (in million hectares)

Region	Value	Region	Value
North America	0.279	Sub-Sahara Africa	0.184
South America	0.106	Oceania	0.308
Asia	0.186	CIS	0.388
MENA	0.297	RoW	0.037

Source: Own calculations and figure

GHG emissions

Overview on the impacts by EU region

This arable land globally needed extra without plant breeding in the EU in the last two decades is not available *per se*. In a situation where recent trends suggest global acreage to be expanded by

21 million hectares per year (FAO, 2021) this land foremost needs to be additionally converted from grassland or natural habitats. However, all this land is yet sequestering carbon both above and below ground. A tremendous part of this carbon would be released into the atmosphere in the form of mainly CO_2 if the land was used for farming. The amount of greenhouse gas (GHG) to be emitted in such a situation, and currently avoided due to lasting genetic crop improvements, can be calculated by using the approach described in annex E and yields the avoided emissions of plant breeding. The resulting effect is visualized in figure 2.99.

Figure 2.99: Avoided regional CO_2 emissions attributable to major arable crops until 2020 with plant breeding progress between 2000 and 2019 in the EU and selected member states (in million tons)

Region	EU	DE	FR	IT	ES	UK
North America	357	50	80	9	12	41
South America	279	30	45	11	11	16
Asia	856	84	136	26	27	55
MENA	701	85	118	26	21	58
Sub-Sahara Africa	456	53	81	18	14	36
Oceania	303	43	67	8	7	35
CIS	899	87	177	26	30	66
RoW	84	10	15	2	3	7

Source: Own calculations and figure.

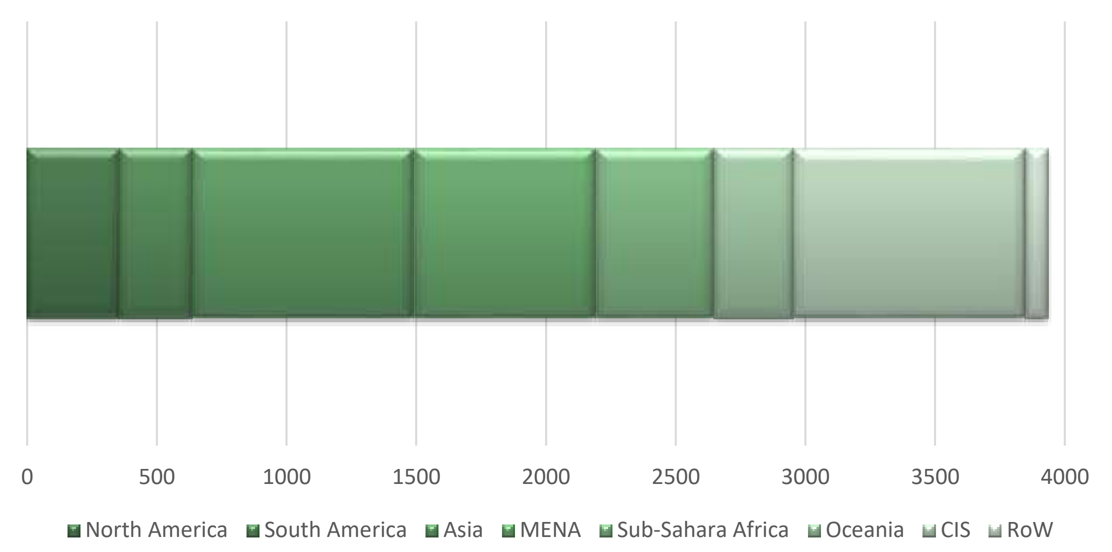
Analysis for the level of the EU in total

Plant breeding successes in the EU since the year 2000 have avoided extra emissions of GHG of almost 4.0 billion tons until 2020 as figure 2.100 reveals. This is almost as large as the entire annual GHG emissions in the EU (EEA, 2020). However, this is a one-time-only effect and putting these savings into perspective is challenging:

- Such non-recurring emissions are typically annualized by dividing total emissions by 20 (years).
- The avoided "annualized" GHG emissions of plant breeding in the EU in the past two decades would consequently amount to approximately 200 million tons.

This is as much as the total annual GHG emissions in a country like the Netherlands (Eurostat, 2021c) and implies that noteworthy and long-lasting efforts to reduce GHG emissions in EU member states would be counteracted in a rather short period of time without plant breeding for arable crops.

Figure 2.100: Avoided regional CO_2 emissions until 2020 with plant breeding progress between 2000 and 2019 in the EU (in million tons)



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Germany

Similarly, plant breeding successes in Germany since the turn of the millennium have avoided an extra emission of GHG of almost 450 million tons as figure 2.101 depicts. This one-time-only effect is more than half the entire annual GHG emissions of the country (OECD, 2021). The avoided "annualized" GHG emissions of plant breeding in the past two decades would consequently amount to 22 million tons. This is as much as the total annual GHG emissions of Lithuania (OECD, 2021).

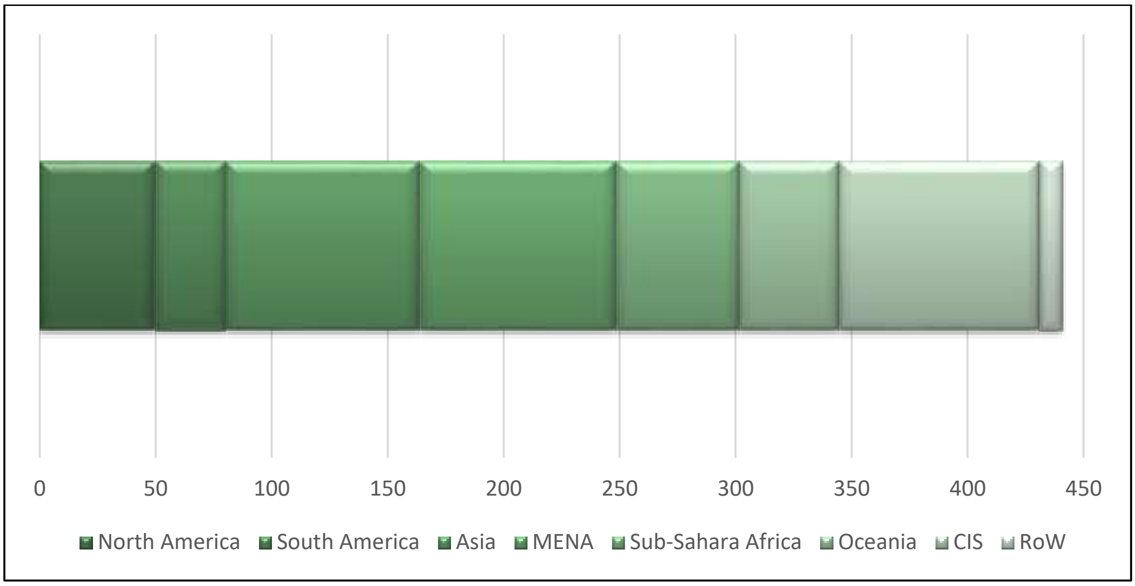
Analysis for the level of EU member states – the case of France

For France, the values are as follows: Plant breeding since 2000 has avoided an extra emission of GHG of more than 700 million tons as figure 2.102 shows. This one-time-only effect is much more than the entire country emits per year (OECD, 2021). The avoided "annualized" GHG emissions of plant breeding in France in the past two decades would consequently amount to 36 million tons. This is twice as much as the total annual GHG emissions of Estonia (OECD, 2021).

Analysis for the level of EU member states – the case of Italy

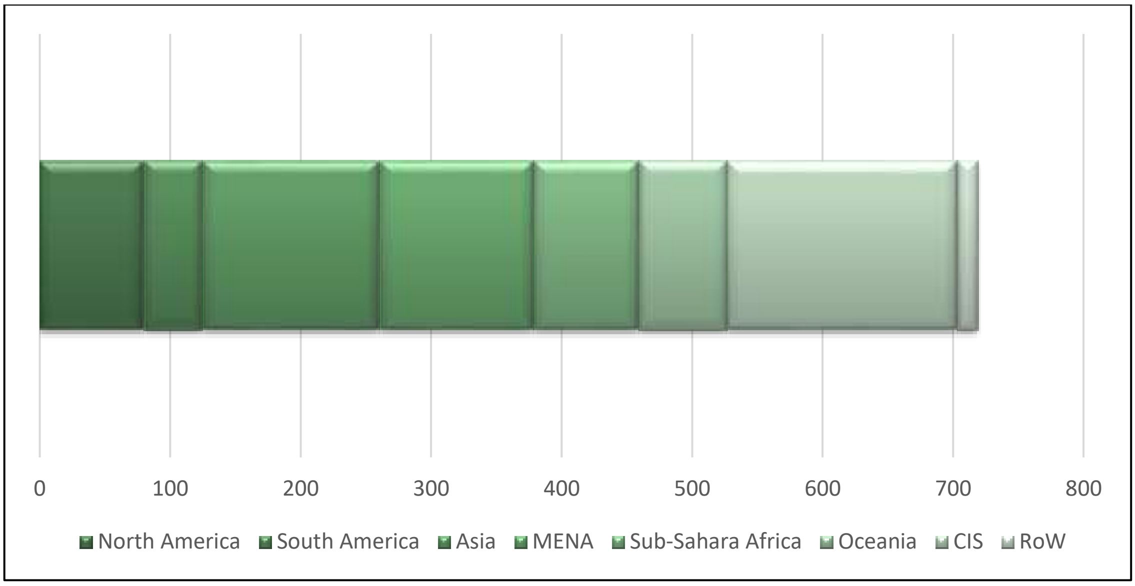
Similarly, plant breeding successes in Italy since the turn of the millennium have avoided an extra emission of GHG of almost 130 million tons as figure 2.103 depicts. This one-time-only effect is more than one third of the entire annual GHG emissions of the country (OECD, 2021). The avoided "annualized" GHG emissions of plant breeding in Italy in the past two decades would consequently amount to approximately 6 million tons. This is as much as half of the total annual GHG emissions of Latvia or Luxembourg (OECD, 2021).

Figure 2.101: Avoided regional CO_2 emissions until 2020 with plant breeding progress between 2000 and 2019 in Germany (in million tons)



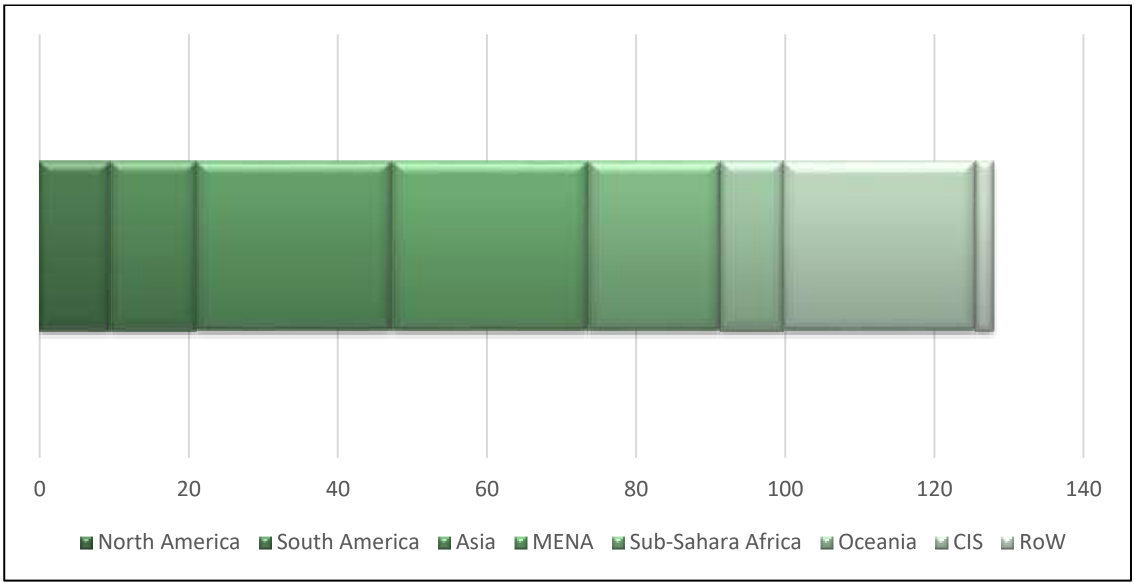
Source: Own calculations and figure.

Figure 2.102: Avoided regional CO_2 emissions until 2020 with plant breeding progress between 2000 and 2019 in France (in million tons)



Source: Own calculations and figure.

Figure 2.103: Avoided regional CO_2 emissions until 2020 with plant breeding progress between 2000 and 2019 in Italy (in million tons)



Source: Own calculations and figure.

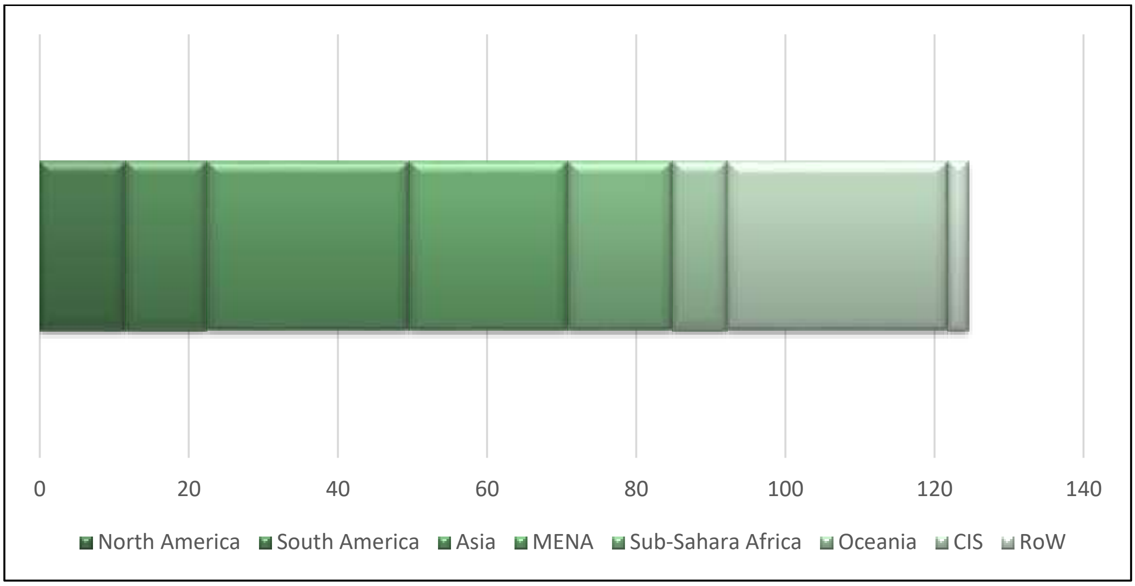
Analysis for the level of EU member states – the case of Spain

Looking at Spain and figure 2.104, the same arguments as in the case of Italy can be provided. The one-time-only effect with respect to the avoided GHG emissions is more than 120 million tons and thus more than one third of the entire annual GHG emissions of the country (OECD, 2021). Consequently, the avoided "annualized" GHG emissions of Spain would amount to approximately 6 million tons. This is as much as half of the total annual GHG emissions of Latvia or Luxembourg (OECD, 2021).

Analysis for the level of EU member states – the case of the UK

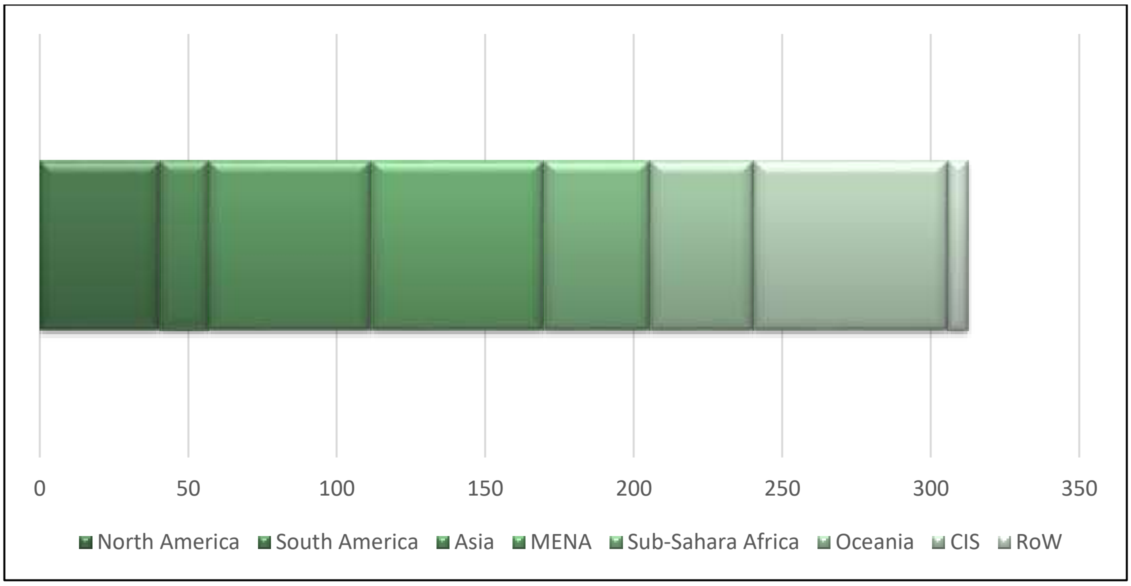
Finally, figure 2.105 visualizes the results for the UK. Accordingly, it can be stated that plant breeding since 2000 has avoided an additional emission of GHG of more than 300 million tons. This one-time-only effect is as large as two thirds of the entire annual GHG emissions of the country (OECD, 2021). The avoided "annualized" GHG emissions of plant breeding in the UK in the past two decades would consequently amount to approximately 16 million tons. This is as much as half of the total annual GHG emissions of Slovakia (OECD, 2021) and highlights once more the in fact tremendous benefits genetic crop improvements are able to offer in terms of mitigating global climate change effects.

Figure 2.104: Avoided regional CO_2 emissions until 2020 with plant breeding progress between 2000 and 2019 in Spain (in million tons)



Source: Own calculations and figure.

Figure 2.105: Avoided regional CO_2 emissions until 2020 with plant breeding progress between 2000 and 2019 in the UK (in million tons)



Source: Own calculations and figure.

Global biodiversity

Overview on the impacts by EU region

Repeating that plant breeding efforts in the EU since the year 2000 have avoided a conversion of grassland and natural habitats of approximately 22 million hectares in various regions of the world (see again figure 2.88), it is also worth quantifying the associated "biodiversity preserving" effect of genetic crop improvements. As outlined in annex E, two methods for capturing this effect are applied:

- First, the Global Environment Facility Benefits Index of Biodiversity (GEF-BIO) is used.
- Second, the National Biodiversity Index (NBI) is employed.

The results with respect to the biodiversity loss per world region of the two separate analyses for the EU and selected member states are depicted in figure 2.106.

Figure 2.106: Avoided biodiversity loss until 2020 with plant breeding progress between 2000 and 2019 in the EU and selected member states (in million points)

Region	EU	DE	FR	IT	ES	UK
GEF-BIO						
North America	100	14	23	3	3	11
South America	113	12	18	5	4	6
Asia	52	5	8	2	2	3
MENA	7	1	1	0	0	1
Sub-Sahara Africa	14	2	2	1	0	1
Oceania	83	12	18	2	2	10
CIS	452	44	89	13	15	33
RoW	16	2	3	0	1	1
NBI						
North America	98	14	22	3	3	11
South America	161	17	26	7	6	9
Asia	113	11	18	3	4	7
MENA	111	13	19	4	3	9
Sub-Sahara Africa	98	11	17	4	3	8
Oceania	121	17	27	3	3	14
CIS	447	43	88	13	15	33
RoW	25	3	4	1	1	2

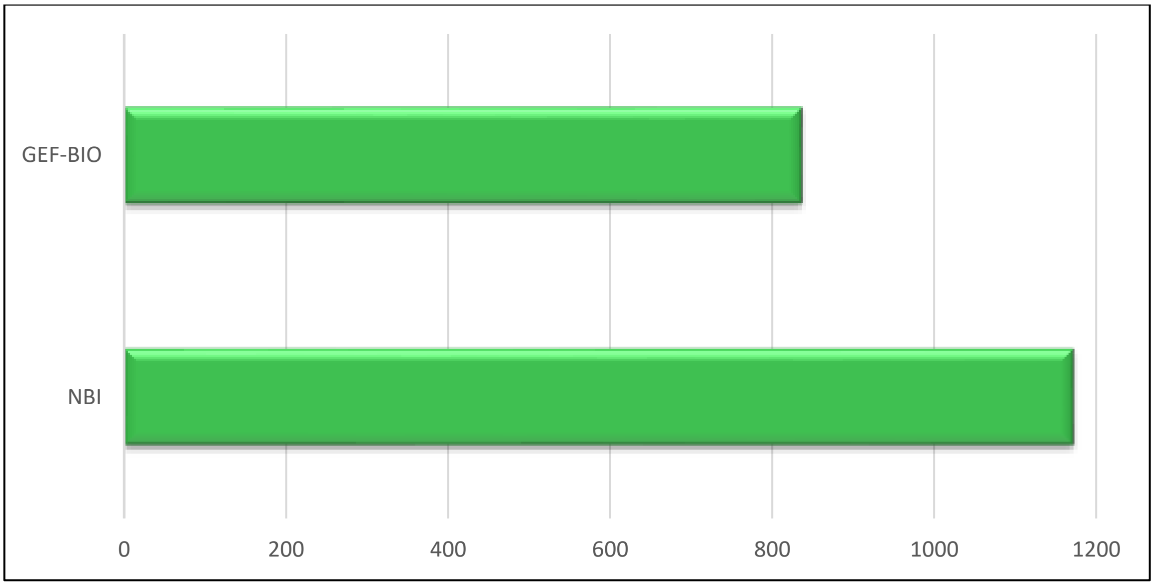
Source: Own calculations and figure.

Analysis for the level of the EU in total

Looking at figure 2.107, the following concept-specific findings with respect to avoided biodiversity losses can be highlighted for the EU in total:

- Based on the GEF-BIO, more than 830 million biodiversity points would have been lost until today by neglecting plant breeding in the EU since the turn of the millennium on top of what has already been lost in terms of global species richness. This is equivalent to the biodiversity found in 8.3 million hectares of rainforest and savannahs in Brazil, the country for which the GEF-BIO approach counts 100 points per hectare. Assuming a current cutting rate in the Brazilian Amazon Forest of 0.75 million hectares per year (Butler, 2020), this implies that plant breeding for major arable crops in the EU between the years 2000 and today has compensated for more than eleven years of deforestation in the Amazon region at current pace.
- However, the NBI suggests an even larger loss in global biodiversity. It would have declined by additional almost 1 200 million points without genetic crop improvements in the EU since the turn of the millennium. Latest available figures for Indonesia, the country for which the NBI concept counts 100 points per hectare, indicate a current annual loss of approximately 0.45 million hectares of rainforest (Wijaya et al., 2019). If plant breeders in the EU had given up their jobs two decades ago, global biodiversity would have been reduced until today by an equivalent of species richness on an additional 11.8 million hectares of Indonesian natural habitats, i.e., as much as the loss of biodiversity that can be attributed to 26 years of cutting rainforests in Indonesia at current deforestation intensity.

Figure 2.107: Avoided global biodiversity loss until 2020 with plant breeding progress between 2000 and 2019 in the EU (in million points)



Source: Own calculations and figure.

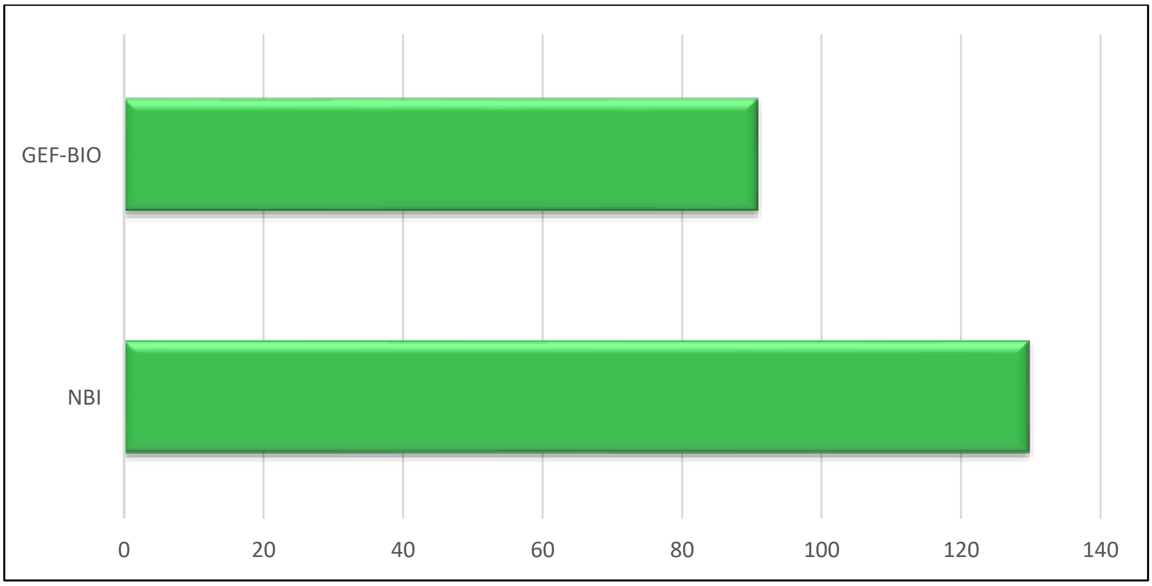
Analysis for the level of EU member states – the case of Germany

Looking at Germany and figure 2.108, the following can be stated as regards avoided biodiversity losses due to plant breeding in the country since 2000:

- Based on the GEF-BIO, more than 90 million biodiversity points would have been lost until today without breeding progress. This is equivalent to the biodiversity found on 0.9 million hectares of rainforest and savannahs in Brazil. Assuming the current cutting rate in the Brazilian Amazon Forest as provided by Butler (2020), this implies that plant breeding for major arable crops in Germany between the years 2000 and today has compensated for more than one year of losing natural habitats in the Amazon region.

- The NBI suggests a larger loss in global biodiversity until today. It would have declined by 130 million points. This is the biodiversity found on 1.3 million hectares of Indonesian rainforests. Using information on the annual loss of habitats there (see Wijaya et al., 2019), this leads to the conclusion that in the past 20 years plant breeders in Germany have compensated for global biodiversity losses similar to almost three years of deforestation in Indonesia.

Figure 2.108: Avoided global biodiversity loss until 2020 with plant breeding progress between 2000 and 2019 in Germany (in million points)



Source: Own calculations and figure.

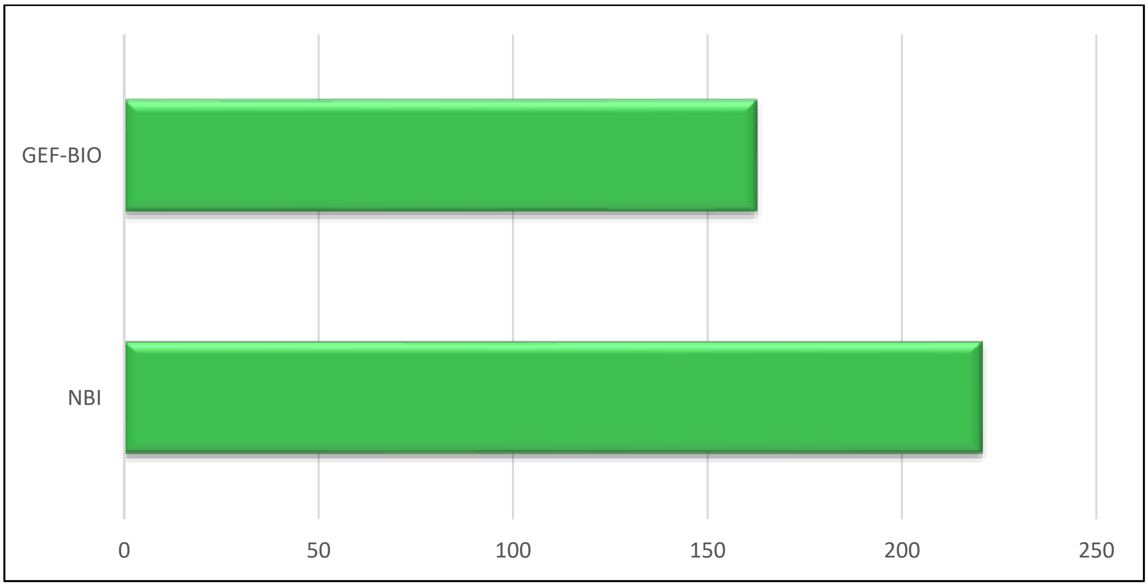
Analysis for the level of EU member states – the case of France

In accordance to figure 2.109, the following can be stated with respect to avoided biodiversity losses until 2020 due to plant breeding in France between 2000 and 2019:

- Based on the GEF-BIO, more than 160 million biodiversity points would have been lost without breeding progress. This is equivalent to the biodiversity found on 1.6 million hectares of rainforest and savannahs in Brazil. Assuming the current cutting rate in the Brazilian Amazon Forest as provided by Butler (2020), this implies that plant breeding for major arable crops in France between the years 2000 and today has compensated for more than two years of losing natural habitats in the Amazon region.

- Again, the NBI suggests an even larger loss in global biodiversity. It would have declined by 220 million points. This is the biodiversity found on 2.2 million hectares of Indonesian rainforests. Using information on the current annual loss of rainforests there (see Wijaya et al., 2019), this leads to the conclusion that in the past 20 years plant breeders in France have compensated for global biodiversity losses as large as losses of almost five years of deforestation in Indonesia.

Figure 2.109: Avoided global biodiversity loss until 2020 with plant breeding progress between 2000 and 2019 in France (in million points)



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Italy

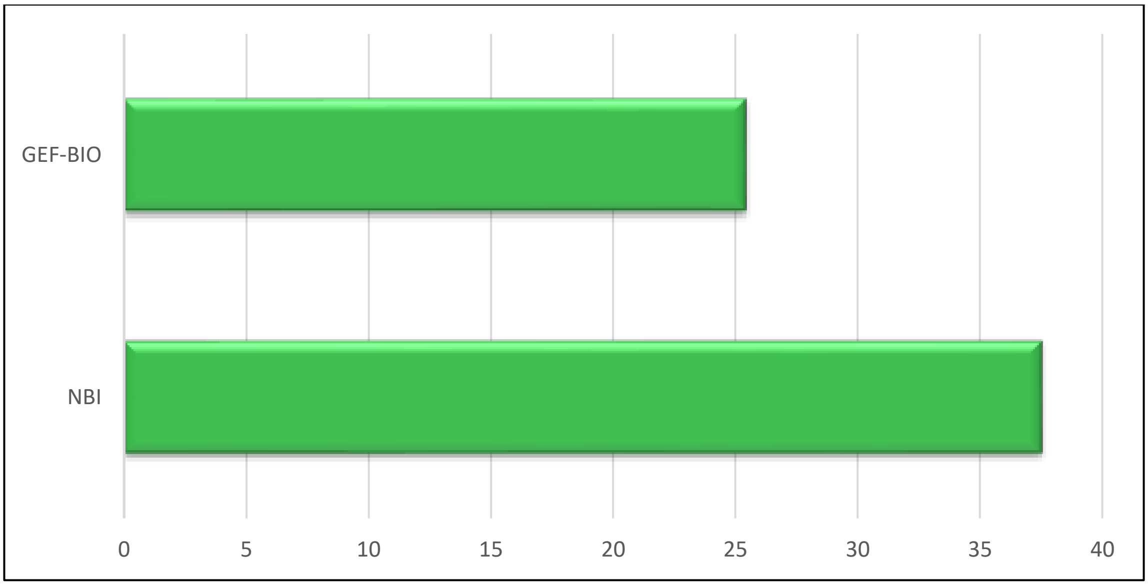
Looking at figure 2.110, the following can be stated as regards avoided biodiversity losses until today due to plant breeding in Italy since 2000:

- Based on the GEF-BIO, more than 25 million biodiversity points would have been lost without breeding progress. This is equivalent to the biodiversity found on 250 000 hectares of rainforest and savannahs in Brazil. Assuming the current cutting rate in the Brazilian Amazon

Forest as provided by Butler (2020), this implies that plant breeding for major arable crops in Italy between the years 2000 and today has compensated for four months of losing natural habitats in the Amazon region.

- The NBI suggests an even larger loss in global biodiversity. It would have declined by 38 million points. This is the biodiversity found on 380 000 hectares of Indonesian rainforests. Using information on the current annual loss of rainforests there (see Wijaya et al., 2019), this leads to the conclusion that in the past 20 years plant breeders in Italy have compensated for global biodiversity losses as large as losses of approximately nine months of deforestation in Indonesia.

Figure 2.110: Avoided global biodiversity loss until 2020 with plant breeding progress between 2000 and 2019 in Italy (in million points)



Source: Own calculations and figure.

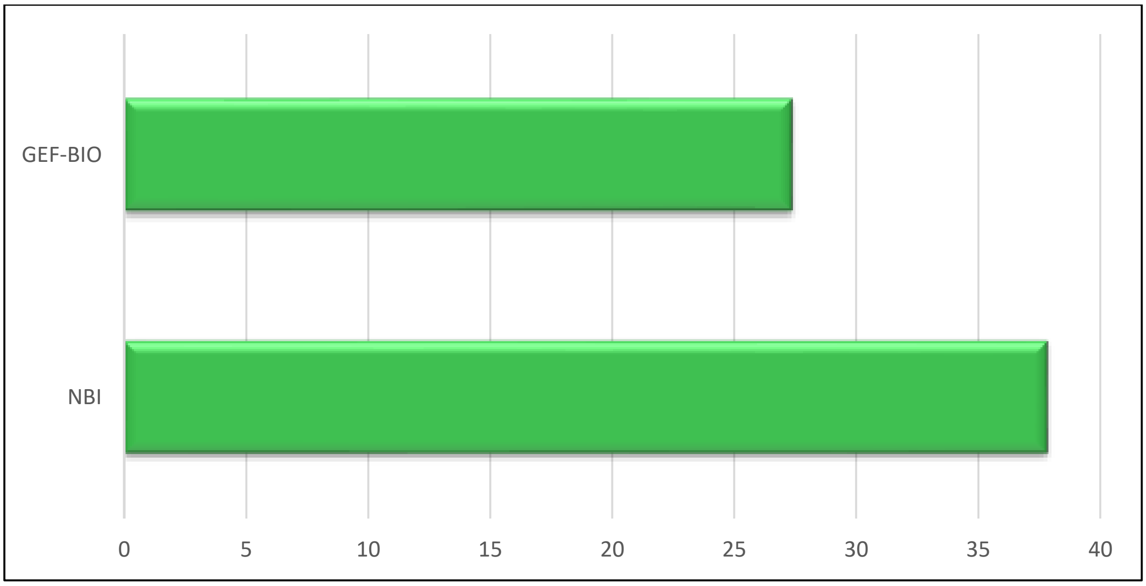
Analysis for the level of EU member states – the case of Spain

In line with figure 2.111, the following can be stated as regards avoided biodiversity losses until 2020 due to plant breeding in Spain between 2000 and 2019:

- Based on the GEF-BIO, more than 27 million biodiversity points would have been lost without breeding progress. This is equivalent to the biodiversity found on 270 000 hectares of rainforest and savannahs in Brazil. Assuming the current cutting rate in the Brazilian Amazon Forest as provided by Butler (2020), this implies that plant breeding for major arable crops in Spain between the years 2000 and today has compensated for more than four months of losing natural habitats in the Amazon region.

- The NBI suggests an even larger loss in global biodiversity. It would have declined by 38 million points. This is the biodiversity found on 380 000 hectares of Indonesian rainforests. Using information on the current annual loss of rainforests there (see Wijaya et al., 2019), this leads to the conclusion that in the past 20 years plant breeders in Spain have compensated for global biodiversity losses as large as losses of approximately nine months of deforestation in Indonesia.

Figure 2.111: Avoided global biodiversity loss until 2020 with plant breeding progress between 2000 and 2019 in Spain (in million points)



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of the UK

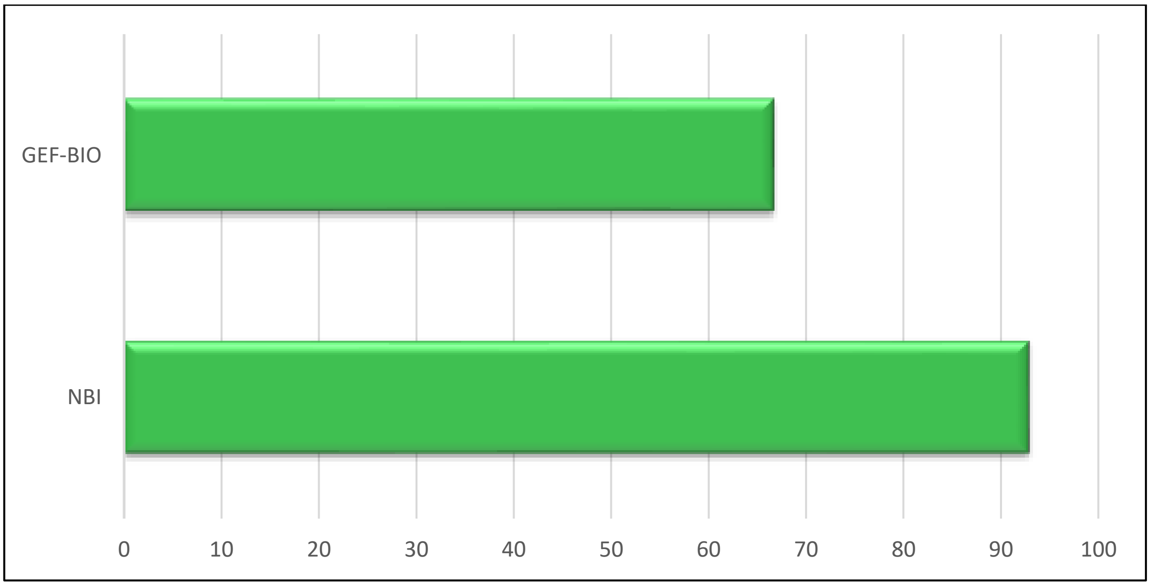
Looking finally at the UK and figure 2.112, the following can be argued as regards avoided biodiversity losses until today due to plant breeding progress in the country since the year 2000:

- Based on the GEF-BIO, almost 70 million biodiversity points would have been lost without breeding progress. This is equivalent to the biodiversity found on 0.7 million hectares of rainforest and savannahs in Brazil. Assuming the current cutting rate in the Brazilian Amazon Forest as provided by Butler (2020), this implies that plant breeding for major arable crops in the UK between the years 2000 and today has compensated for almost one year of losing natural habitats in the Amazon region.

- The NBI suggests an even larger loss in global biodiversity. It would have declined by more than 90 million points. This is the biodiversity found on more than 0.9 million hectares of Indonesian rainforests. Using information on the current annual loss of habitats there (see

Wijaya et al., 2019), this leads to the conclusion that in the past 20 years plant breeders in the UK have compensated for global biodiversity losses similar to more than two years of deforestation in Indonesia.

Figure 2.112: Avoided global biodiversity loss until 2020 with plant breeding progress between 2000 and 2019 in the UK (in million points)



Source: Own calculations and figure.

Water use

Overview on the impacts by EU region and crop

Analyzing the impact of plant breeding in the EU on global water demand requires a twofold approach. It must be discussed (1) how water use in domestic production is stimulated and (2) how virtual water trade (via trade of agricultural commodities and products thereof) is affected.

The production of agricultural commodities needs water. The more tonnages of a crop are produced the more water is needed. Given the fact, that plant breeding in the EU and its member states proves to increase domestic production of arable crops (see above), more water is used domestically to do so. However, via higher exports and/or lower imports of the EU due to plant breeding here, water use abroad is also affected. In case of higher (lower) water productivity in the EU and its member states than in other countries of the world, the subsequently avoided water use abroad must consequently be higher (lower) than the additional water used here in the EU. The net effect of both developments, (a) the additional water used in the EU due to higher domestic production and (b) water savings abroad (due to higher imports from and/or lower exports to the EU) is displayed in figure 2.113.

Figure 2.113: Global water use balance in 2020 with plant breeding progress between 2000 and 2019 in the EU and selected member states (in billion m^3)

Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	-13.765	-2.094	-4.654	-0.225	0.042	-2.310
Corn	-15.734	-0.855	-2.583	-0.787	-0.626	-0.006
Other cereals	-13.339	-2.095	-1.627	-0.394	-0.161	-1.191
OSR	-2.845	-0.678	-1.184	0.016	-0.012	-0.664
Sunflower seeds	-1.958	0.005	-0.198	-0.008	0.163	N.A.
Other oilseeds	-0.234	0.000	-0.010	-0.070	0.008	-0.006
Raw sugar	-0.514	-0.140	-0.286	-0.008	-0.012	-0.047
Potatoes	-3.052	-0.328	-0.221	-0.029	-0.053	-0.234
Pulses	-2.156	-0.363	-0.529	-0.101	-0.146	-0.473
Green maize	4.848	1.027	0.577	0.082	0.107	0.152

Source: Own calculations and figure.

It turns out that in all cases, except for green maize, which is not traded, the balance is negative. This means, plant breeding in the EU and its member states does reduce global water use because the additional water needed here in the EU is lower than the water use that can be avoided abroad since the EU is either exporting more or importing less due to higher domestic production of agricultural commodities.

Analysis for the level of the EU in total

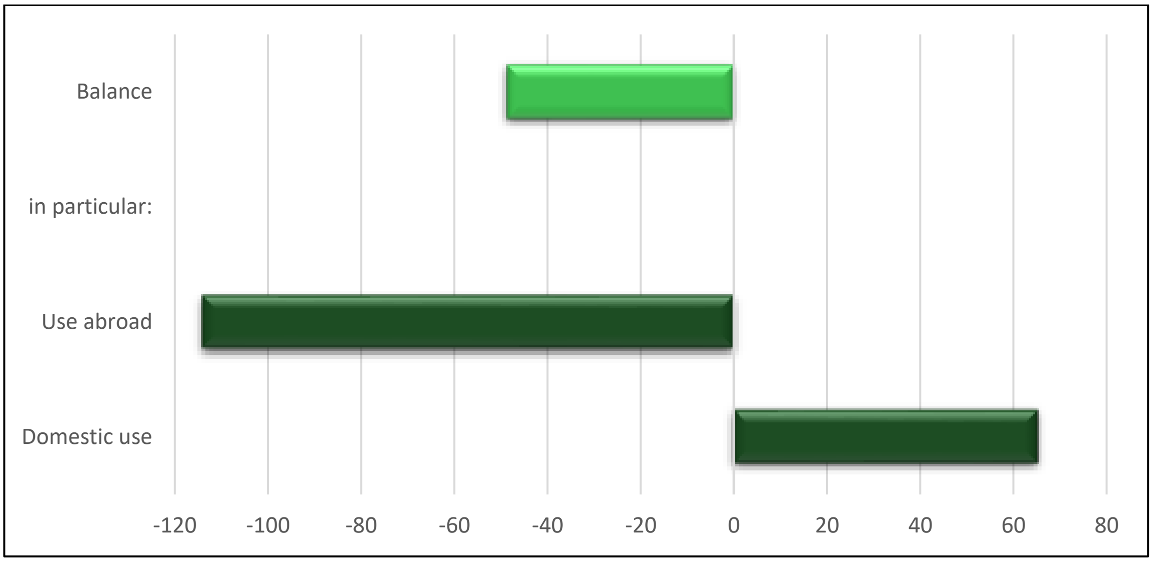
The two underlying gross effects and the resulting net effect as regards regional water use for plant breeding in the EU in total are displayed in figure 2.114. In this respect, the following three particularities can be highlighted:

- Due to plant breeding between 2000 and 2019, EU arable crop production in 2020 is higher than it would be without genetic crop improvements. The additionally embedded domestic water in this additional crop amounts to 65.4 billion m^3.

- Higher crop production in the EU, however, allows to export more and/or import less. Subsequently, production incentives in foreign countries shrunk and water is currently saved abroad due to plant breeding activities in the EU in the past two decades. In total, 114.1 billion m^3 of water are saved this way.

- On balance, a net saving of 48.7 billion m^3 occurs. This is approximately the same amount of water Lago di Garda has in terms of volume.

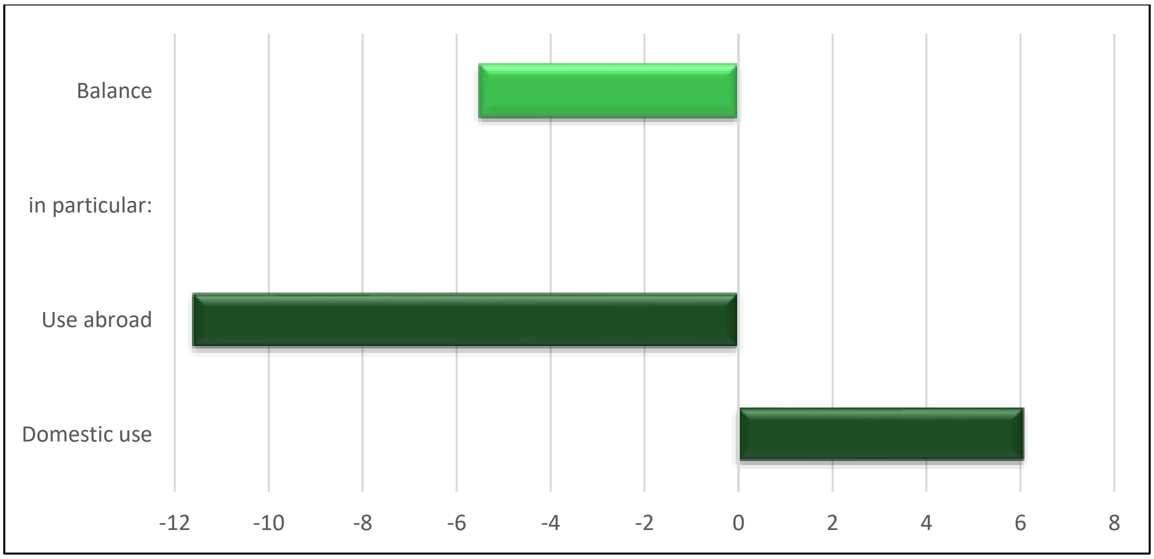
Figure 2.114: Global and regional water use balances in 2020 with plant breeding progress between 2000 and 2019 in the EU (in billion m³)



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Germany

Figure 2.115: Global and regional water use balances in 2020 with plant breeding progress between 2000 and 2019 in Germany (in billion m³)



Source: Own calculations and figure.

Looking at Germany and figure 2.115, it can be stated that due to plant breeding since the turn of the millennium:

- The additionally embedded domestic water in extra German crop production amounts to 6.1 billion m³ in 2020,
- Whereas the saved water abroad today totals 11.6 billion m³.

Hence, a net saving of 5.5 billion m³ occurs. This is approximately a tenth of the water Lake Constance has in terms of volume.

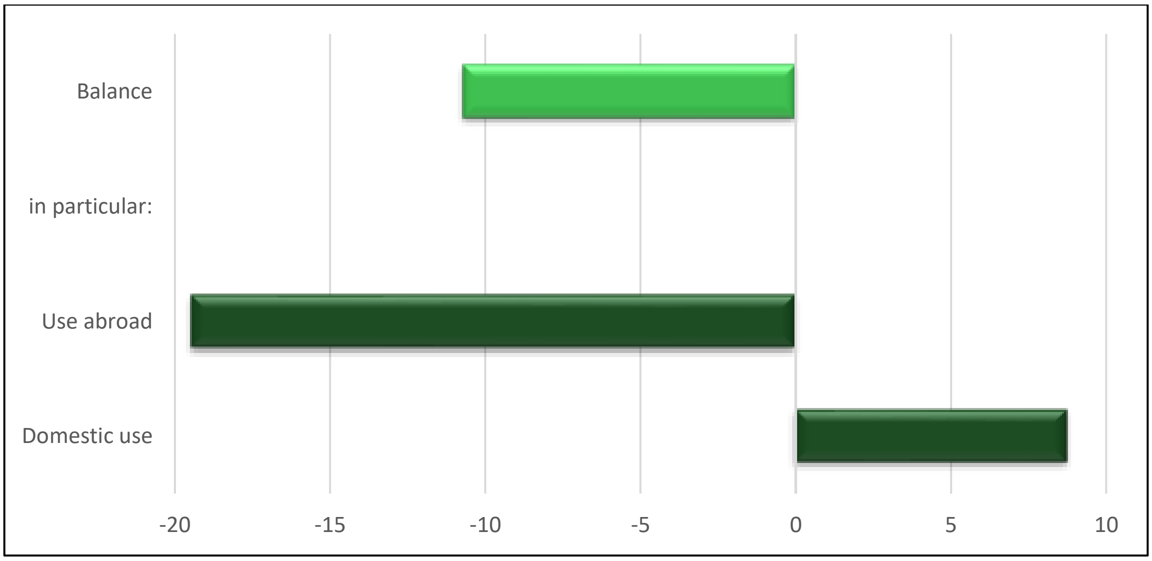
Analysis for the level of EU member states – the case of France

The picture for France is provided with figure 2.116. Accordingly, it can be highlighted that due to plant breeding between 2000 and 2019:

- The additionally embedded domestic water in extra French crop production amounts to 8.8 billion m³ in 2020,
- Whereas the saved water abroad today totals 19.7 billion m³.

Hence, a net saving of 10.7 billion m³ occurs. This is more than ten times the water Étang de Berre has in terms of volume.

Figure 2.116: Global and regional water use balances in 2020 with plant breeding progress between 2000 and 2019 in France (in billion m³)



Source: Own calculations and figure.

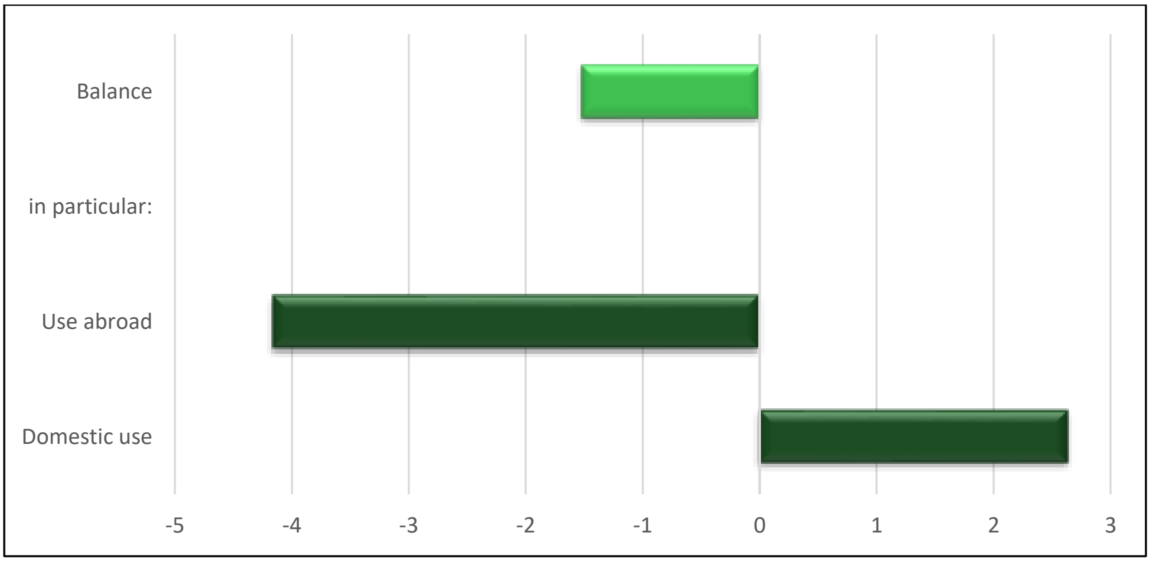
Analysis for the level of EU member states – the case of Italy

Looking at Italy and figure 2.117, it can be argued that due to plant breeding since the year 2000:

- The additionally embedded domestic water in extra Italian crop production amounts to 2.7 billion m³ in 2020,
- Whereas the saved water abroad today totals 4.2 billion m³.

Hence, a net saving of 1.5 billion m³ occurs. This is approximately three times the water Lago di Trasimeno has in terms of volume.

Figure 2.117: Global and regional water use balances in 2020 with plant breeding progress between 2000 and 2019 in Italy (in billion m³)



Source: Own calculations and figure.

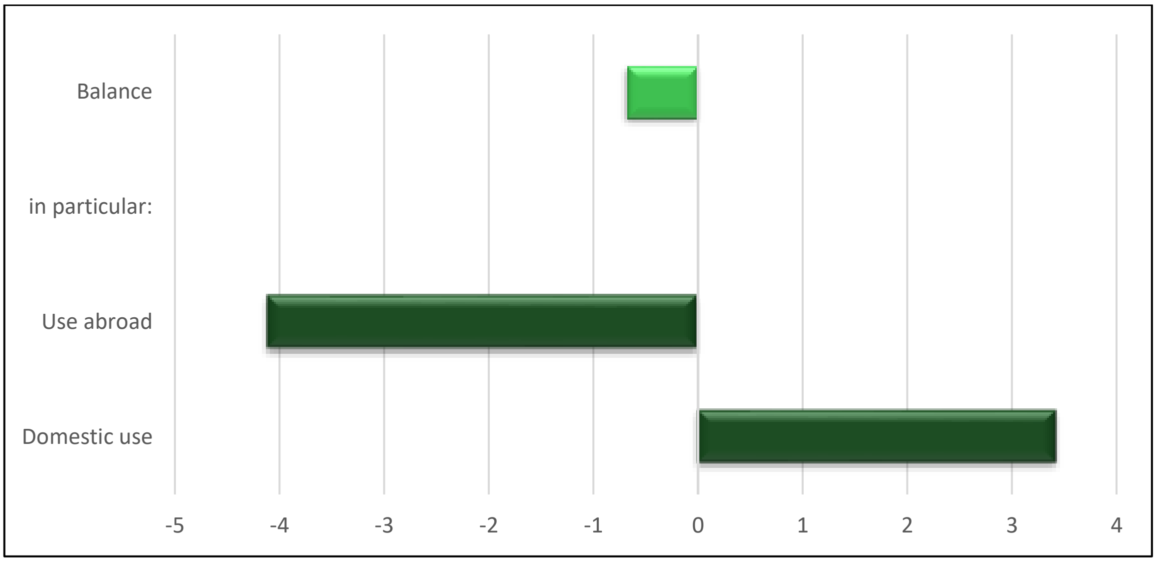
Analysis for the level of EU member states – the case of Spain

The balance for Spain can be seen in figure 2.118. Looking at the figure, it can be stated that due to plant breeding since the turn of the millennium:

- The additionally embedded domestic water in extra Spanish crop production amounts to 3.4 billion m³ in 2020,
- Whereas the saved water abroad today totals 4.1 billion m³.

Hence, a net saving of 0.7 billion m³ occurs. This is approximately the same amount of the water Mar Menor has in terms of volume.

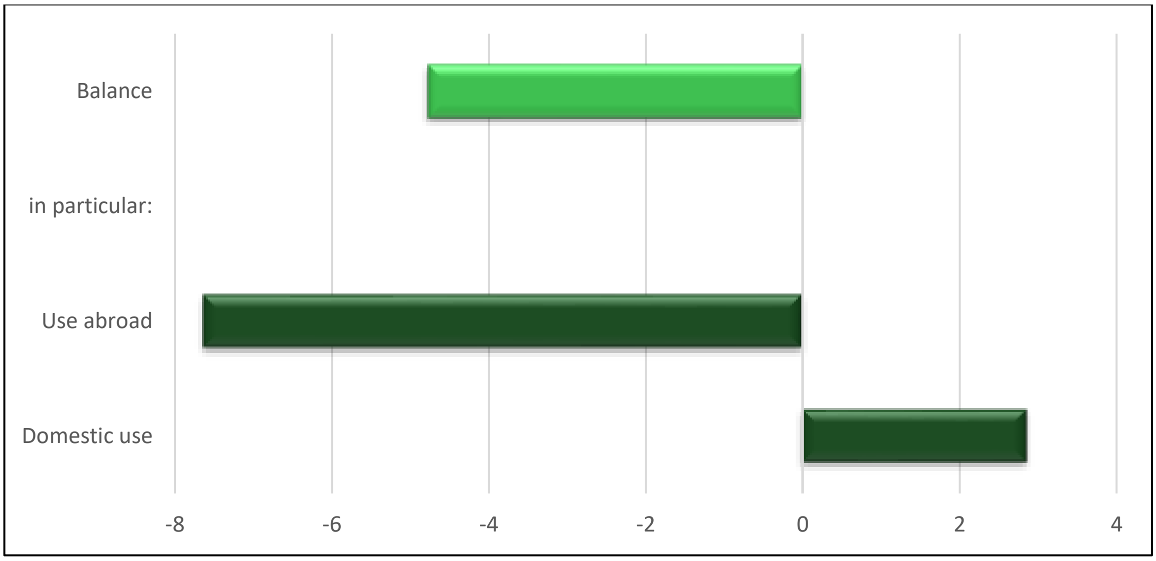
Figure 2.118: Global and regional water use balances in 2020 with plant breeding progress between 2000 and 2019 in Spain (in billion m³)



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of the UK

Figure 2.119: Global and regional water use balances in 2020 with plant breeding progress between 2000 and 2019 in the UK (in billion m³)



Source: Own calculations and figure.

Finally looking at the UK and figure 2.119, it can be stated that due to plant breeding between 2000 and 2019:

- The additionally embedded domestic water in extra crop production of the country amounts to 2.9 billion m^3 in 2020,
- Whereas the saved water abroad today totals 7.6 billion m^3.

Hence, a net saving of 4.7 billion m^3 occurs. This is more than the water Lough Neagh has in terms of volume.

Short topical summary

Plant breeding for arable crops in the EU has contributed a lot to yield progress since the turn of the millennium. Genetic crop improvements, on average, allow to generate an additional harvest of more than 1.16 percent per year for the EU in total and between 0.59 and 1.06 percent in the selected EU member states. This surely creates opportunities for the agrarian economy and the rural environment.

In fact, it becomes obvious that EU plant breeding in arable farming is an essential part of the overall economic and social performance of the agricultural sector as it creates not only additional output but thereby also:

- farm and societal income,
- jobs on farm and along the value chains, as well as
- market and trading opportunities which not only benefit the farmer but also the consumer.

It becomes obvious, too, that plant breeding for arable crops in the EU additionally offers various environmental benefits:

- Due to a more efficient land use in the EU, it helps to avoid additional use of still natural or nature-like habitats for agricultural purposes outside of the EU.
- This leads to less GHG emissions and biodiversity losses at global scale.
- A more efficient use of water being a globally scarce resource can be attributed to plant breeding progress in the EU as well.

Consequently, it can be stated at this stage of the analysis that plant breeding for major arable crops in the EU has achieved a lot since the turn of the millennium and has helped to meet various challenges EU farmers have been facing in the past two decades. The working hypothesis is that future plant breeding for major arable crops in the EU will continue to offer benefits and thereby create values for farmers in particular and the broader society – facing even more challenges in future than in the past – in general.

3 Ex-ante assessment of the importance of plant breeding in the EU for upcoming decades

This research does not only aim at discussing the various benefits European plant breeding has offered to the EU and its member states in the past decades, but also at the values this activity will potentially add in future to farmers and the society at large. Therefore, an *ex-ante* assessment will be made in addition to the *ex-post* evaluation. Consequently, the following analysis looks ahead and seeks to discuss socio-economic as well as environmental effects of plant breeding in the EU until 2030 and 2040 also considering the EU's "Farm to Fork" and "Biodiversity" strategies.

3.1 Definition of the scenarios for further analysis

The basic scenario

It is beyond the scope of this research to forecast all market developments until 2030 and 2040 with respect to the EU arable crops being in the focus of this study. Various projections already exist, which – among others – also look at future developments for EU agricultural markets (see, e.g., Alexandratos and Bruinsma, 2012; OECD and FAO, 2020; USDA, 2021b). In the following, however, EC (2020c) is used since it provides the most complete picture (facing the scope of this research) and solely argues from a European perspective. Accordingly, agricultural markets in the EU in total and its member states until 2030 are projected to develop into the following directions (since 2020):

- The EU wheat market will be confronted with a production increase of 4.3 percent and a shrinking in consumption of 1.9 percent. The market price will increase by 11.9 percent.
- The corn market in the EU will change as follows: The production will increase by 7.6 percent, and the consumption will rise by 2.6 percent. The market price will increase by 16.9 percent.
- The EU market for other cereals[35] will experience a production decrease of 6.0 percent and a consumption which declines by 5.8 percent. Here, the market price will increase by 17.5 percent.
- The EU production with respect to OSR will increase by 6.2 percent, whereas the consumption of the crop will increase by 3.6 percent. The market price for OSR will increase by 26.6 percent.
- Sunflower seeds production will increase by 8.0 percent. The consumption of this crop in the EU will also increase by 3.6 percent, and the crop-specific market price will rise by 20.0 percent.

35 EC (2020c) uses barley as a specific other cereal. The development as regards this crop will be used hereafter to properly approximate.

- Market developments as regards other oilseeds[36] are projected as follows: Production will increase by 26.1 percent and consumption by 3.6 percent; the market price will rise by 13.0 percent.
- Raw sugar production will shrink by 0.6 percent, whereas consumption will decrease by 4.9 percent. The market price will increase by 15.0 percent.
- Projections for potatoes as well as pulses are not given in EC (2020c). Here an average development is assumed to properly include both crops into the following analysis. The following applies: Production increases by 5.2 percent and consumption will decrease by 0.3 percent[37]. The price for both crops increases by 15.1 percent.
- Green maize production and consumption is forecasted to decrease by 3.4 percent[38].

The projections of EC (2020c) can be summarized as figure 3.1 depicts. Since EU (2020c) does not distinguish between the EU in total and its individual member states, the visualized changes until 2030 apply for all regions being in the focus of this study.

Figure 3.1: Basic assumption for supply and demand as well as price changes on EU arable markets in 2030 compared to 2020 (in percent)

Region	Change in supply	Change in demand	Change in prices
Wheat	4.3	-1.9	11.9
Corn	7.6	2.6	16.9
Other cereals	-6.0	-5.8	17.5
OSR	6.2	3.6	26.6
Sunflower seeds	8.0	3.6	20.0
Other oilseeds	26.1	3.6	13.0
Raw sugar	-0.6	-4.9	15.0
Potatoes	5.2	-0.3	15.1
Pulses	5.2	-0.3	15.1
Green maize	3.4	3.4	0.0

Source: Own figure and calculations based on EC (2020c).

36 EC (2020c) uses soya as a specific other oilseed. The development as regards this crop will be used hereafter to properly approximate.

37 Especially in the case of pulses, this demand development might not properly reflect potential developments with respect to a more plant-based nutrition. However, for the following analysis, this is insofar not important as it will only influence the outcome with respect to the trade impact.

38 A price change is not provided with EC (2020c). The assumption is that the price remains unchanged.

The projections of EC (2020c) suffer from at least two shortcomings that must be considered in this research:

- First, the numbers just listed refer to the projected developments until 2030. Data for 2040 is not available. To meaningfully include this larger time horizon into the chosen approach, a continuation of the various trends as projected by EC (2020c) is assumed hereafter. This means, all changes displayed in figure 3.1 double in value as regards 2040 compared to 2020.

- Second, the projections do not include potential outcomes of an implementation of the "Farm to Fork" and the "Biodiversity" strategies of the EU.

Inclusion of the "Farm to Fork" and "Biodiversity" strategies' scenario

In fact, the two strategies (see again EC, 2020a; b) aim at considerable changes along the various agricultural and food value chains. However, whether substantial adjustments of the two strategies are likely to happen or not remains to be observed. Given the various yet unclear policy decisions to be made and the vague framework conditions for the two strategies entering into force, any early approach to quantify the consequences of the two strategies is a challenge. In fact, impact assessments of the two strategies are rare. Currently, there is only one assessment available made by the USDA (Beckman et al., 2020), which obviously suffers from various questionable assumptions and methodological shortcomings (Zimmer, 2020).

For the purpose of this study, the following four important aspects of the two strategies are included in the calculations of the potential partial outcome[39] of implementing these strategies:

1. An inclusion of non-productive land – 10 percent of all agricultural land by 2030

2. An increase of the area under organic farming – 25 percent of all agricultural land by 2030

3. A reduction of the use of chemical PPP – 50 percent reduction by 2030 vs. the status quo and

4. A reduction of nitrogen fertilizers – 20 percent reduction by 2030 vs. the status quo

In the following, the projected partial impacts of each of the four strategies' aspects are derived by transparently pointing at the given baseline data and the various assumptions to be made[40].

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39 The following concentrates on potential adjustments in EU agricultural production only since plant breeding in the EU – the driver of all impact analyses included in this research – targets agricultural raw production. Potential developments due to the two strategies as regards the consumption of agricultural products are still very unclear since the strategies' objectives aiming at a decrease of this demand (for instance, as regards change in eating habits and less food waste) compete with goals fostering this demand (for instance, with respect to further developing a bioeconomy) and are not included hereafter. This has to be kept in mind while discussing the following assumptions and findings.

40 Nevertheless, all the following is – in part highly – speculative and describes only one of many possible future outcomes of implementing the two strategies. This should especially be kept in mind when discussing and interpreting the subsequent results in the following.

1. Inclusion of 10 percent non-productive land

   The assumption is that all farmers in the EU must set aside non-productive land amounting to 10 percent of all agricultural land. The setting-aside similarly affects arable land and grassland. The subsequent assumption is that nothing can be harvested from that land as it will be "zero" productive – by definition. The projected partial impact with respect to the arable crops being in the focus of this study, thus, is a reduction of 10.0 percent in overall arable production of the EU in total and all the selected member states.

2. Increase of the area under organic farming to 25 percent

   Currently 8.5 percent of all agricultural land in the EU is managed organically (Eurostat, 2021e). This means that 91.5 percent of the land are still used by conventional farmers. Increasing the share of organic farming from 8.5 to 25.0 percent, or in other words: tripling organic farming in the EU, would lower average arable yields and, hence, overall arable production in the EU. If all arable crops show a similar relative change (a tripling) in specific land allocation towards organic farming, the average arable production decrease for the EU in total will amount to 4.4 percent[41]. The corresponding yield decreases in the selected EU member states are 8.5 percent for Germany, 4.5 percent for France, 2.9 percent for Italy, 4.0 percent for Spain, and 8.9 percent for the UK. They can further be broken down by crops[42].

   Assuming that not only conventional but also organic farmers must set-aside 10 percent of land towards non-productive use, the first two effects can be combined, and the following average projected partial production impacts would occur: 14.0 percent for the EU in total, 17.6 percent for Germany, 14.1 percent for France, 12.6 percent for Italy, 13.6 percent for Spain, and 18.0 percent for the UK.

3. 50 percent reduction of chemical PPP

   The two strategies aim at a 50 percent reduction of chemical PPP, which are defined hereafter as PPP used in conventional farming. Applying this assumption, a considerable decrease of chemical PPP use already comes from the setting-aside for non-productive land and an accelerated switch of arable land towards organic farming as the additional areas under organic and non-productive farming are defined as not receiving chemical PPP. Following the argumentation above, this already implies an arable area-based reduction of chemical PPP use of 22 percent for the EU in total, as well as of 24 percent in Germany, 22 percent in France, 19 percent in Italy, 23 percent in Spain, and 30 percent in the UK.

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41 According to Noleppa et al. (2013), the average yield in organic arable farming of the EU is 31 percent lower than in conventional farming; and following EC (2019b), 7.0 percent of all arable land in the EU is already used organically.

42 Again, information provided by Noleppa et al. (2013) and EC (2019b) as well as Noleppa (2016) were used to calculate the crop-specific yield effects per region.

It is now not an easy task to allocate a yield and subsequent production impact to the necessary further reduction of chemical PPP use for the EU in total (amounting to 28 percent), as well as for Germany (26 percent), France (28 percent), Italy (31 percent), Spain (27 percent) and the UK (20 percent) since it depends on the plant protection alternatives conventional farmers have available and how these alternative management options will be regulated in future. For reasons of simplicity, it is therefore assumed in the following that full (zero) application of chemical PPP in conventional farming of the EU in total yields on average 100 (100-31=69)[43] percent of arable harvest. Then, a 1.0 percent reduction of chemical PPP linearly results in a yield decrease of 0.31 percent in the EU.

Conventional farmers, however, will have to contribute the above-mentioned further reduction of chemical PPP use while having less arable land available due to setting-aside land for non-productive use and the switch of some land towards organic farming. This means, on the remaining conventionally managed arable land an average chemical PPP use reduction higher than the above displayed percentages must be achieved[44]. Accordingly, the following approximate average partial yield losses on remaining conventionally managed arable land can be derived with respect to the meeting of the 50 percent reduction target for overall chemical PPP use[45]: EU in total: 11 percent, Germany: 17 percent, France: 12 percent, Italy: 11 percent, Spain: 10 percent, and the UK: 10 percent.

4. 20 percent reduction of nitrogen fertilizers

Both, conventional and organic farming use nitrogen fertilizers. Therefore, it is assumed that both management options must reduce the use of the specific input. However, 10 percent of the reduction already comes from the introduction of non-productive land (assuming that no nitrogen will be applied there). Since the then still necessary 10 percent reduction have to be achieved by only using 90 percent of all land excluding the non-productively used land, the reduction of the input per hectare is 11 percent. Zimmer (2020) argues that a 20 percent nitrogen fertilizer reduction should be associated with a, at least, 5.0 percent yield reduction. Subsequently, an additional production decrease of 2.75 percent applies to organic as well as conventional harvests hereafter to incorporate this potential partial effect into further analysis.

The above described four potential partial effects can now be combined and lead to the following potential reductions of arable production displayed in figure 3.2 being the impact until 2030 defined hereafter, ceteris paribus, from the full implementation of the "Farm to Fork" and "Biodiversity"

43 See, again, Noleppa et al. (2013).

44 For the EU in total, it is almost 36 percent, and the corresponding average chemical PPP reduction targets for farmers on remaining conventionally managed arable land in the selected EU member states are as follows: Germany – slightly more than 34 percent, France – around 36 percent, Italy – more than 38 percent, Spain – approximately 35 percent, and the UK – almost 29 percent.

45 Again, information on yield differences between organic and conventional farming provided by Noleppa et al. (2013) and Noleppa (2016) were used to calculate the yield effects.

strategies of the EU[46]. With slightly above 20 percent for the EU in total, the own approximated impact of the two strategies is much lower than the corresponding impact calculated in the much-criticized analysis of Beckman et al. (2020).

Figure 3.2: Assumed production cuts in 2030 of full implementation of the "Farm to Fork" and "Biodiversity" strategies in the EU and selected member states (in percent)

Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	26	32	29	23	22	31
Corn	22	30	22	19	19	23
Other cereals	23	31	22	22	21	23
OSR	24	28	25	19	19	26
Sunflower seeds	22	28	22	19	19	23
Other oilseeds	22	28	22	19	19	23
Raw sugar	21	19	25	27	27	26
Potatoes	23	29	24	22	22	26
Pulses	20	30	18	24	24	19
Green maize	23	30	24	22	22	26

Source: Own calculations and figure.

These assumed region-specific and crop specific percentage losses and the assumed scenario changes as displayed in figure 3.1 for 2030 as well as their double values for 2040 will now be used, ceteris paribus, to showcase and compare the various socio-economic and environmental benefits in 2030 of plant breeding progress at current pace between 2020 and 2029 as well as in 2040 of plant breeding progress at current pace between 2020 and 2039, respectively.

3.2 Particular importance of plant breeding for meeting the "Farm to Fork" and "Biodiversity" strategies scenario until 2030

Before these partial impacts of future genetic crop improvements in the EU will be highlighted in more detail, plant breeding progresses will be set into perspective. The two strategies until 2030, if fully implemented then as described above, will obviously add to considerably decrease arable production in the EU. Production losses in the EU, however, tend to create various disadvantages – as chapter 2 of this report has made clear using the case of missing plant breeding progress post 2000 until today. Against this background, it makes sense to compare the relative production losses that can be attributed to the upcoming full implementation of the two strategies by 2030 (see, again,

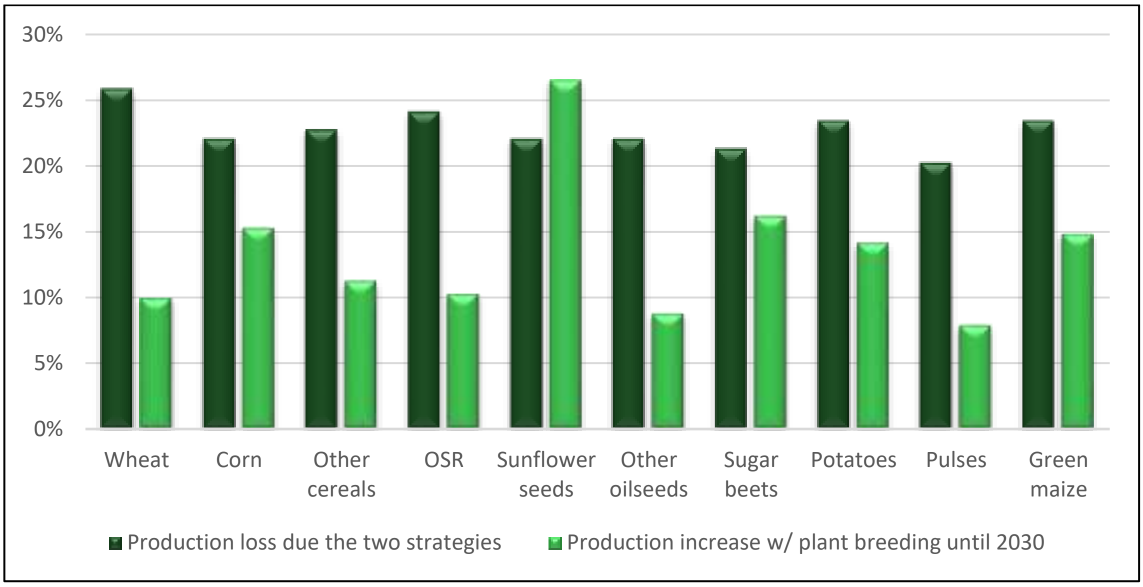
46 Note that also the full implementation of the two strategies until 2030 is currently (highly) speculative.

figure 3.2), on the one hand, with the production gains that can potentially be offered by plant breeding activities at the end of the current decade, i.e., by 2030, on the other hand. A respective comparison with EU plant breeding until 2040 can be obtained from annex F.

Analysis for the level of the EU in total

Using the annualized plant breeding yield growth rates referring to 2000-2020 (see sub-chapter 2.1) also as a proxy to describe the expectable plant breeding-induced yield growth until 2030, figure 3.3 visualizes the comparison of production losses in 2030 due to the two strategies with the expectable positive production impact in that year offered by plant breeding between 2020 and 2029 in the EU in total – all other factors being constant. As can be seen, the potential plant breeding-induced production surplus in 2030 will be lower than the production loss that can be attributed in that year to the two strategies in nine of the ten cases. Only with respect to sunflower seeds, the gain related to plant breeding will be larger than the loss due to the strategies. Weighted by hectare, the production loss would amount to 23.7 percent. The effect due to plant breeding is just 12.3 percent, i.e., slightly more than 50 percent of the loss due to a full implementation of the two strategies.

Figure 3.3: Production effects in 2030 of the "Farm to Fork" and "Biodiversity" strategies vs. with plant breeding progress between 2020 and 2029 in the EU

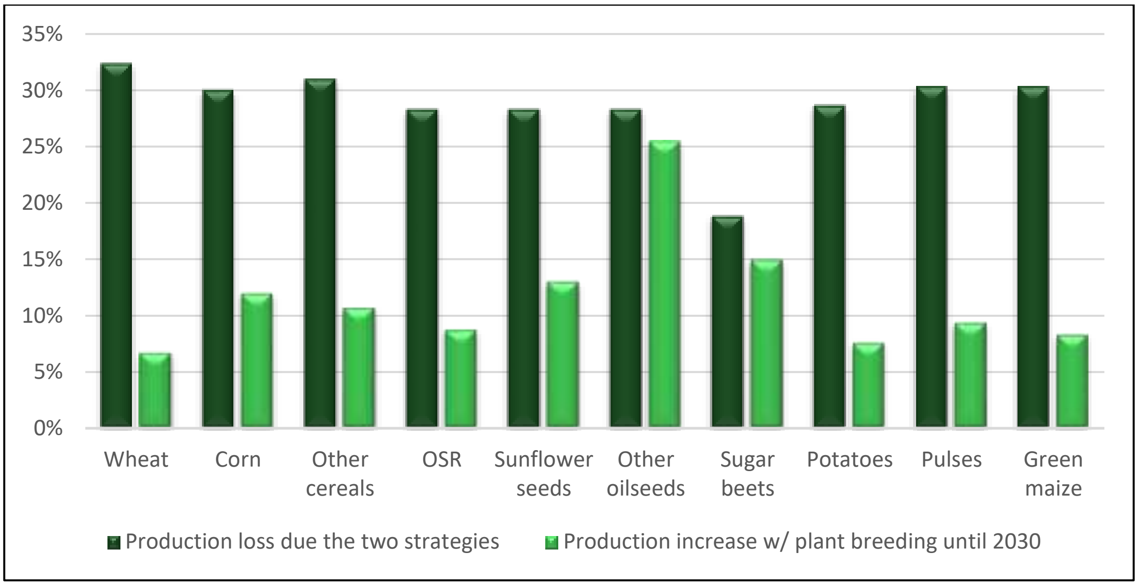


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Germany

Similarly, figure 3.4 visualizes the comparison of potential production losses in 2030 due to the strategies with the expectable positive production impact in that year offered by plant breeding between 2020 and 2029 in Germany. It becomes obvious that the potential plant breeding-induced production surplus will be considerably lower than the production loss that can be attributed to the two strategies in all ten cases of (groups of) arable crops. Weighted by hectare, the production loss would amount to 30.2 percent, the effect due to plant breeding is just 9.3 percent, i.e., less than one third of the loss due to a full implementation of the two strategies.

Figure 3.4: Production effects in 2030 of the "Farm to Fork" and "Biodiversity" strategies vs. with plant breeding progress between 2020 and 2029 in Germany



Source: Own calculations and figure.

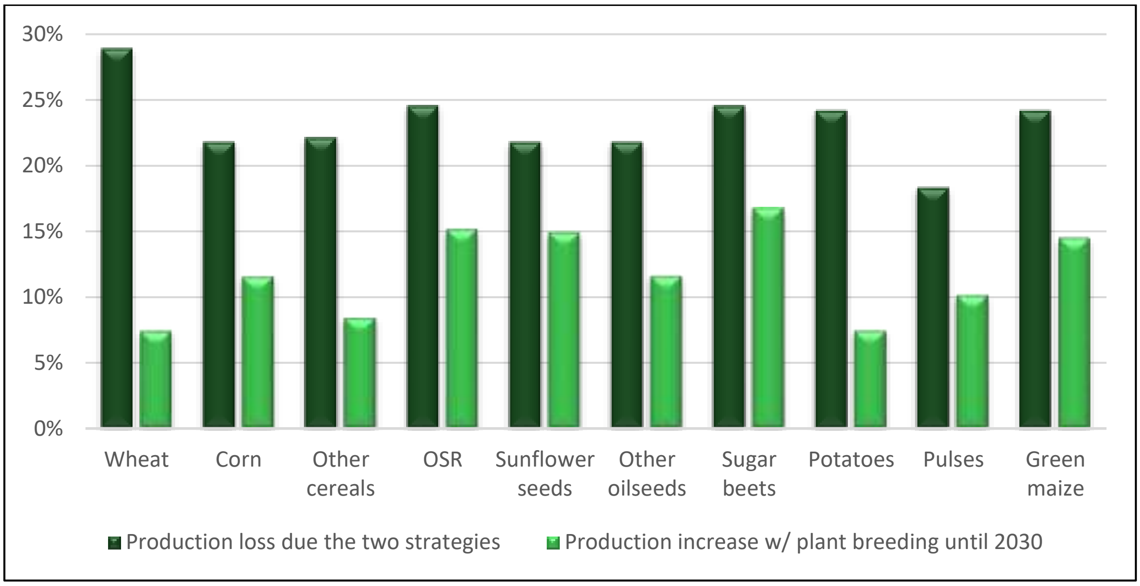
Analysis for the level of EU member states – the case of France

Looking at figure 3.5, the comparison of potential production losses in 2030 due to the strategies with the expectable positive production impact in that year offered by plant breeding between 2020 and 2029 in France also shows what has been stated for Germany: The potential plant breeding-induced production surplus will always be remarkably lower than the production loss that can be attributed to the two strategies in all ten cases of (groups of) arable crops. Weighted by hectare, the production loss until 2030 would amount to 25.1 percent, while the effect due to plant breeding is just 10.3 percent, i.e., less than half of the loss due to a full implementation of the two strategies.

Analysis for the level of EU member states – the case of Italy

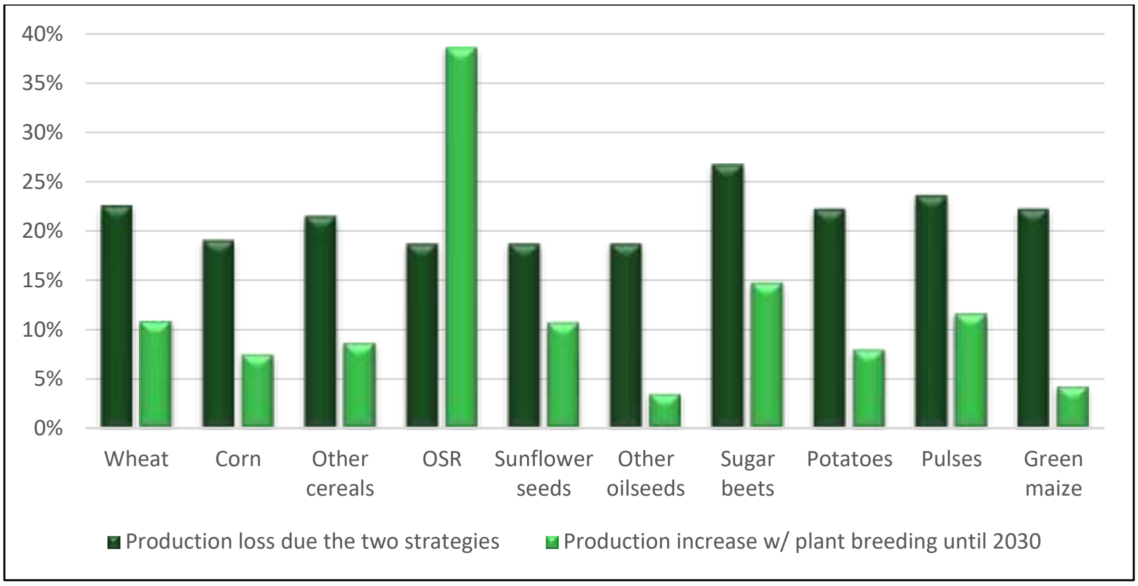
Figure 3.6 visualizes the comparison of potential production losses in 2030 due to the strategies with the expectable production impact in that year due to plant breeding until 2030 in Italy. The plant breeding-induced production surplus will be lower than the production loss that can be attributed to the two strategies in nine of the ten cases. Only with respect to OSR, the gain related to plant breeding is larger than the loss due to the strategies. Weighted by hectare, the production loss would amount to 21.5 percent, and the effect due to plant breeding is just 8.9 percent, i.e., less than half of the loss due to a full implementation of the two strategies.

Figure 3.5: Production effects in 2030 of the "Farm to Fork" and "Biodiversity" strategies vs. with plant breeding progress between 2020 and 2029 in France



Source: Own calculations and figure.

Figure 3.6: Production effects in 2030 of the "Farm to Fork" and "Biodiversity" strategies vs. with plant breeding progress between 2020 and 2029 in Italy

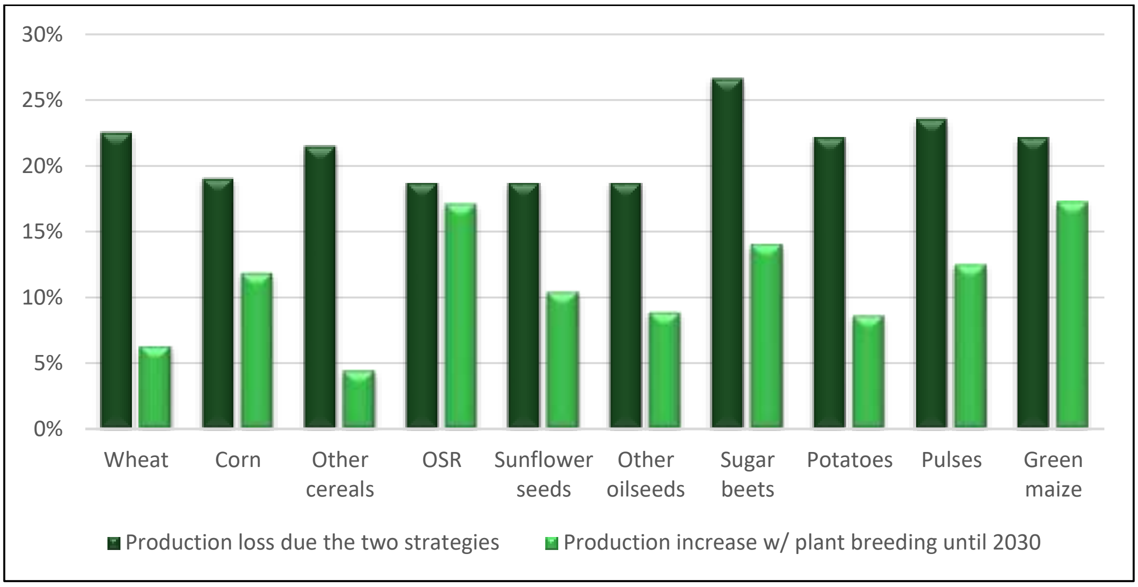


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Spain

Similarly, figure 3.7 visualizes the comparison of potential production losses in 2030 due to the strategies with the expectable positive production impact in that year offered by plant breeding between 2020 and 2029 in Spain. It becomes obvious that the potential plant breeding-induced production surplus will partly be considerably lower than the production loss that can be attributed to the two strategies in all ten cases of (groups of) arable crops. Weighted by hectare, the production loss would amount to 21.5 percent, the effect due to plant breeding is just 6.7 percent, i.e., less than a third of the loss, which would occur if the "Farm to Fork" and "Biodiversity" strategies were fully implemented as defined above.

Figure 3.7: Production effects in 2030 of the "Farm to Fork" and "Biodiversity" strategies vs. with plant breeding progress between 2020 and 2029 in Spain

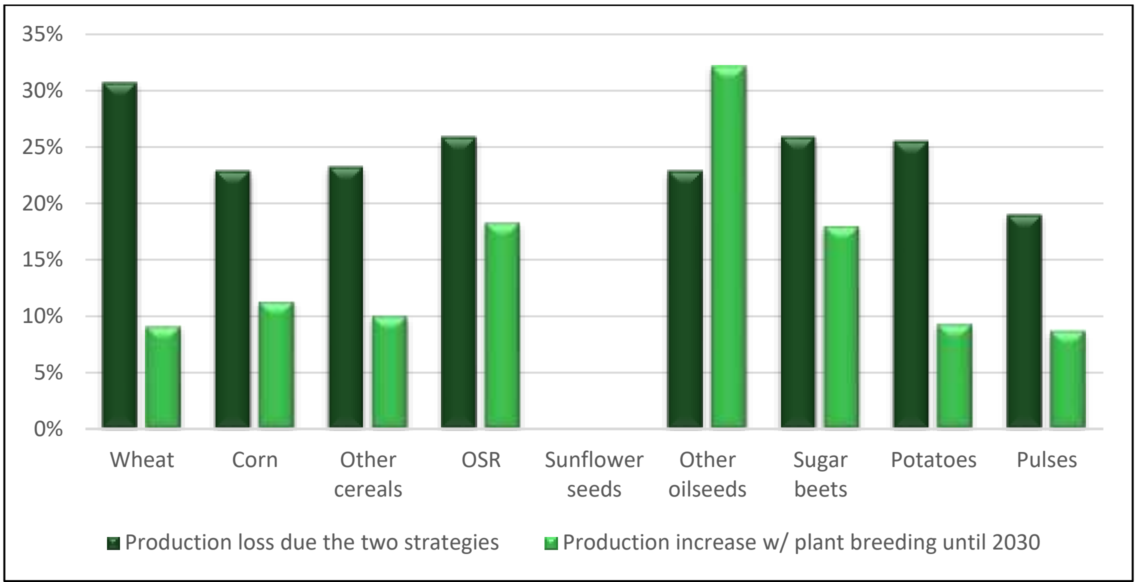


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of the UK

Finally, figure 3.8 visualizes the afore-mentioned comparison for the UK. The potential plant breeding-induced production surplus in 2030 will be considerably lower than the production loss that can be attributed to a full implementation of the two strategies until 2030 in all ten cases of (groups of) arable crops, except other oilseeds. Weighted by hectare, the production loss would amount to 26.6 percent, whereas the effect due to plant breeding is 11.2 percent, i.e., well below half the loss that can be attributed to a full implementation of the "Farm to Fork" and "Biodiversity" strategies if applicable in the UK.

Figure 3.8: Production effects in 2030 of the "Farm to Fork" and "Biodiversity" strategies vs. with plant breeding progress between 2020 and 2029 in the UK



Source: Own calculations and figure.

Topical summary

The figures and discussion above make it obvious: Fulfilling the various objectives of the "Farm to Fork" and "Biodiversity" strategies of the EU within the defined timeframe marks a considerable challenge for farmers in the EU and its member states as agricultural production will tend to considerably decrease.

Plant breeders are certainly able to help compensate the negative effects that may arise from a production decline due to the full implementation of "Farm to Fork" and "Biodiversity" strategies. However, plant breeding-induced innovations at current pace might obviously not be enough to fully counteract the potential impact arising from an implementation of the two strategies until 2030 and in various crop-country cases also not until 2040 (see annex F).

Much more investments into plant breeding are needed to fully compensate and have to be induced. In fact, higher yield improvements as in the past two decades are needed to make up for the negative production and attributable socio-economic as well as environmental effects of a full implementation of the two strategies by 2030, thereby helping assure meeting the strategies' objectives. To better highlight this need for more plant breeding progress further analysis is necessary and will be conducted in the following.

3.3 Future socio-economic consequences

In the following, the various benefits of plant breeding activities, which have been analyzed for the past, will be discussed for the time horizons until 2030 and 2040. Thereby, the market environment as defined in sub-chapter 3.1 and the strategies' enforcement as discussed in sub-chapter 3.2 are considered. Foremost, the outcome for the year 2040 is discussed in greater detail. This perspective is chosen to better compare the future benefits of plant breeding progress with the past values as both scenarios cover a time horizon of 20 years. However, the time horizon until 2030 is not neglected. It will be an essential part of the discussion for the level of the EU in total and additionally be covered via various annexes to allow for a proper discussion at the level of EU member states.

Definition of shift factors to derive plant breeding impacts

Overview on defined shift factors by EU region and crop

Analyzing the various values plant breeding in the EU and its member states will have in the future requires to specify a scenario for arable farming with yield increases induced by plant breeding efforts in the upcoming years. Again, a shift factor to shock the models (see annex D) will be defined. This shift factor simulates a relative yield change expressed in terms of percent by accumulating the average annual plant breeding-induced yield growth for the entire time horizon starting in 2020 and lasting over (10) 20 years. Here, the basic assumption is that the annualized plant breeding-induced yield growth of the past as depicted in figure 2.23 can be maintained. Consequently, figure 3.9 displays the simulated potential yield gain with plant breeding in the EU and selected member states for the next two decades, this means until 2040, and for the chosen major arable crops. Annex G provides similar information for the time horizon until 2030.

Figure 3.9: Simulated potential yield gain for major arable crops in 2040 with plant breeding progress between 2020 and 2039 in the EU and selected member states (in percent)

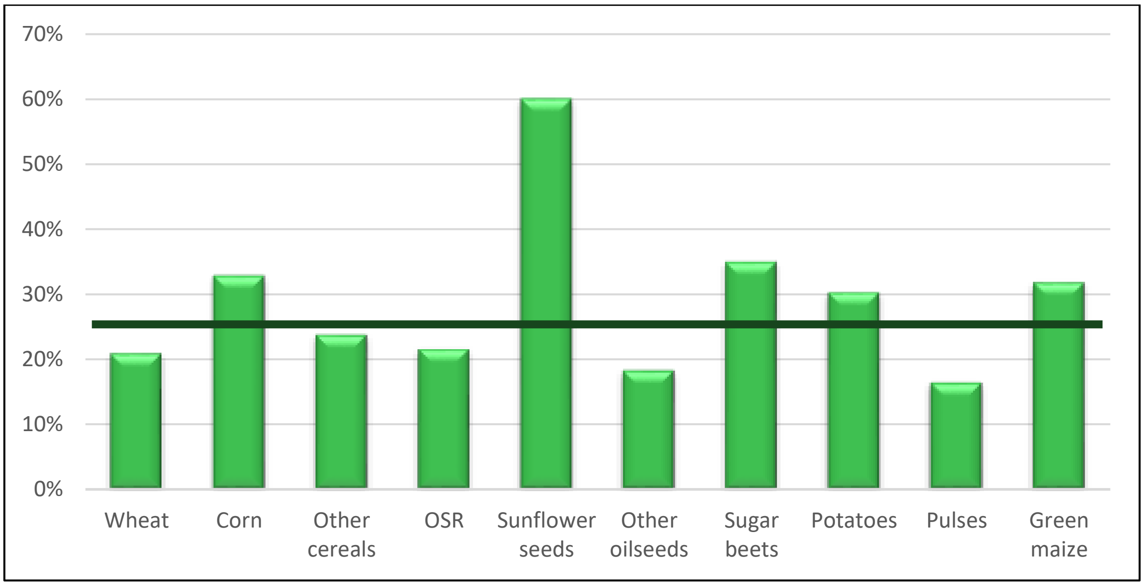
Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	20.8	13.3	15.0	22.9	12.5	18.8
Corn	32.8	24.9	23.9	14.5	24.6	23.2
Other cereals	23.7	22.3	17.1	17.6	8.2	20.7
OSR	21.5	17.9	33.2	97.0	38.1	40.9
Sunflower seeds	60.1	26.0	30.6	20.7	20.0	N.A.
Other oilseeds	18.2	60.0	24.8	6.3	18.4	78.5
Sugar beets	35.0	32.0	36.5	31.5	29.7	39.3
Potatoes	30.2	14.8	14.6	15.7	17.2	18.8
Pulses	16.3	19.7	21.5	25.0	27.1	18.1
Green maize	31.8	16.4	31.1	7.3	37.9	35.0

Source: Own calculations and figure.

Analysis for the level of the EU in total

A remarkable increase in arable yield until 2040 should be envisaged across all crops with future genetic crop improvements as figure 3.10 indicates. Weighted by future acreage use[47], the yield increase in 2040 that can be associated with future plant breeding efforts between 2020 and 2039 will account for 26.3 percent of current yield in the EU in total (see the bold dark green line in figure 3.10).

Figure 3.10: Simulated potential yield gain for major arable crops in 2040 with plant breeding between 2020 and 2039 in the EU



Source: Own calculations and figure.

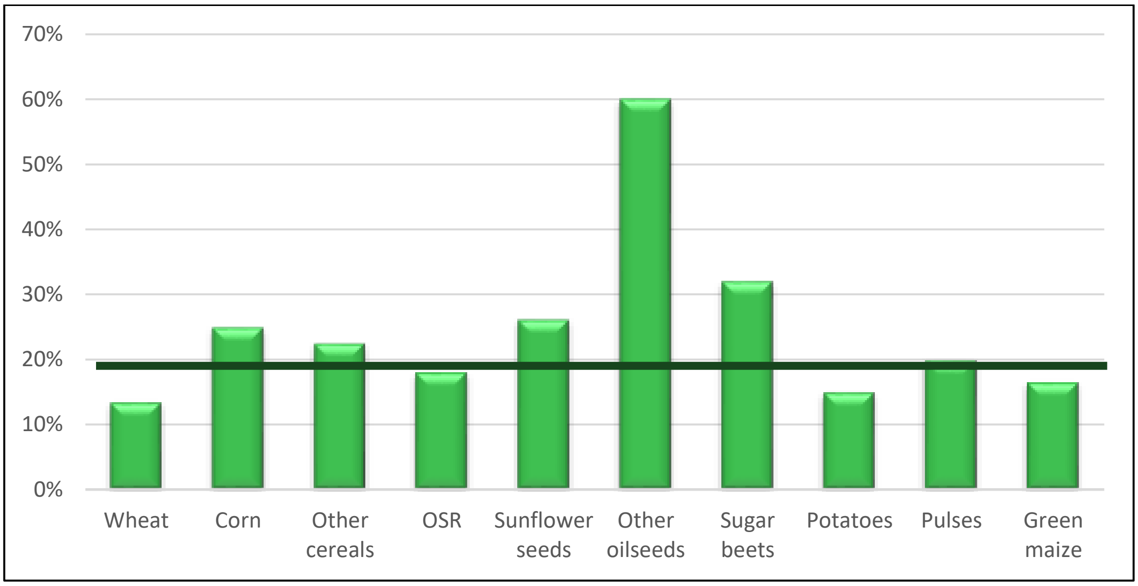
Analysis for the level of EU member states – the case of Germany

In Germany, also a considerable increase in arable yield will occur until 2040 with progress in plant breeding between 2020 and 2039 as figure 3.11 indicates. Weighted by hectare, the land productivity gain that can be related to plant breeding activities in the next wo decades will account for 19.3 percent of current arable yield in this EU member state (see the bold dark green line in figure 3.11)[48].

47 EC (2020c) also provides data on changing land use for arable crops in the EU, which is used here and hereafter. By and large, the shares of the individual (groups of) arable crops do not change a lot. Most prominent is the change in land use for pulses, which increases by 30 percent compared to 2020.

48 A high plant breeding-induced annual yield growth rate in other oilseeds has been achieved in the past. This might not keep going on. However, to be consistent, the growth remains unchanged until 2040.

Figure 3.11: Simulated potential yield gain for major arable crops in 2040 with plant breeding between 2020 and 2039 in Germany

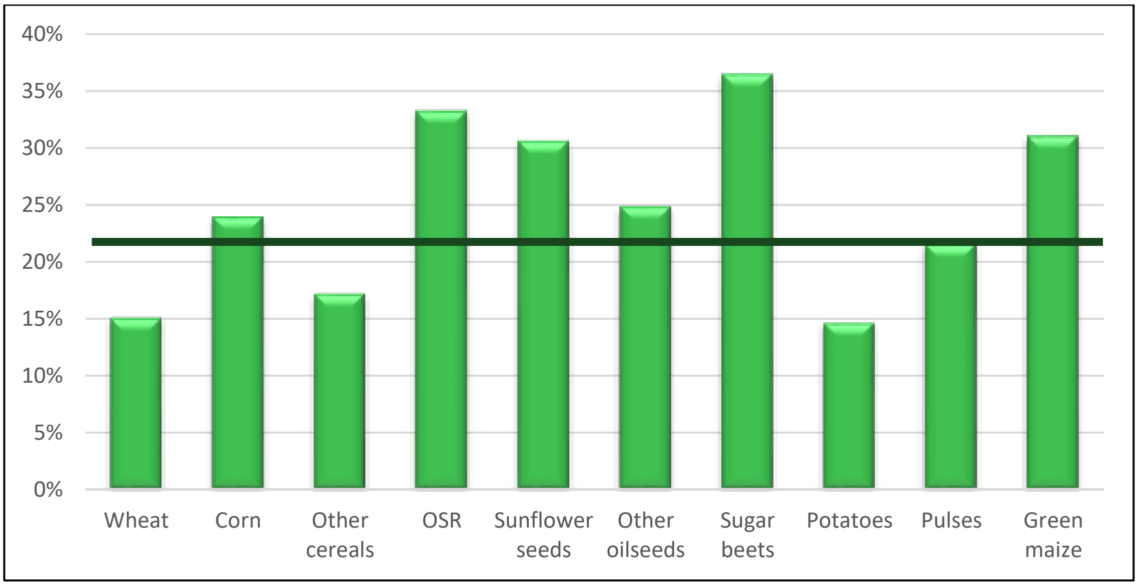


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of France

The hectare-weighted average of yield gains due to future plant breeding progress until 2040 will be 21.6 percent in the case of French arable farming as the bold dark green line in figure 3.12 shows.

Figure 3.12: Simulated potential yield gain for major arable crops in 2040 with plant breeding between 2020 and 2039 in France

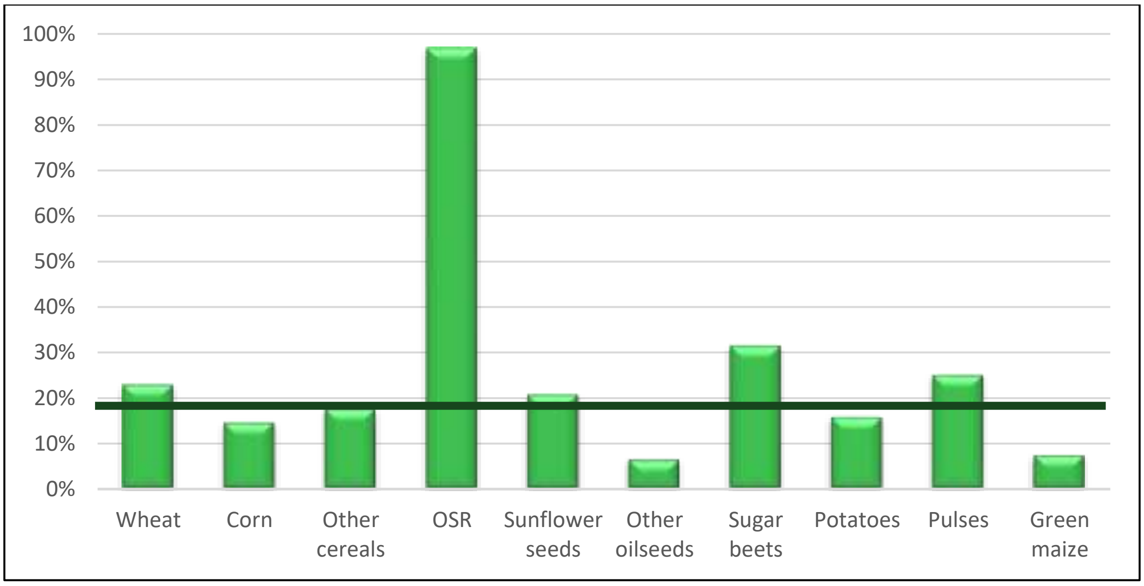


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Italy

Weighted by future acreage, the yield gain in 2040 that can be attributed to plant breeding efforts between 2020 and 2039 will account for 18.6 percent of current arable yields in Italy (see the bold dark green line in figure 3.13)[49].

Figure 3.13: Simulated potential yield gain for major arable crops in 2040 with plant breeding between 2020 and 2039 in Italy



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Spain

Looking at Spain, it turns out that the hectare-weighted yield increase in 2040 due to future plant breeding progress will be 13.9 percent as the bold dark green line in figure 3.14 shows.

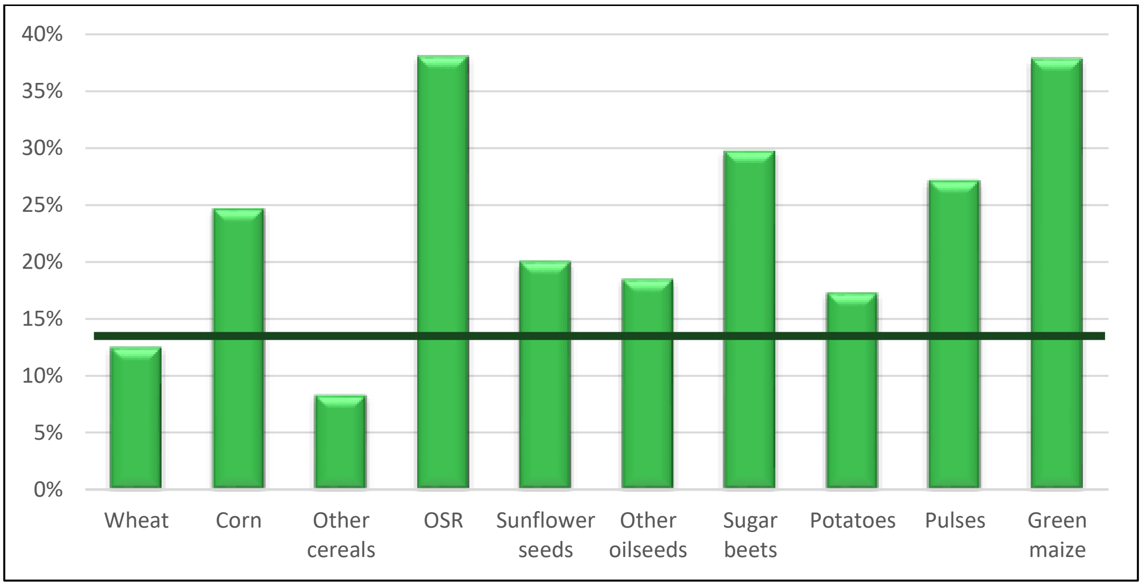
Analysis for the level of EU member states – the case of the UK

In the UK, also a considerable gain in arable yields will occur until 2040 with plant breeding progress between 2020 and 2039 as figure 3.15 depicts. Weighted by future hectare use, the increase that can be related to plant breeding in the next two decades will account for 24.0 percent of current yields in this former EU member state as the bold dark green line in figure 3.15 visualizes[50].

49 A high plant breeding-induced annual yield growth rate in OSR has been achieved in the past. This might not keep going on. However, to be consistent, the growth remains unchanged until 2040.

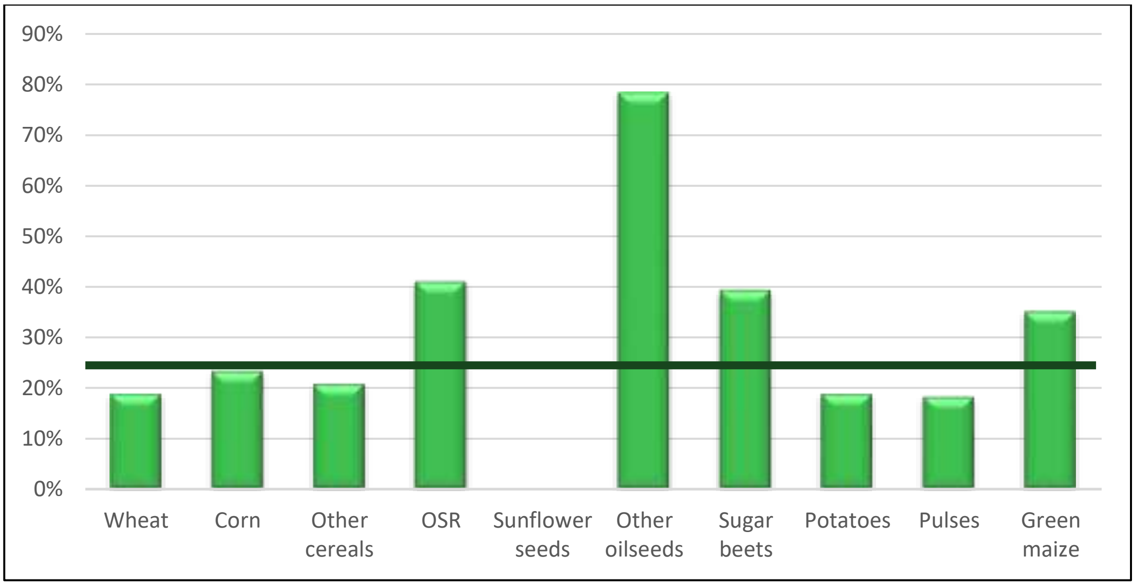
50 A high plant breeding-induced annual yield growth rate in other oilseeds has been achieved in the past. This might not keep going on. However, to be consistent, the growth remains unchanged until 2040.

Figure 3.14: Simulated potential yield gain for major arable crops in 2040 with plant breeding between 2020 and 2039 in Spain



Source: Own calculations and figure.

Figure 3.15: Simulated potential yield gain for major arable crops in 2040 with plant breeding between 2020 and 2039 in the UK



Source: Own calculations and figure.

Impacts of plant breeding on market supply

Overview on the impacts by EU region and crop

The obvious yield gains with plant breeding progress in the next decades will also affect future market supply. Figure 3.16 shows this potential extra market supply in 2040 for the EU and selected member states. Annex H provides similar information for the time horizon until 2030.

Figure 3.16: Potential extra market supply for major arable crops in 2040 with plant breeding progress between 2020 and 2039 in the EU and selected member states (in million tons)

Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	25.069	2.614	4.765	1.005	0.592	2.355
Corn	19.989	0.939	3.123	0.930	1.014	0.007
Other cereals	15.178	2.317	1.717	0.516	0.508	1.030
OSR	4.105	0.708	1.518	0.031	0.054	0.850
Sunflower seeds	5.977	0.011	0.434	0.059	0.181	N.A.
Other oilseeds	0.536	0.023	0.071	0.074	0.009	0.019
Raw sugar	7.252	1.513	2.471	0.123	0.181	0.504
Potatoes	14.820	1.379	1.007	0.189	0.344	0.934
Pulses	0.715	0.116	0.169	0.037	0.102	0.142
Green maize	22.239	4.323	2.628	0.369	0.511	0.709

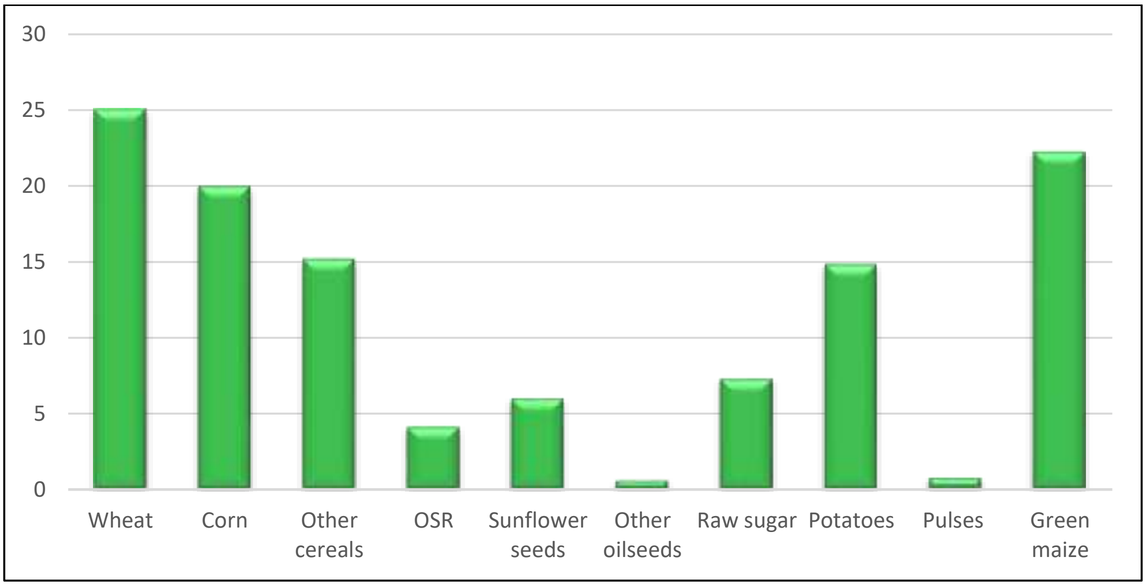
Source: Own calculations and figure.

Analysis for the level of the EU in total

Using a similar discussion approach as in the case of the *ex-ante* assessment, it can firstly be concluded that plant breeding between 2020 and 2039 will allow the EU in total to supply additional market volumes in 2040 as depicted in figure 3.17:

- For cereals in total, the supply effect will be around 60 million tons, and wheat alone will account for additional 25 million tons.
- Oilseeds will aggregate to additional 10.6 million tons almost equally shared between sunflower seeds and other oilseeds (including OSR).
- Raw sugar and potatoes will add 7.2 and 14.8 million tons, respectively.
- The supply of pulses will increase by more than 0.7 million tons, and in terms of dry matter, more than 22 million tons of green maize gains will additionally be available.

Figure 3.17: Potential extra market supply for major arable crops in 2040 with plant breeding progress between 2020 and 2039 in the EU (in million tons)



Source: Own calculations and figure.

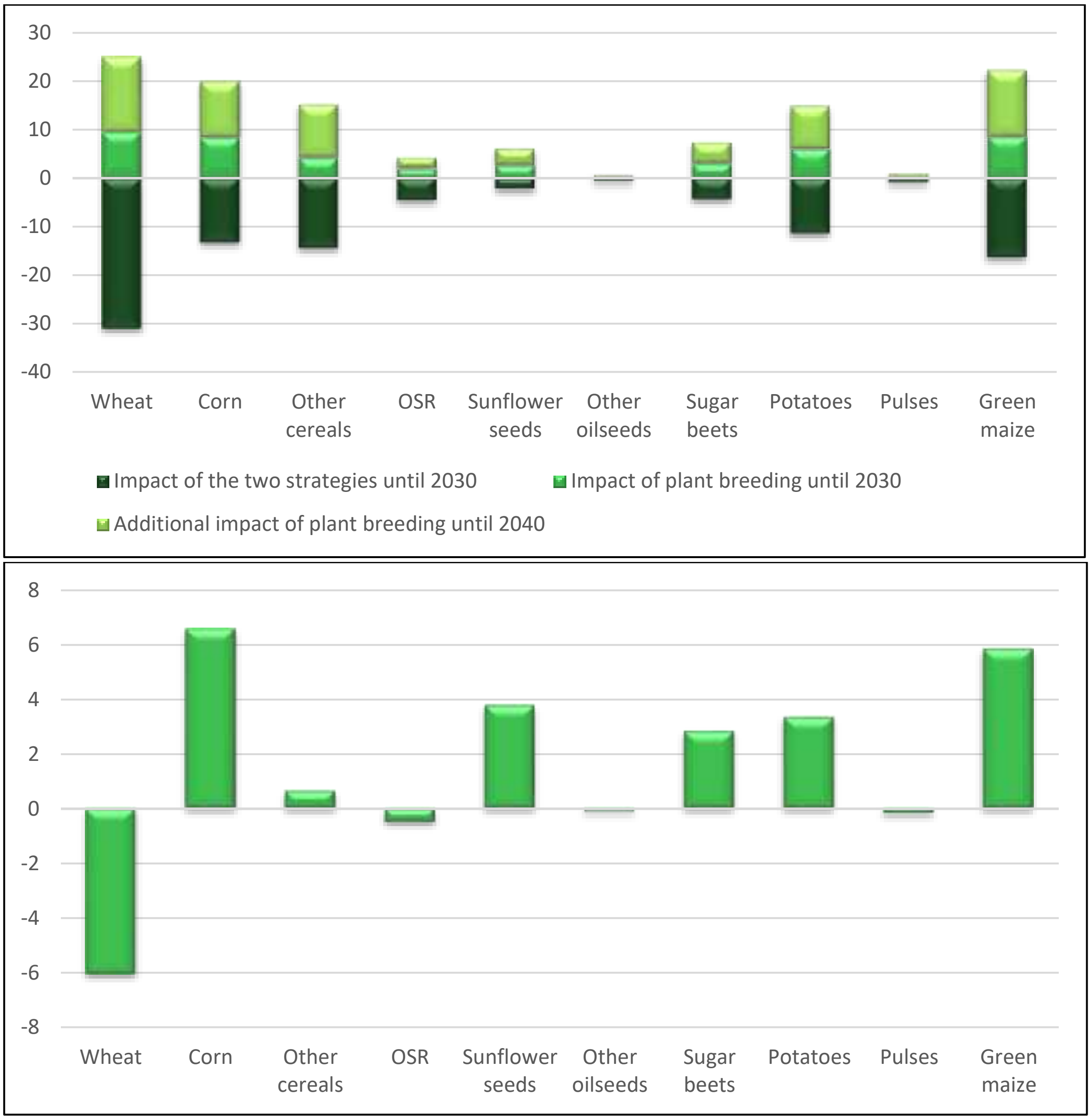
Apart from that, it is secondly also interesting to discuss at the EU level[51], to what extent this extra market supply with plant breeding in the next decades will influence the potential to compensate for the obvious market supply losses due to a full implementation of the two strategies. The result until 2040 can be seen in figure 3.18.

It turns out that the additional market supply in 2030 with plant breeding between 2020 and 2029 will not be enough to compensate for apparent losses due to a full implementation of the two strategies until 2030. Even two decades of plant breeding progress at current pace will potentially not be sufficient to compensate for market supply losses due to the enforcement of the two strategies until 2040 in the cases of pulses, other oilseeds, OSR, and wheat. However, in the other six cases of (groups of) arable crops, plant breeding progress between 2020 and 2039 might be adequate to (even over-) compensate market losses embedded in the full implementation of the "Farm to Fork" and "Biodiversity" strategies. The specific finding is important as it already points at the need for further and more short-term plant breeding successes which must be higher than in past

51 This part of the analysis will only be conducted at the level of the EU in total and not at the level of individual EU member states. The implementation of the "Farm to Fork" and "Biodiversity" strategies in terms of concrete measures and timing is highly speculative, as has been made clear above. This creates remarkable uncertainty. Against this background the following is only meant to provide a "best guess" as to what extent plant breeding in the EU may help to fulfill the objectives of the two strategies while counteracting negative impacts of these strategies.

decades to support the achievement of the economic and environmental objectives of the two strategies.

Figure 3.18: Comparing (above) and balancing (below) partial market supply effects of the two strategies with plant breeding progress until 2040 in the EU (in million tons)

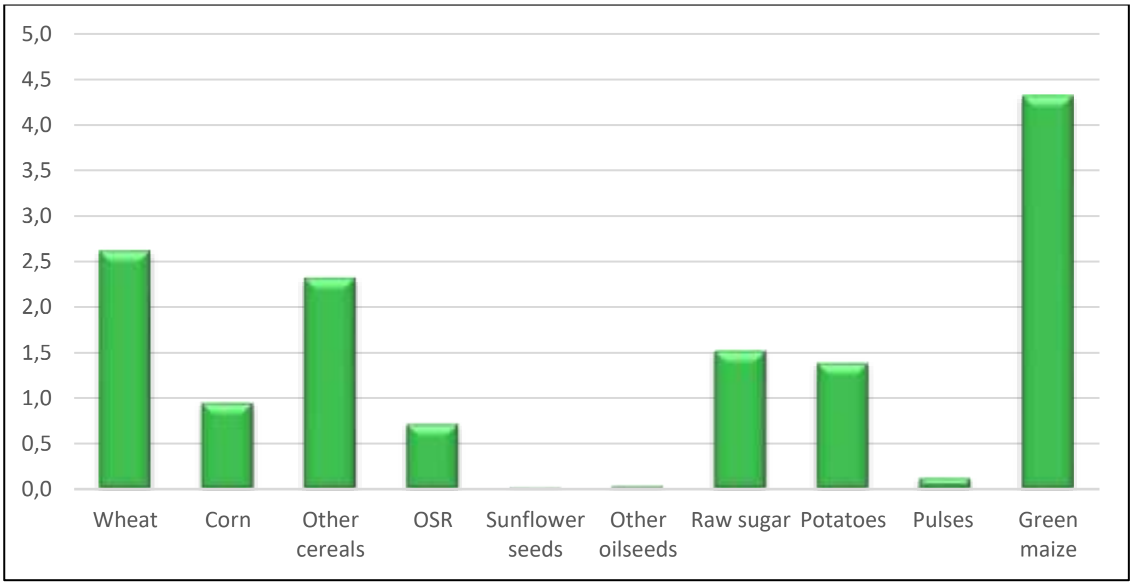


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Germany

Looking at Germany, plant breeding between 2020 and 2039 will allow the country to additionally supply market volumes in 2040 as depicted in figure 3.19. For cereals in total, the supply effect will be almost 5.9 million tons, and wheat alone will account for additional 2.6 million tons. OSR supply will increase by more than 0.7 million tons. Raw sugar produced from sugar beets and potatoes will add more than 1.5 million tons and more than 1.3 million tons, respectively. Pulses will still play a minor part and additionally supply in a range of slightly more than 0.1 million tons. Finally, more than 4.3 million tons of green maize (dry matter) will additionally become available.

Figure 3.19: Potential extra market supply for major arable crops in 2040 with plant breeding progress between 2020 and 2039 in Germany (in million tons)



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of France

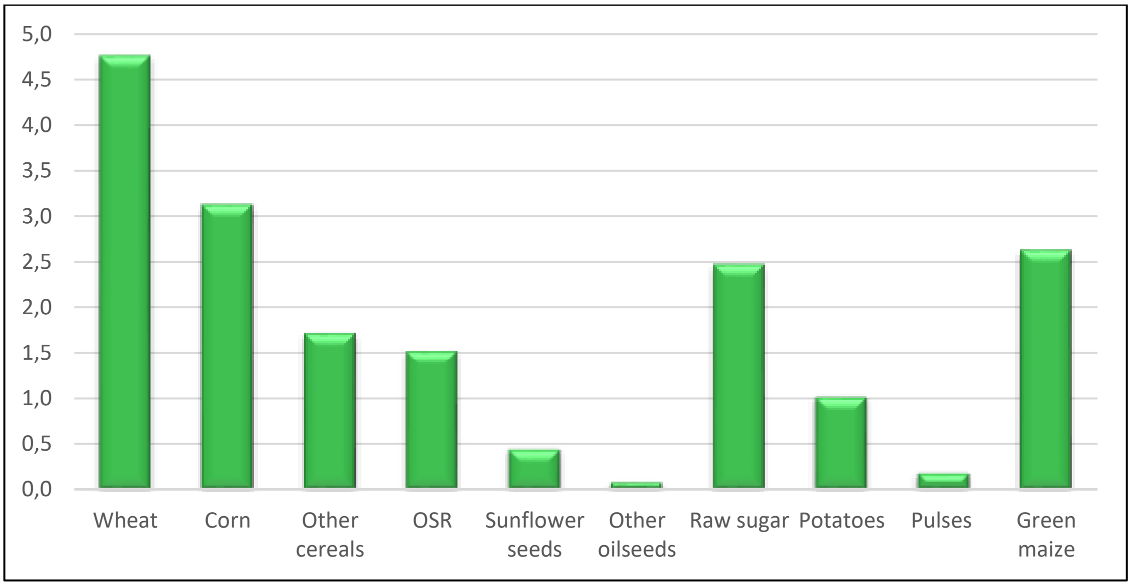
In the case of France, plant breeding between 2020 and 2039 will contribute to the additional market volumes in 2040 shown in figure 3.20. For cereals in total, an additional supply of more than 9.6 million tons can be noted. Wheat alone will account for almost 4.8 million additional tons. Oilseeds will aggregate to approximately 2.0 million tons. The majority will come from OSR (1.5 million tons). Almost 2.5 million tons of raw sugar and more than 1.0 million tons of potatoes will additionally be produced. Pulses will contribute less than 0.2 million tons in addition to what is currently supplied, and green maize supply will increase by 2.6 million tons dry matter content.

Analysis for the level of EU member states – the case of Italy

Figure 3.21 displays the market supply impacts in 2040 of plant breeding progress between 2020 and 2039 for Italy. For cereals in total, an additional supply of more than 2.4 million tons can be noted. Both wheat and corn will contribute approximately 1.0 million tons each to an increased market volume. Oilseed supply will increase as well. However, on aggregate it will be less than 0.2

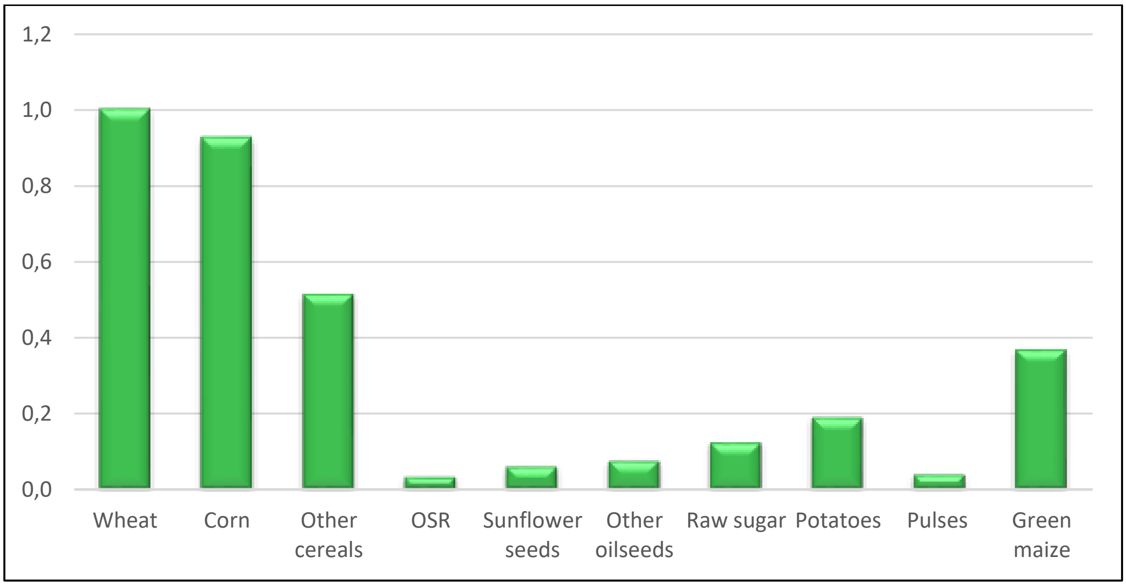
million tons. Raw sugar and potatoes supply will also increase by less than 0.2 million tons each. And the additional supply of pulses will be even less. Green maize supply will increase by 0.4 million tons dry matter content compared to what is currently produced in this EU member state.

Figure 3.20: Potential extra market supply for major arable crops in 2040 with plant breeding progress between 2020 and 2039 in France (in million tons)



Source: Own calculations and figure.

Figure 3.21: Potential extra market supply for major arable crops in 2040 with plant breeding progress between 2020 and 2039 in Italy (in million tons)

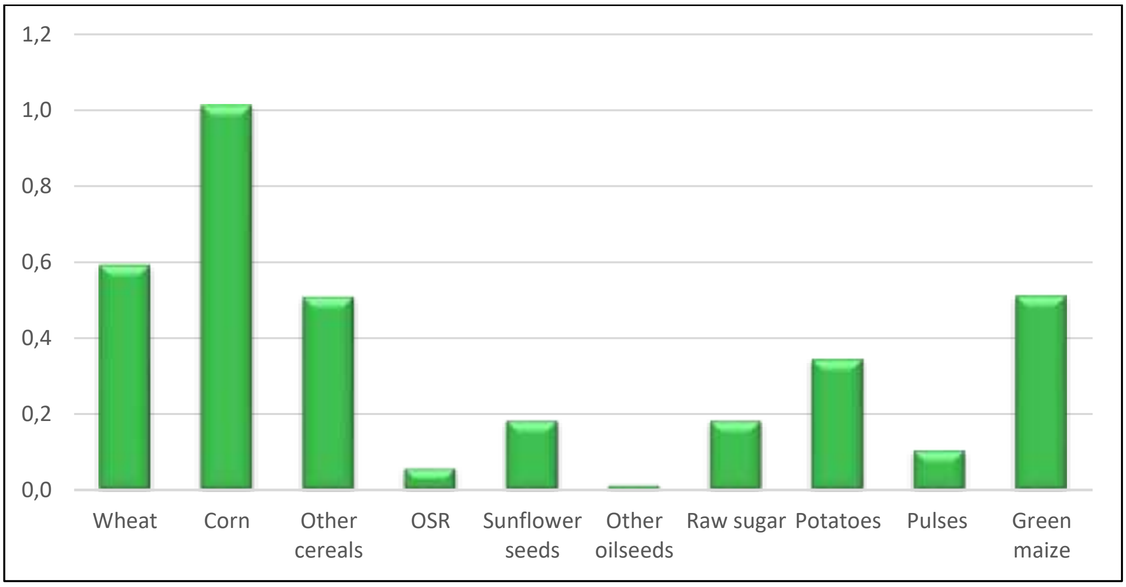


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Spain

Figure 3.22 provides the details on additional market supply in 2040 with respect to Spain. In this EU member state, plant breeding between 2020 and 2039 will contribute to the following additional market volumes. For cereals in total, an additional supply of more than 2.1 million tons can be noted. Corn alone will account for more than 1.0 million additional tons. Oilseeds will aggregate to more than 0.2 million tons. The majority will come from sunflower seeds. Almost 0.2 million tons of raw sugar and more than 0.3 million tons of potatoes will additionally be produced. Pulses will add approximately 0.1 million tons, and green maize supply will increase by more than 0.5 million tons dry matter content.

Figure 3.22: Potential extra market supply for major arable crops in 2040 with plant breeding progress between 2020 and 2039 in Spain (in million tons)

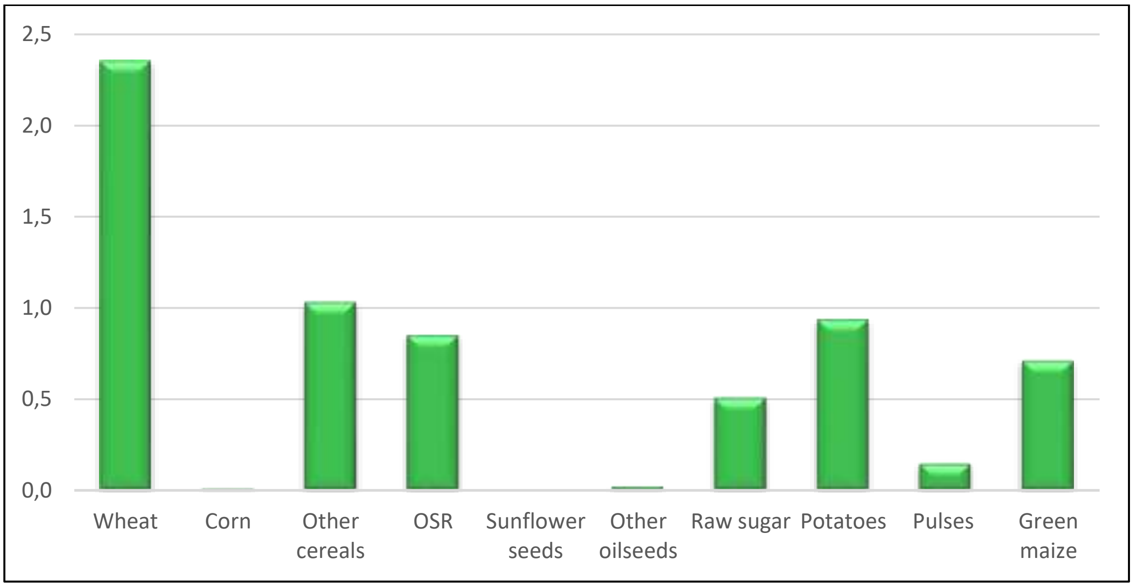


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of the UK

Plant breeding between 2020 and 2039 will also allow the UK to additionally supply market volumes in 2040 as depicted in figure 3.23. For cereals in total, the supply effect will be almost 3.4 million tons, and wheat alone will account for additional 2.3 million tons. OSR supply will increase by more than 0.8 million tons. Raw sugar produced from sugar beets will add 0.5 million tons, and potatoes supply will increase by more than 0.9 million tons. Pulses will add to the supply in a range of more than 0.1 million tons, and finally more than 0.7 million tons of green maize (dry matter) will additionally become available.

Figure 3.23: Potential extra market supply for major arable crops in 2040 with plant breeding progress between 2020 and 2039 in the UK (in million tons)



Source: Own calculations and figure.

Impacts of plant breeding on net trade volumes

Overview on the impacts by EU region and crop

Changing market supply does affect trade volumes. However, a comparable overview cannot be given. It shall be repeated: The EU acts as a single market. For the EU in total, this means that trade can only be measured in terms of trade between the EU and other countries outside the EU. This is different for the EU member state perspective. An EU member state is confronted with EU-extra trade and EU-intra trade. Therefore, aggregated trade data and information for the EU in total and its member states cannot properly be contrasted.

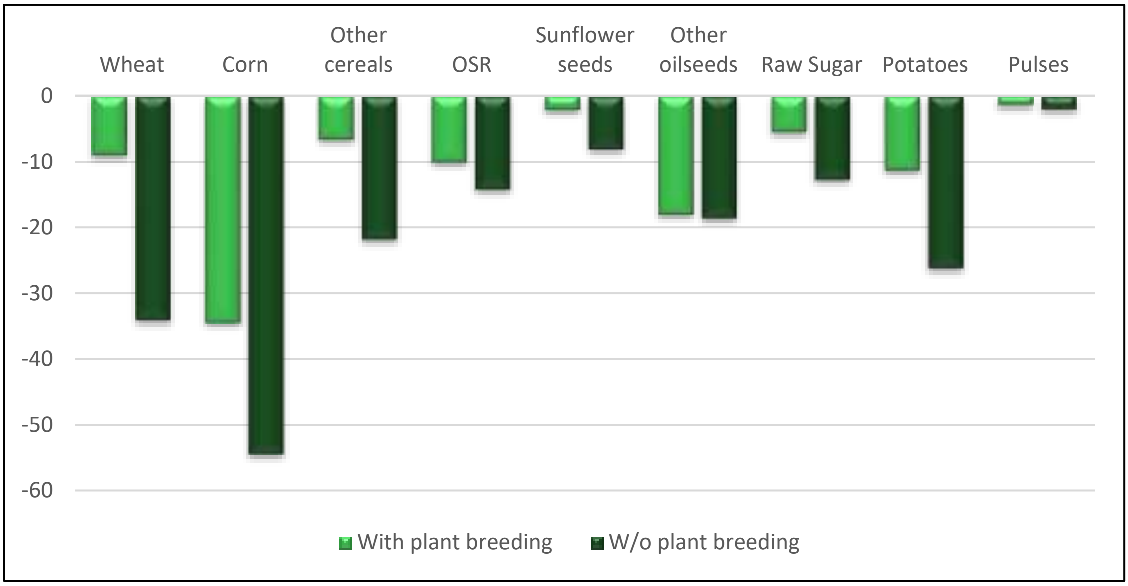
For the following it must also be noted that while analyzing the trade impacts, the reference net trade balances in the future to be confronted with effects due to plant breeding do not only have to take into account trade changes in the next two decades as postulated by the basic scenario (see EC, 2020c) – and applying the Armington assumption (see Allen and Arkolakis, 2014) – but also the production cut effects of an implementation of the "Farm to Fork" and "Biodiversity" strategies of the EU until 2030[52].

[52] These potential impacts on trade will most probably be tremendous if only the production site effects of the two strategies are considered (see again figure 3.2) and ceteris paribus lead to a considerable worsening of the EU's trade position in all agricultural commodity markets being in the focus of this study. A part of this trade impact might be mitigated through strategy-induced demand changes.

Analysis for the level of the EU in total

The resulting changes – in terms of the potential EU-extra trade incorporating the basic scenario as well as the implementation of the two strategies for the year 2040 – in the case of missing plant breeding progress between 2020 and 2040 for the EU in total are depicted in figure 3.24. Annex I provides the details for the time horizon until 2030.

Figure 3.24: Potential net trade volumes of the EU for major arable crops in 2040 with and without plant breeding progress between 2020 and 2039 (in million tons)



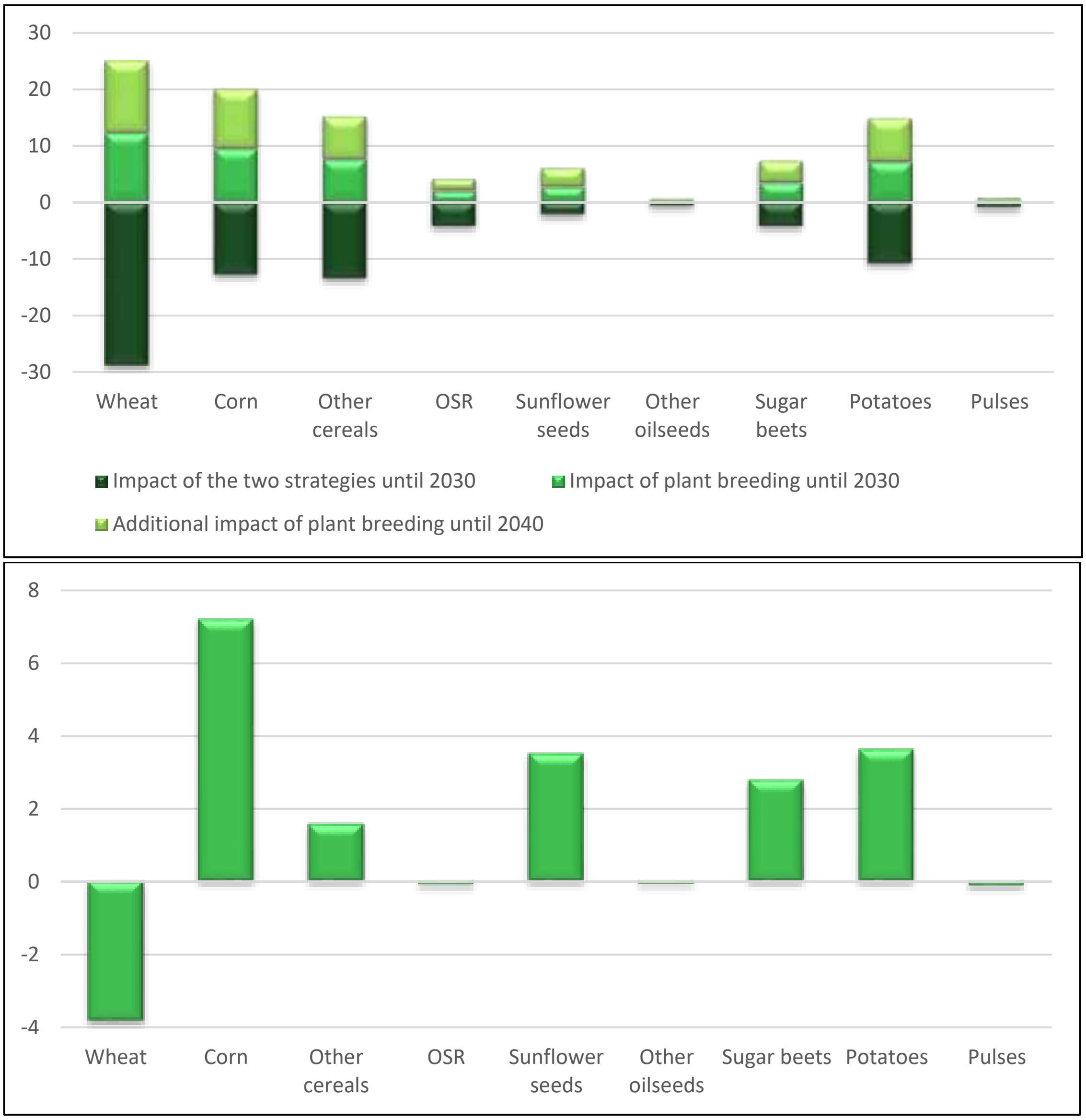
Source: Own calculations and figure.

The figure reveals that without plant breeding in the next two decades, the trade position of the EU will further deteriorate in 2040 since the EU while implementing the two strategies would become a net importer with respect to all major arable crops including wheat and other cereals. If further progress in crop genetics did not occur in the next 20 years, the EU in the chosen scenario would have to import more than 30 million tons of wheat and more than 50 million tons of corn, for instance, in 2040.

The underlying partial effects of the full implementation of the two strategies on the one hand and future plant breeding progress on the other hand can be obtained from figure 3.25. The results basically mirror what has already been discussed with respect to market volumes (see figure 3.18) and do not need further discussion[53].

53 Note that demand effects that can be associated with plant breeding and the two strategies as defined above are usually small since attributable price developments (see, for instance, figure 2.57) are small too. Note also that changing export and/or import incentives abroad slightly alter the traded volumes.

Figure 3.25: Comparing (above) and balancing (below) partial net trade effects of the two strategies with plant breeding progress until 2040 in the EU (in million tons)

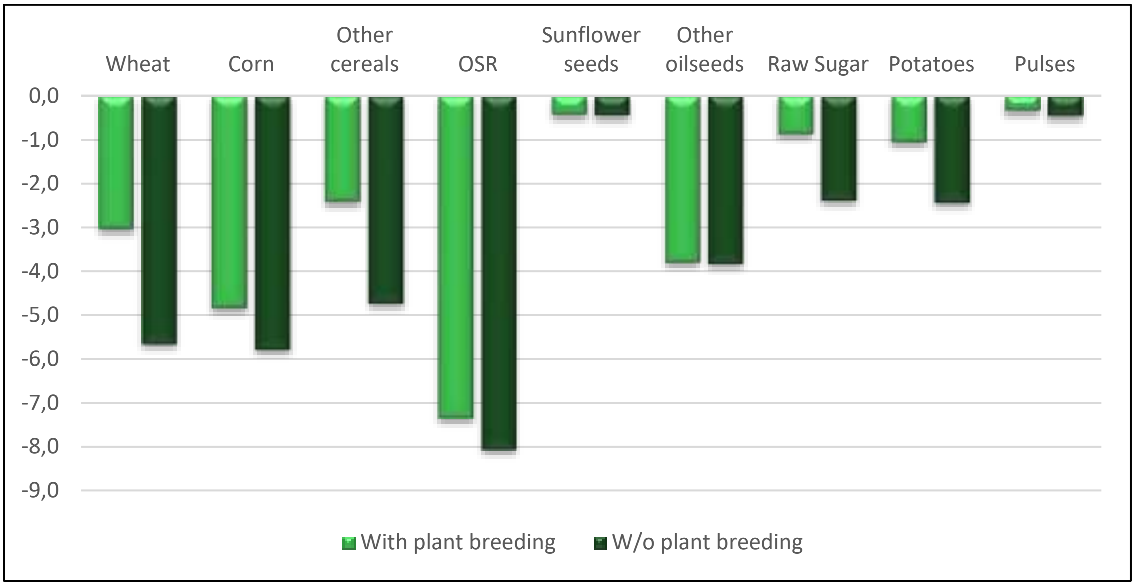


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Germany

The resulting changes in the case of missing plant breeding progress between 2020 and 2039 for Germany can be obtained from figure 3.26. It becomes obvious that future plant breeding within these 20 years will help Germany to not fall into a greater dilemma as the country – under normal circumstances – will be in a net import situation in 2040 with respect to all arable crops post the implementation of the "Farm to Fork" and "Biodiversity" strategies. The net import of wheat and other cereals, to take an example, would be twice as high without future plant breeding progress.

Figure 3.26: Potential net trade volumes of Germany for major arable crops in 2040 with and without plant breeding progress between 2020 and 2039 (in million tons)



Source: Own calculations and figure.

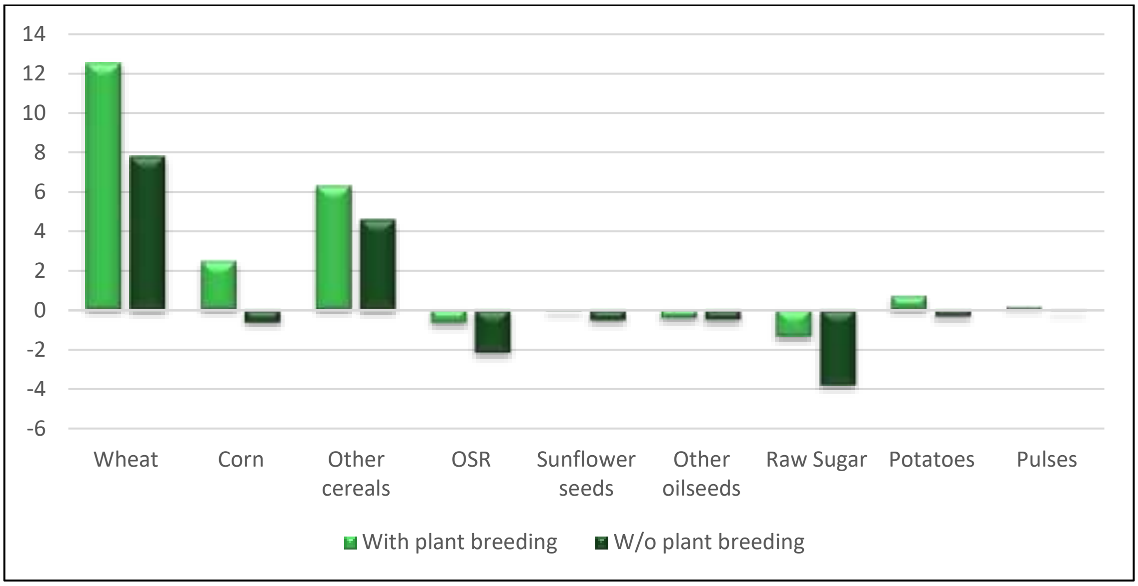
Analysis for the level of EU member states – the case of France

France is currently still a leading net exporter of major arable crops. But this position will weaken somewhat if we consider that – apart from other market forces (see EC, 2020c) – the two strategies of the EU will be implemented in future. This can be seen by comparing the situation with plant breeding in figure 2.46 (referring to 2020) and figure3.27 (describing the situation in 2040). Thanks to plant breeding in the next two decades, the trade balance in 2040 will still be positive as regards corn, for instance. But without future plant breeding corn must also be net imported by this EU member state in 2040. Apart from that, French wheat exports would considerably decrease in 2040 without progress in plant breeding in the next 20 years, and the other trade positions of France would also suffer a lot by 2040 in the absence of further genetic crop improvements.

Analysis for the level of EU member states – the case of Italy

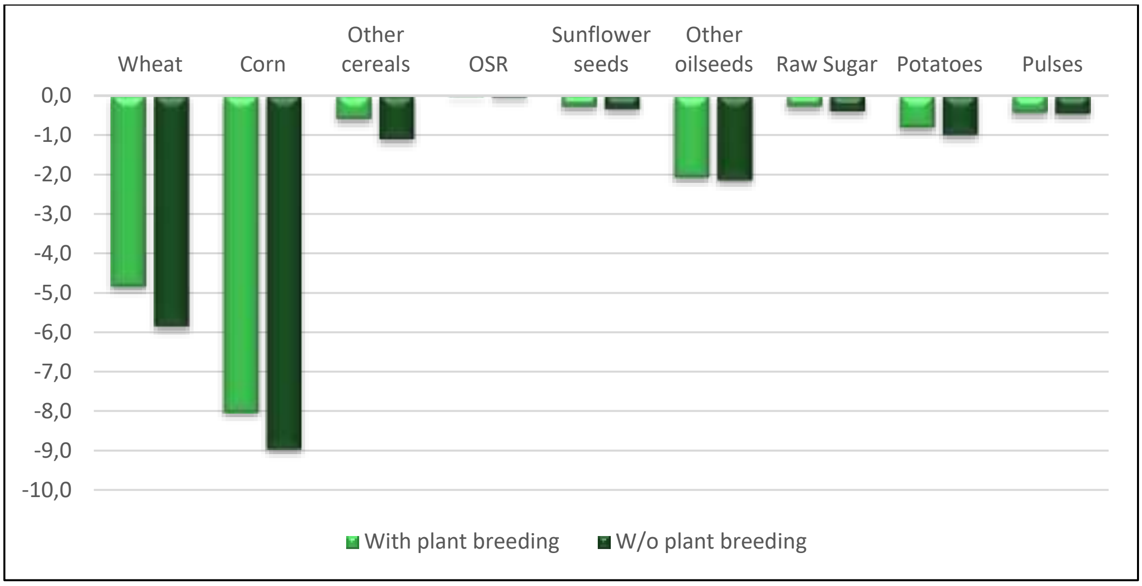
Italy will be in a net import situation with respect to all the ten (groups of) crops included here in 2040 as it becomes obvious by looking at figure 3.28. Without plant breeding for the selected arable crops in the next two decades, the net import situation with respect to all commodities will further deteriorate. To take an example: The net import volume for wheat and corn in 2040 would increase by more than 1.0 million tons each in the absence of plant breeding achievements between 2020 and 2039.

Figure 3.27: Potential net trade volumes of France in for major arable crops 2040 with and without plant breeding progress between 2020 and 2039 (in million tons)



Source: Own calculations and figure.

Figure 3.28: Potential net trade volumes of Italy for major arable crops in 2040 with and without plant breeding progress between 2020 and 2039 (in million tons)



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Spain

What has been stated with respect to Italy can basically be repeated for Spain as figure 3.29 displays. This EU member state will also be in a net import situation in 2040 as regards every major arable crop being in the focus of this study, and without future plant breeding progress between 2020 and 2039, this net import position would be even more pronounced as for instance an additional 1.0 million tons of corn would have to be imported.

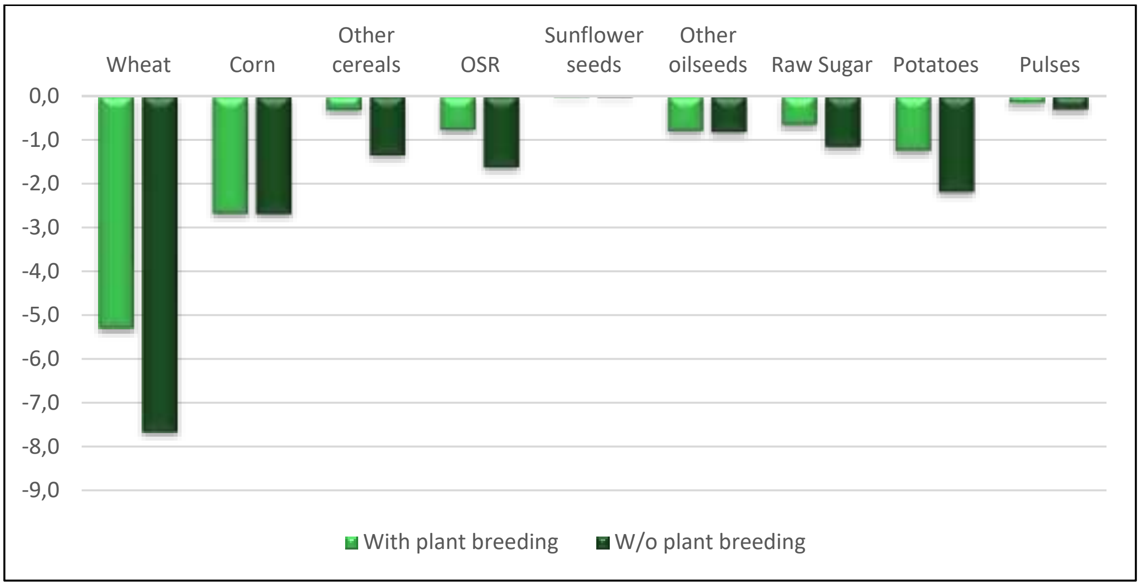
Figure 3.29: Potential net trade volumes of Spain for major arable crops in 2040 with and without plant breeding progress between 2020 and 2039 (in million tons)

Source: Own calculations and figure.

Analysis for the level of EU member states – the case of the UK

The resulting net trade changes in the case of missing plant breeding progress between 2020 and 2039 for the UK can finally be obtained from figure 3.30. It becomes obvious that the UK will fall into a net import position in 2040 with respect to all ten (groups of) arable crops being in the focus of this study once the two strategies of the EU are implemented and market forces as described in EC (2020c) act. Without plant breeding in the next two decades, this net trade position will become even more negative. Net imports of wheat, for instance, would considerably increase. And in the two cases of other cereals and potatoes, where the UK by 2020 still is in a net export situation (see again figure 2.49), a remarkable additional net import would also occur without progress in plant breeding in the next two decades.

Figure 3.30: Potential net trade volumes of the UK for major arable crops in 2040 with and without plant breeding progress between 2020 and 2039 (in million tons)



Source: Own calculations and figure.

Food availability

Overview on the impacts by EU region

Since plant breeding in the EU will also act in future to increase production, a part of this additional production can be used as food. Accordingly, plant breeding will increase food availability (and with that food security). In the following the increase of food availability (or security) in 2040 that can be attributed to plant breeding progress between 2020 and 2039 shall be analysed, whereas annex J provides the details for 2030. Therefore, the same food basket as defined in sub-chapter 2.2 is used. Consequently, figure 3.31 displays the number of people that can additionally be provided with a full food basket in 2040 due to plant breeding progress between 2000 and 2039.

Figure 3.31: Potential additionally available food in 2040 with plant breeding progress between 2020 and 2039 in the EU and selected member states (in food for million people)

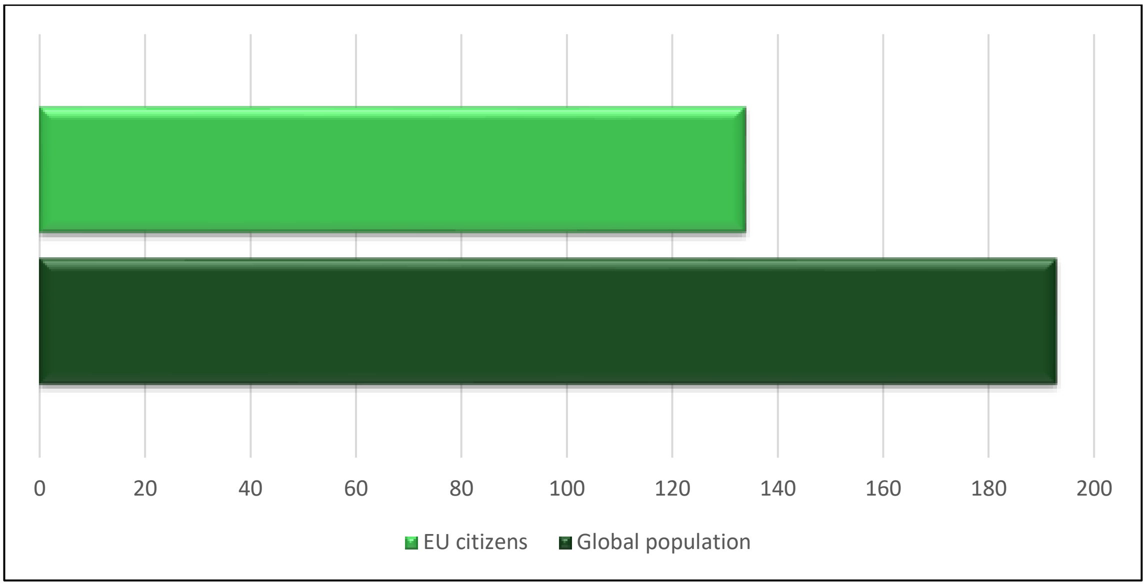
Food basket of ...	EU	DE	FR	IT	ES	UK
EU citizens	134.1	16.9	24.5	3.5	3.5	10.0
Global population	193.1	23.9	32.3	5.9	5.5	14.4

Source: Own calculations and figure.

Analysis for the level of the EU in total

As figure 3.32 visualizes, plant breeding progress in the EU in total in the next two decades has the potential to remarkably increase global food availability. In 2040, food baskets filled with produce from the nine relevant (groups of) crops for an additional more than 190 million people will become available worldwide. Alternatively, more than 134 million additional Europeans could be provided with food.

Figure 3.32: Potential additionally available food in 2040 with plant breeding progress between 2020 and 2039 in the EU in total (in food for million people)

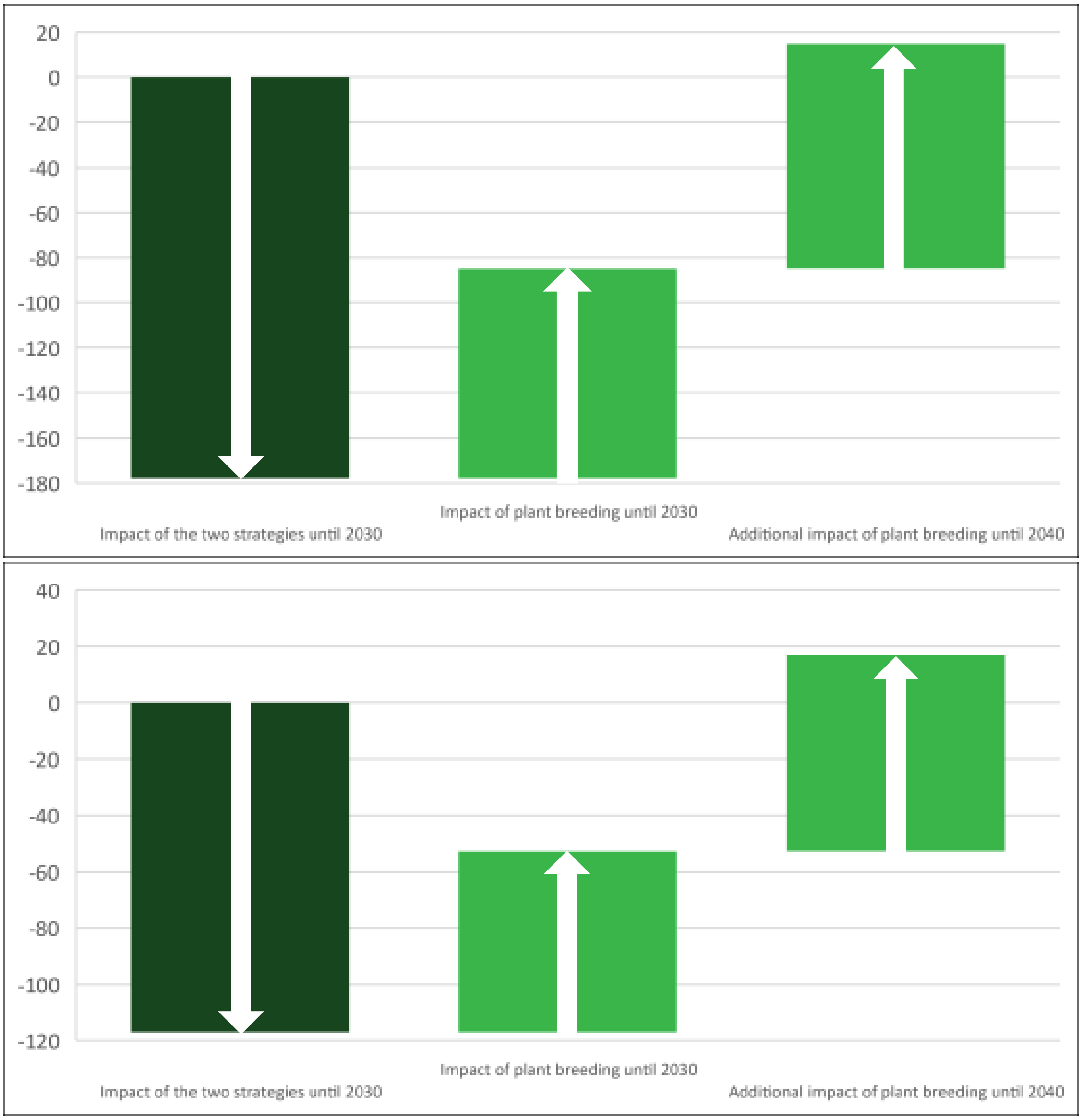


Source: Own calculations and figure.

This can help mitigate negative food availability consequences being the result of an enforcement of the "Farm to Fork" and "Biodiversity" strategies of the EU as these strategies add to lower production and, hence, food availability. This becomes obvious by looking at figure 3.33.

With respect to global population, the two strategies – if fully implemented until 2030 – would lead to a food shortage equivalent to 178 million food baskets. In opposite to that, plant breeding progress in the EU at current pace would be able to refill 93 million of these food baskets in the next decade, and two decades of upcoming genetic crop improvements will potentially be able to refill 193 million food baskets. Hence, plant breeding is potentially able to (over-) compensate in the long run. If only the EU population is considered, the two strategies would lead to missing 117 million food baskets which can potentially be refilled in part (in full) due to plant breeding progress until 2030 (2040) as enough additional food for 64 (134) million EU citizens would be available.

Figure 3.33: Comparing and balancing partial food availability effects of the two strategies with plant breeding progress until 2040 in the EU for global population (above) and EU citizens (below) (in food for million people)

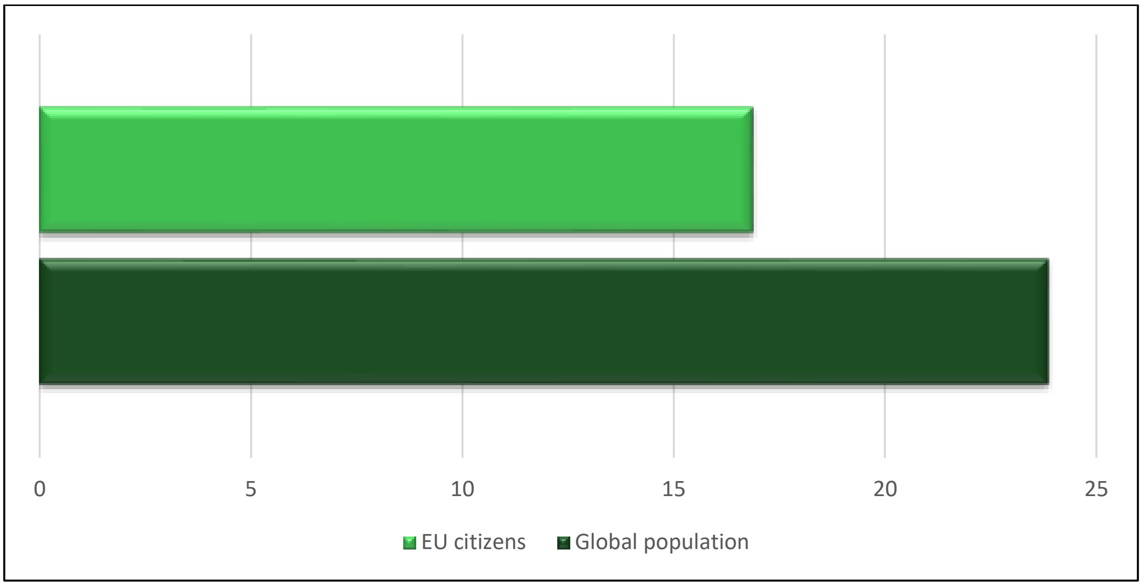


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Germany

Plant breeding progress in Germany in the next two decades will also contribute to an increased food availability in 2040 as figure 3.34 depicts. In 2040, food baskets for an additional more than 23 (almost 17) million people at global scale (at EU scale) will become available.

Figure 3.34: Potential additionally available food in 2040 with plant breeding progress between 2020 and 2039 in Germany (in food for million people)



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of France

In the case of France, food baskets for an additional almost 33 (more than 24) million people at global scale (at EU scale) will become available in 2040 due to plant breeding progress between 2020 and 2039 as figure 3.35 shows.

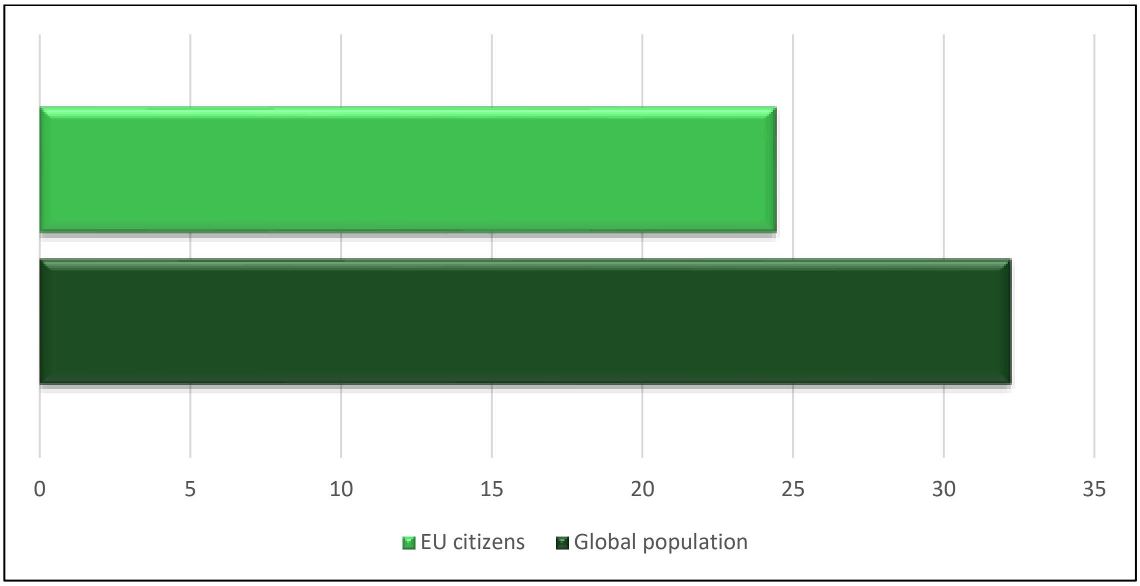
Analysis for the level of EU member states – the case of Italy

As figure 3.36 visualizes, plant breeding progress in Italy in the next two decades will also remarkably contribute to an increased future food availability. In 2040, food baskets filled with produce from the nine relevant (groups of) crops for an additional almost 6 million people globally will become available. Alternatively, much more than 3 million additional Europeans could be provided with food baskets.

Analysis for the level of EU member states – the case of Spain

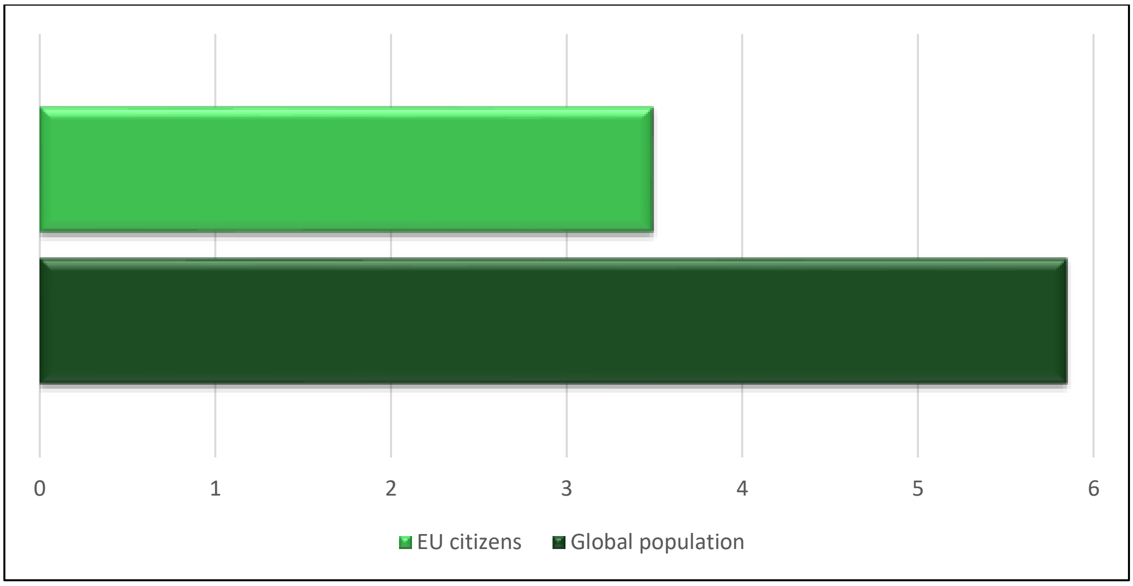
Plant breeding progress in Spain between 2020 and 2039 will also contribute to an increased food availability as figure 3.37 depicts. In 2040, food baskets for an additional more than 5 million people at global scale will become available this way. And at EU scale it will be enough food to fill baskets for much more than 3 million people.

Figure 3.35: Potential additionally available food in 2040 with plant breeding progress between 2020 and 2039 in France (in food for million people)



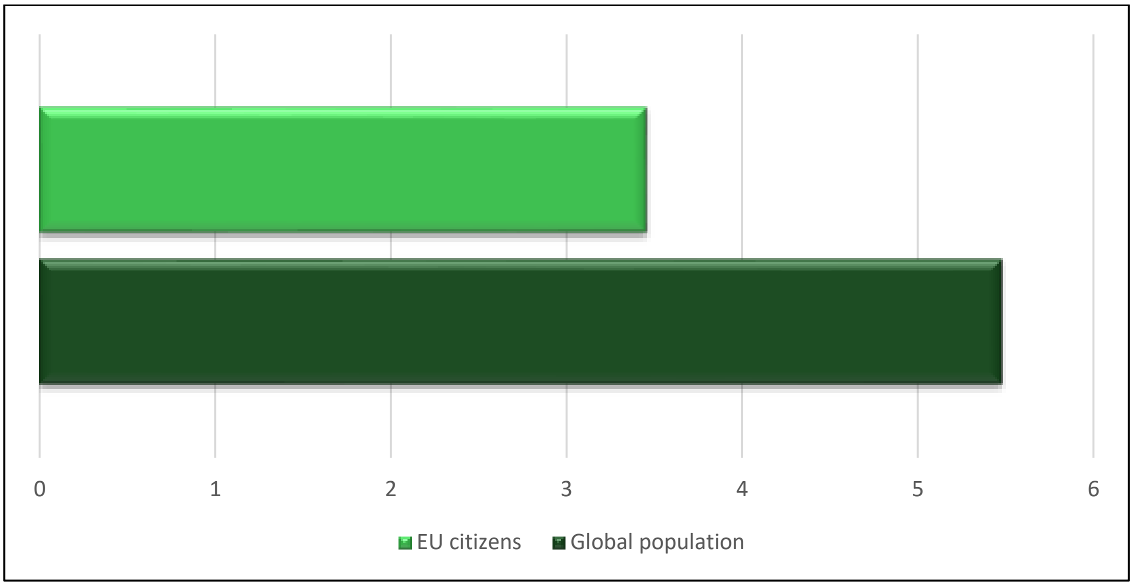
Source: Own calculations and figure.

Figure 3.36: Potential additionally available food in 2040 with plant breeding progress between 2000 and 2039 in Italy (in food for million people)



Source: Own calculations and figure.

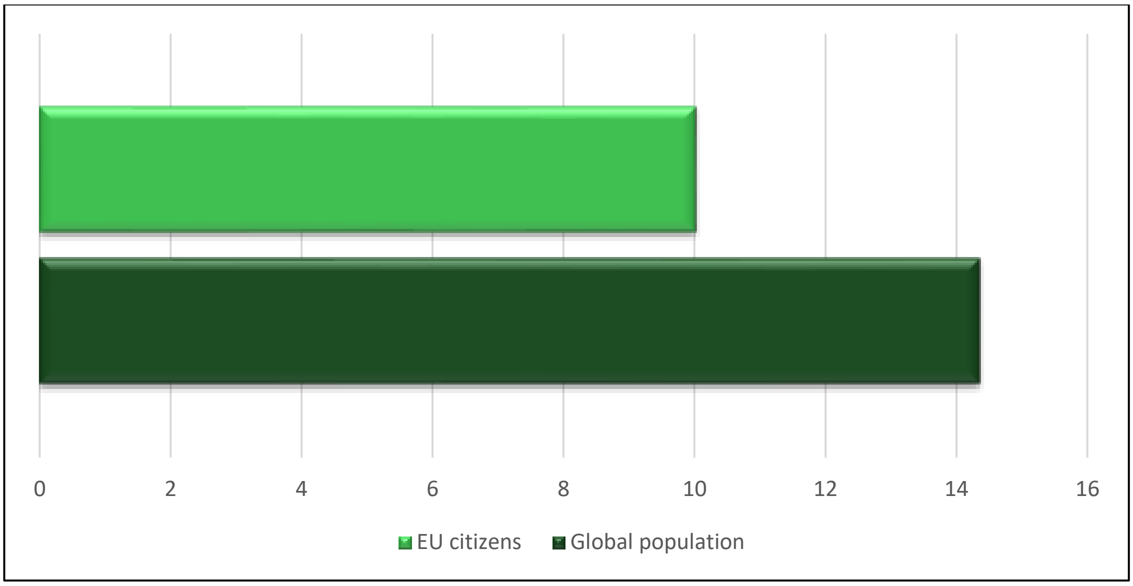
Figure 3.37: Potential additionally available food in 2040 with plant breeding progress between 2000 and 2039 in Spain (in food for million people)



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of the UK

Figure 3.38: Potential additionally available food in 2040 with plant breeding progress between 2000 and 2039 in the UK (in food for million people)



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of the UK

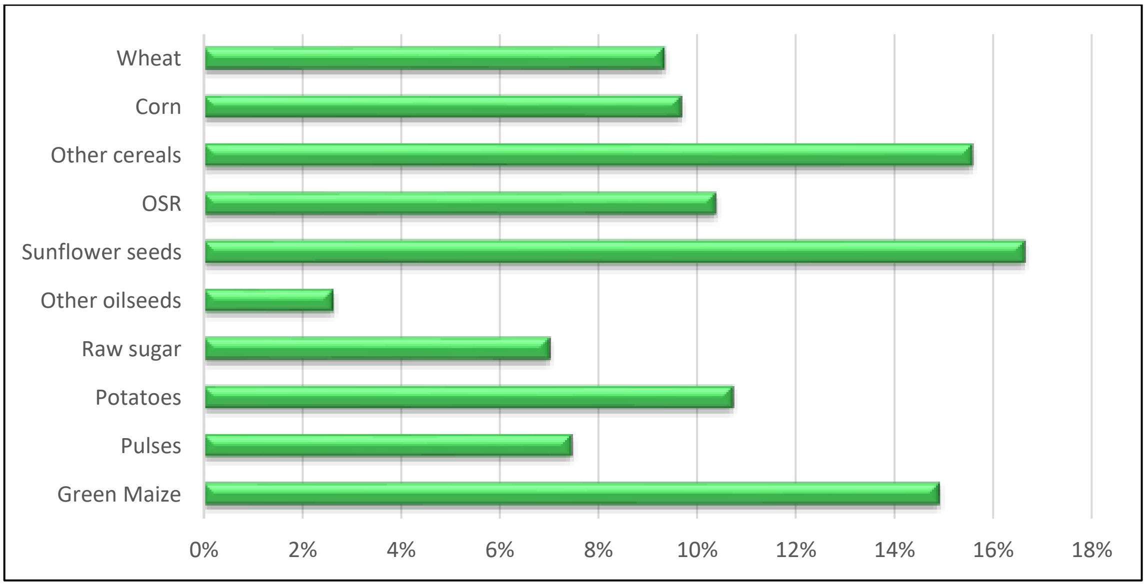
Finally, the specific impact for the UK shall be discussed. As can be seen by looking at figure 3.38, food baskets for more than 14 million people at global scale will become available in 2040. And at EU scale it will then be enough food to fill baskets for approximately 10 million people.

Market prices

Overview on the impacts by EU region and crop[54]

It has already been stated above that a rather high market supply volume with plant breeding does not only create a benefit in terms of the trade balance, but additionally enables consumers in the EU and around the globe to buy food and agricultural raw materials at affordable prices. Against this background, figure 3.39 displays the market price effect of plant breeding in the EU between 2020 and 2039, i.e., the avoided price increases in 2040. Annex K provides similar information for the time horizon until 2030.

Figure 3.39: Potentially avoided price increases for major agricultural commodity markets in 2040 with EU plant breeding between 2020 and 2039 in the EU



Source: Own calculations and figure.

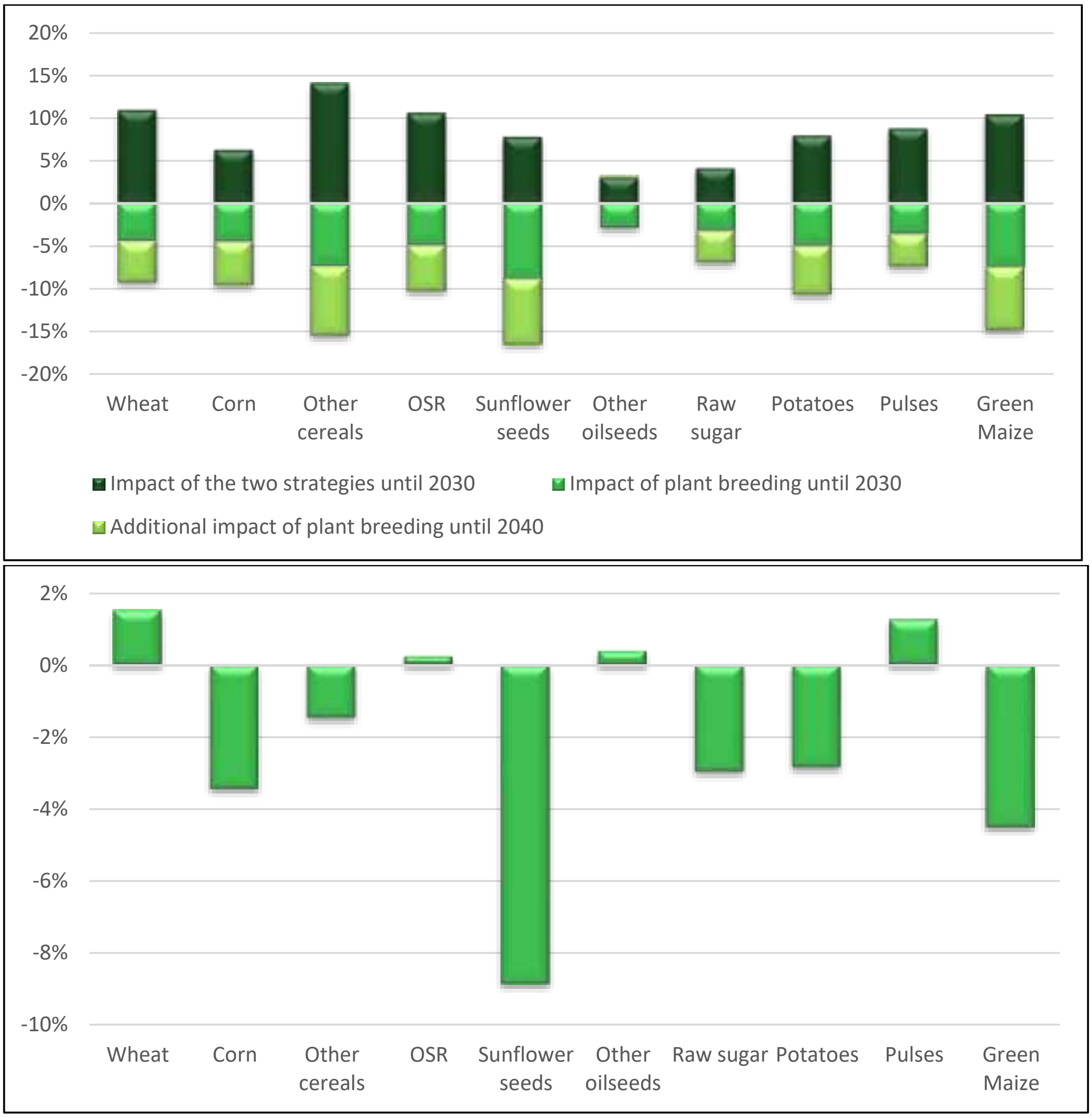
By and large, prices on internationally linked agricultural commodity markets would be 3 to 17 per-cent higher in 2040 without plant breeding in the EU during the next two decades. The avoided

54 The following analysis, again, does not distinguish an EU from a member state level. Keep in mind that the EU is a single market. Changes in market prices, therefore, reflect the situation in the EU in total as well as in its individual member states.

price increase would be highest for the case of sunflower seeds. Here, annual yield progress induced by plant breeding in the EU will be rather high. In opposite to that, no major price changes will be observable in the case of other oilseeds as the EU is just a small producer but an important consumer. Even major production changes in the EU, thus, would not significantly alter the amount of internationally traded soybeans, for instance.

Again, the partial effects of plant breeding on market prices shall be set into perspective by comparing them with respective impacts that can be attributed to a full implementation of the two strategies. Figure 3.40 shows the results.

Figure 3.40: Comparing (above) and balancing (below) partial market price effects of the two strategies with plant breeding progress until 2040 in the EU



Source: Own calculations and figure.

It turns out that a full implementation of the "Farm to Fork" and "Biodiversity" strategies – as defined above – would increase market prices between 3.0 percent in the case of other oilseeds and 14.1 percent in the case of other cereals. Plant breeding progress between 2020 and 2039 has the potential to partially counteract this development as the partial effect will be able to almost entirely "delete" price increases due to the strategies. In fact, only in the cases of wheat, OSR, other oilseeds, and pulses a small net price increase (of less than 1.5 percent) would remain if the two partial effects of the two strategies, on the one hand, and of plant breeding until 2040, on the other hand, would be added. For the other (groups of) crops, a negative net price impact would be the result, i.e., plant breeding efforts might be able to overcompensate the price increasing effect of the two strategies until 2040.

Sectoral income

Overview on the impacts by EU region and crop

The social welfare effects in 2040 being a proxy for agricultural income generated by future plant breeding activities between 2020 and 2039 for the crops and regions included in this analysis are now listed in figure 3.41, while annex L provides similar information for the time horizon until 2030.

Figure 3.41: Potential additional sectoral income for major arable crops in 2040 with plant breeding progress between 2020 and 2039 in the EU and selected member states (in billion EUR)

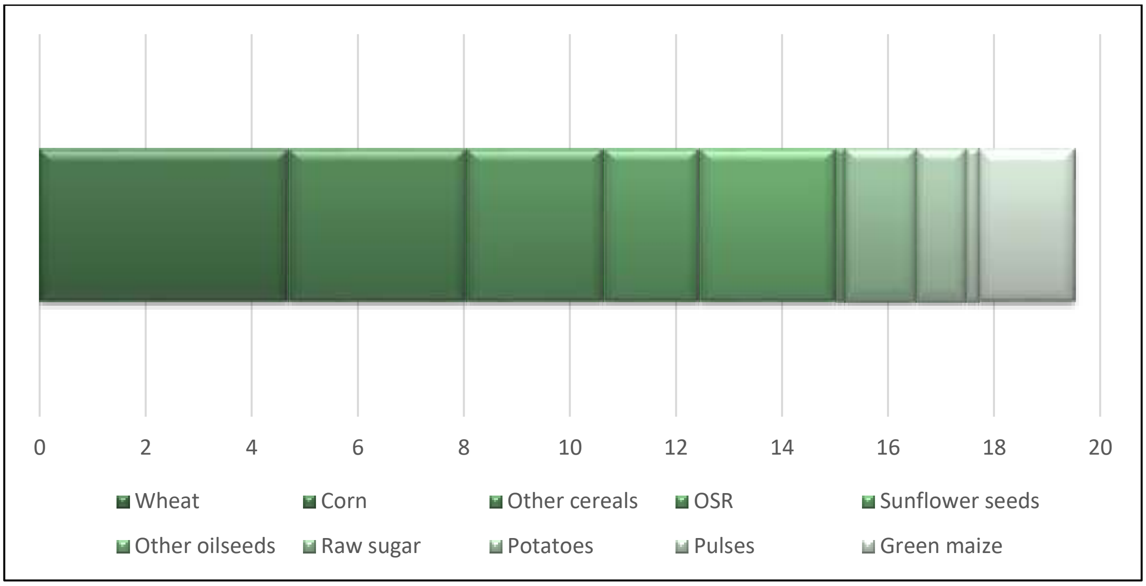
Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	4.703	0.490	0.894	0.188	0.111	0.442
Corn	3.362	0.158	0.525	0.156	0.171	0.001
Other cereals	2.575	0.393	0.291	0.088	0.086	0.175
OSR	1.810	0.312	0.670	0.014	0.024	0.375
Sunflower seeds	2.572	0.005	0.187	0.025	0.078	N.A.
Other oilseeds	0.170	0.007	0.023	0.023	0.003	0.006
Raw sugar	1.341	0.280	0.457	0.023	0.033	0.093
Potatoes	0.937	0.087	0.064	0.012	0.022	0.059
Pulses	0.247	0.040	0.058	0.013	0.035	0.049
Green maize	1.821	0.354	0.215	0.030	0.042	0.058

Source: Own calculations and figure.

Analysis for the level of the EU in total

The total social welfare gain in 2040 of plant breeding between 2020 and 2039 for the analysed crops in the EU amounts to more than EUR 19 billion as figure 3.42 displays. This is comparable to almost 8.0 percent of the current gross value added in the agriculture sector (including forestry and fishery) of the EU (see Eurostat, 2021d) and implies a considerable future contribution of plant breeding to economic prosperity of the overall sector.

Figure 3.42: Potential additional sectoral income for major arable crops in 2040 with plant breeding progress between 2020 and 2039 in the EU (in billion EUR)



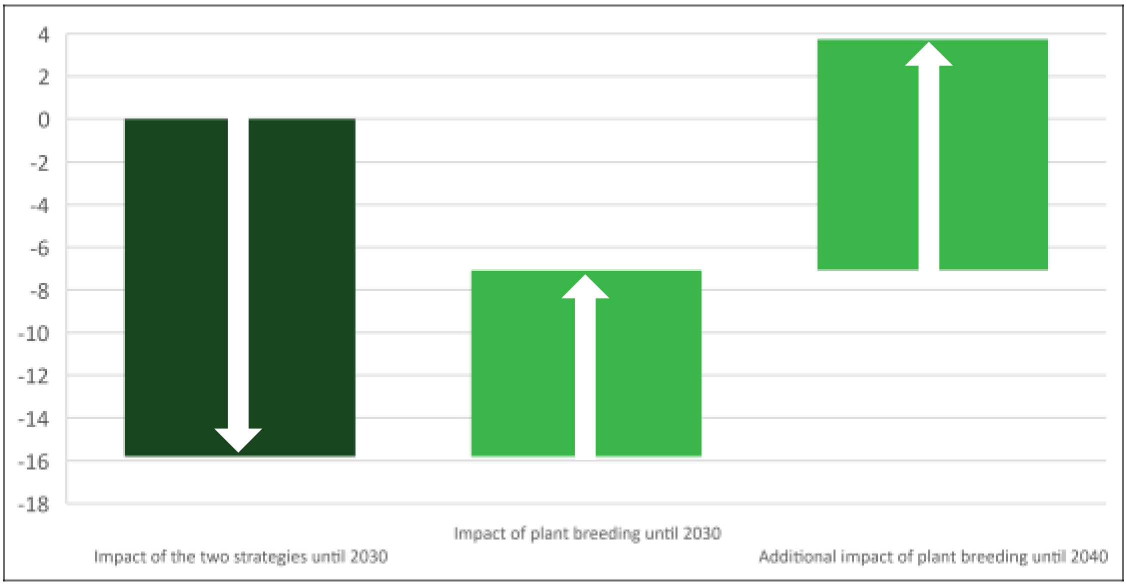
Source: Own calculations and figure.

This should be considered a huge future impact as the partial effect will allow for a full compensation of the negative sectoral income effects that can be associated with the full implementation of the "Farm to Fork" and "Biodiversity" strategies and the subsequent production losses. In fact, figure 3.43 shows that the two strategies would lead to a partial sectoral income loss of more than EUR 15 billion. Plant breeding progress until 2030 will have the potential to partly compensate this loss (with an additional sectoral income of almost EUR 9 billion), and in 2040, a net surplus (of more than EUR 3 billion) might be the result if the partial effects incorporated in the enforcement of the two strategies, on the one hand, and in plant breeding progress at current pace between 2020 and 2039, on the other hand, are added.

Analysis for the level of EU member states – the case of Germany

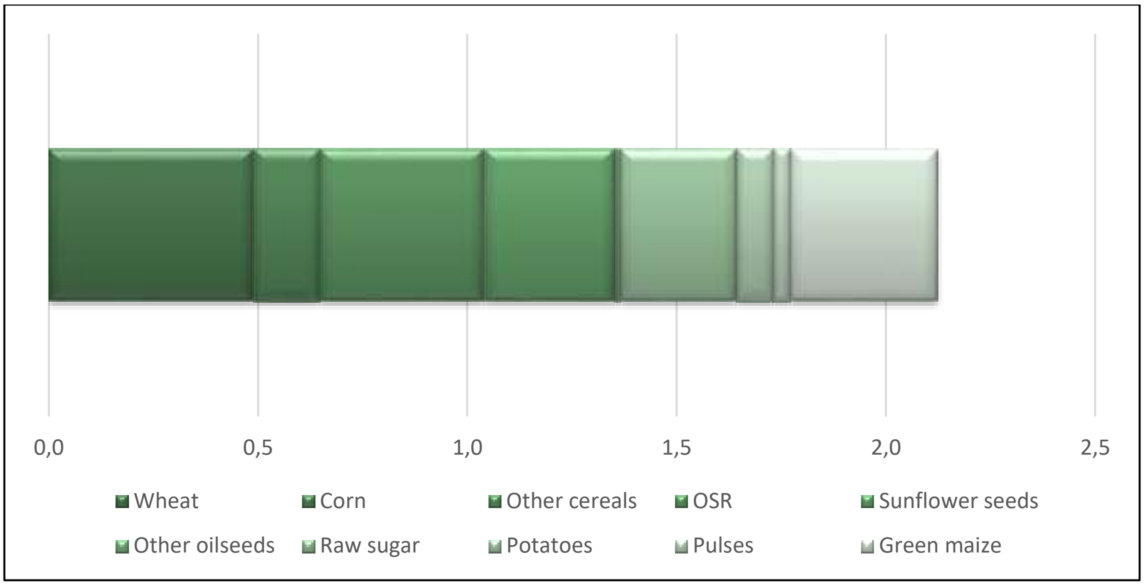
Figure 3.44 depicts the outcome of this specific analysis for Germany. Accordingly, it can be stated that plant breeding progress between 2020 and 2039 will potentially enable this EU member state to generate an extra sectoral income of almost EUR 2.2 billion in 2040, what is comparable to roundabout 10 percent of the current gross value added in the German agricultural sector (see Eurostat, 2021d).

Figure 3.43: Comparing and balancing partial sectoral income effects of the two strategies with plant breeding progress until 2040 in the EU (in billion EUR)



Source: Own calculations and figure.

Figure 3.44: Potential additional sectoral income for major arable crops in 2040 with plant breeding progress between 2020 and 2039 in Germany (in billion EUR)

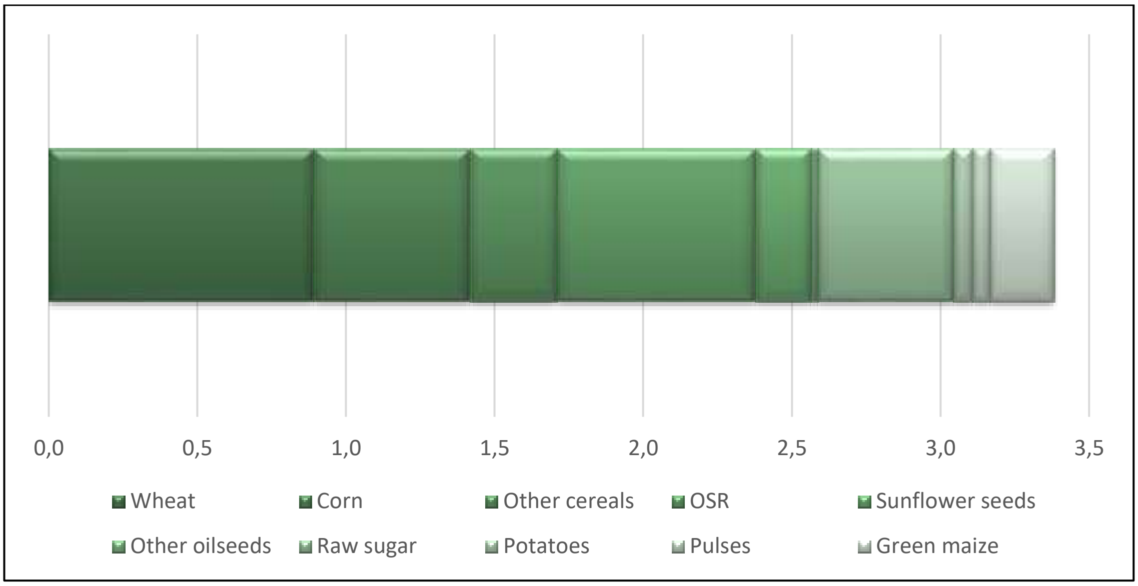


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of France

According to figure 3.45, it can be argued that plant breeding improvements between 2020 and 2039 will enable France to add an extra sectoral income of more than EUR 3.3 billion in 2040. This is comparable to approximately 8.5 percent of the current gross value added in the agriculture sector of France (see Eurostat, 2021d).

Figure 3.45: Potential additional sectoral income for major arable crops in 2040 with plant breeding progress between 2020 and 2039 in France (in billion EUR)



Source: Own calculations and figure.

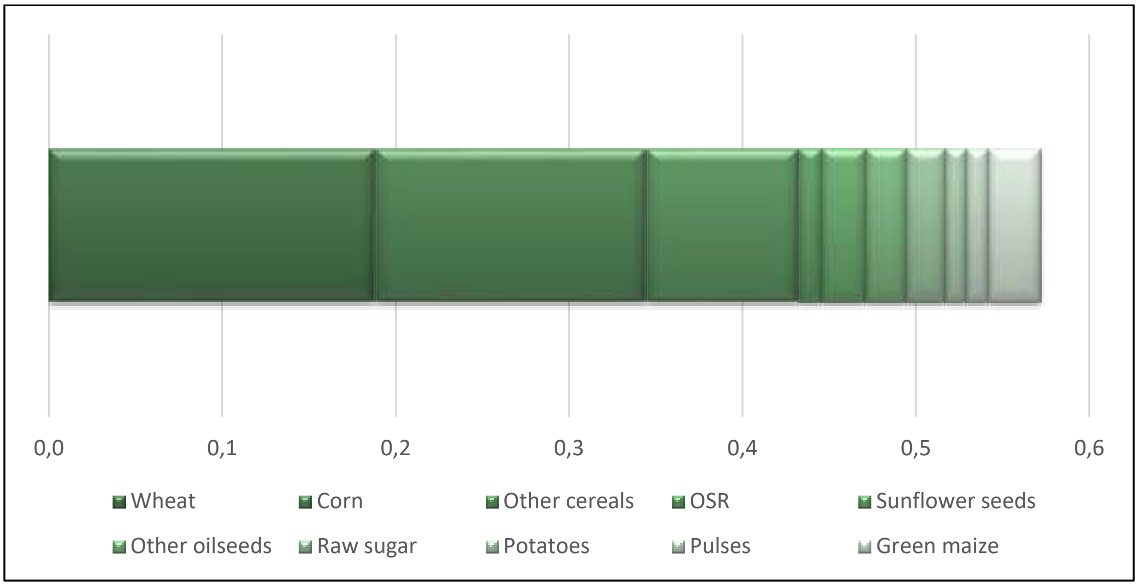
Analysis for the level of EU member states – the case of Italy

Looking at the results for Italy, as displayed in figure 3.46, it can be highlighted that progress in plant breeding between 2020 and 2039 will contribute to a sectoral income in 2040 that is almost EUR 0.6 billion higher than without the future progress. According to Eurostat (2021d), this is comparable to 1.7 percent of the current gross value added in the agriculture sector of Italy.

Analysis for the level of EU member states – the case of Spain

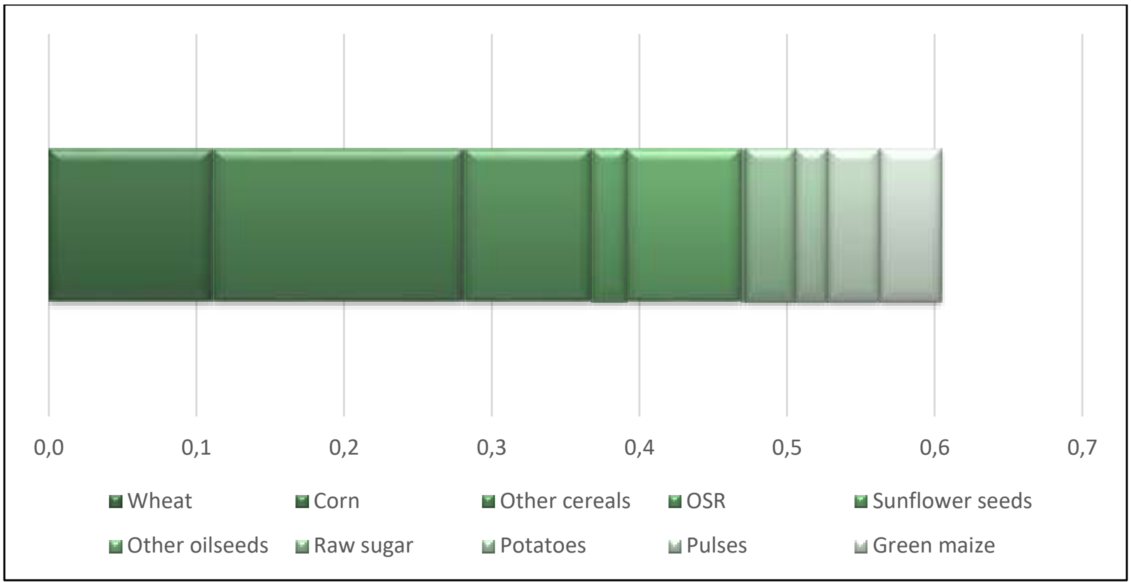
Figure 3.47 displays the outcome of this specific analysis for Spain. Accordingly, it can be stated that plant breeding progress in the next two decades will enable the country to generate an extra sectoral income in 2040 of more than EUR 0.6 billion. This is comparable to approximately 2 percent of the current gross value added in the agriculture sector comprising agriculture, forestry, and fishery of this EU member state (see Eurostat, 2021d).

Figure 3.46: Potential additional sectoral income for major arable crops in 2040 with plant breeding progress between 2020 and 2039 in Italy (in billion EUR)



Source: Own calculations and figure.

Figure 3.47: Potential additional sectoral income for major arable crops in 2040 with plant breeding progress between 2020 and 2039 in Spain (in billion EUR)

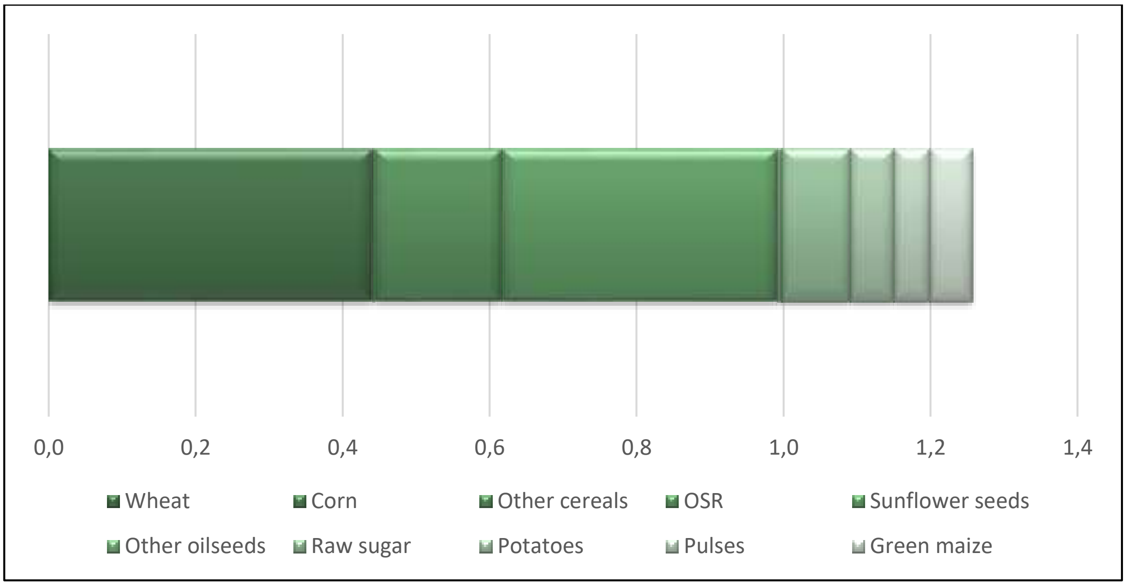


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of the UK

The total sectoral income gain in 2040 of plant breeding between 2020 and 2039 for the analyzed crops in the UK will amount to more than EUR 1.2 billion as figure 3.48 displays. According to latest available information, this is comparable to more than 8.0 percent of the current gross value added in the agriculture sector (see again Eurostat, 2021d) and implies – as in the case of the other EU member states – that without plant breeding progress the sector might suffer from shrinking economic prosperity.

Figure 3.48: Potential additional sectoral income for major arable crops in 2040 with plant breeding progress between 2020 and 2039 in the UK (in billion EUR)



Source: Own calculations and figure.

GDP contributions

Overview on the impacts by EU region and crop

It has already been stated above: Plant breeding does not only benefit the primary agricultural sector but the society in total. It particularly creates an economic value not only for farmers but for (mainly rural) citizens upstream and downstream the value chain because the additionally produced agricultural raw material must be transported, processed, traded, retailed etc. This tends to increase the generation of income in other sectors. Accordingly, the producer surplus additionally generated through plant breeding being a substantial part of the future societal welfare (or sectoral income) effect displayed in figure 3.41 must be linked to GDP multipliers as described in annex D. Accordingly, figure 3.49 gives an overview on the results for the EU and its selected member states referring to the year 2040. Annex M provides similar information for the other time horizon, i.e., for 2030.

Figure 3.49: Potential additional GDP attributable to major arable crops in 2040 with plant breeding progress between 2020 and 2039 in the EU and selected member states (in billion EUR)

Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	8.578	0.866	1.827	0.414	0.247	0.810
Corn	6.133	0.279	1.074	0.344	0.379	0.002
Other cereals	4.697	0.695	0.595	0.192	0.192	0.320
OSR	2.939	0.491	1.218	0.026	0.047	0.612
Sunflower seeds	4.176	0.007	0.339	0.049	0.154	N.A.
Other oilseeds	0.276	0.012	0.041	0.046	0.006	0.010
Raw sugar	3.022	0.611	1.154	0.061	0.092	0.211
Potatoes	2.113	0.190	0.161	0.032	0.060	0.134
Pulses	0.556	0.087	0.147	0.035	0.097	0.111
Green maize	3.287	0.619	0.435	0.066	0.092	0.105

Source: Own calculations and figure.

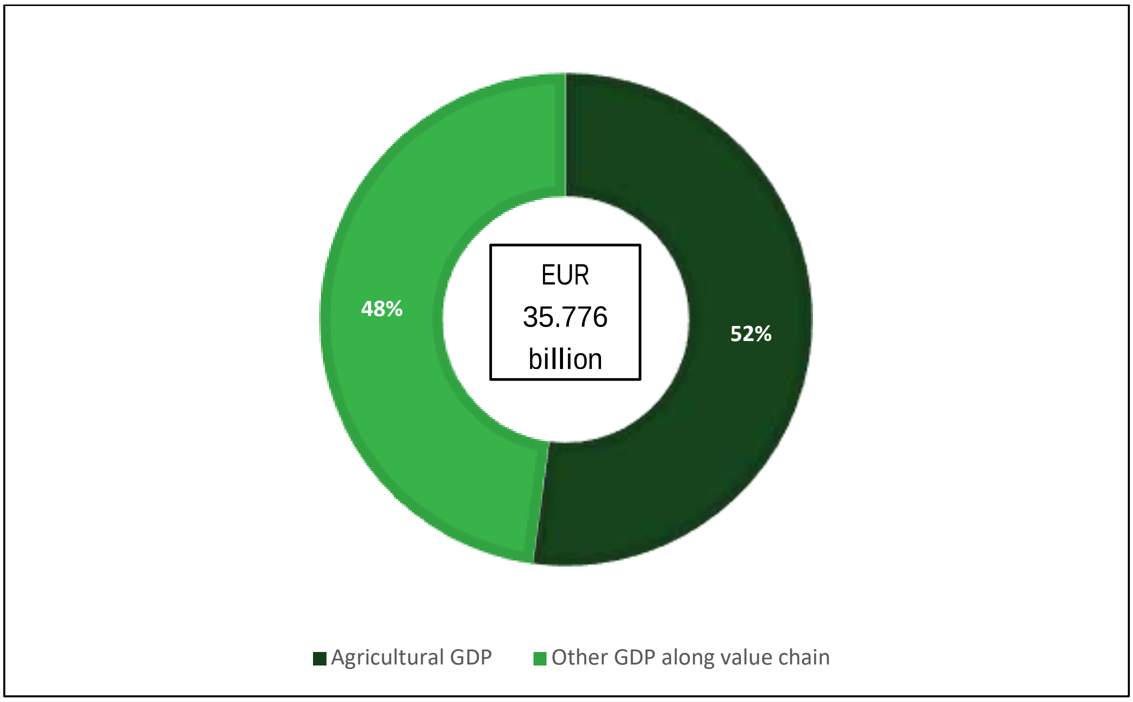
Analysis for the level of the EU in total

According to this exercise, the overall GDP impact in 2040 should be valued almost EUR 36 billion for the EU in total. Its overall composition – consisting of the sectoral (agricultural) effect and the effect belonging to sectors upstream and downstream the agricultural value chain – is subsequently presented with figure 3.50. This can be compared to the entire GDP of a country like Latvia (IMF, 2020).

As in the case of the analysis with respect to the sectoral income, a comparison of the GDP effects of an enforcement of the "Farm to Fork" and "Biodiversity" strategies with the impacts of future plant breeding progress at current pace leads to the conclusion, that genetic crop improvements have the potential to partly compensate the negative GDP impact of the two strategies until 2030 and to overcompensate this impact until 2040. This becomes obvious by looking at figure 3.51. The following can be highlighted with respect to partial effects:

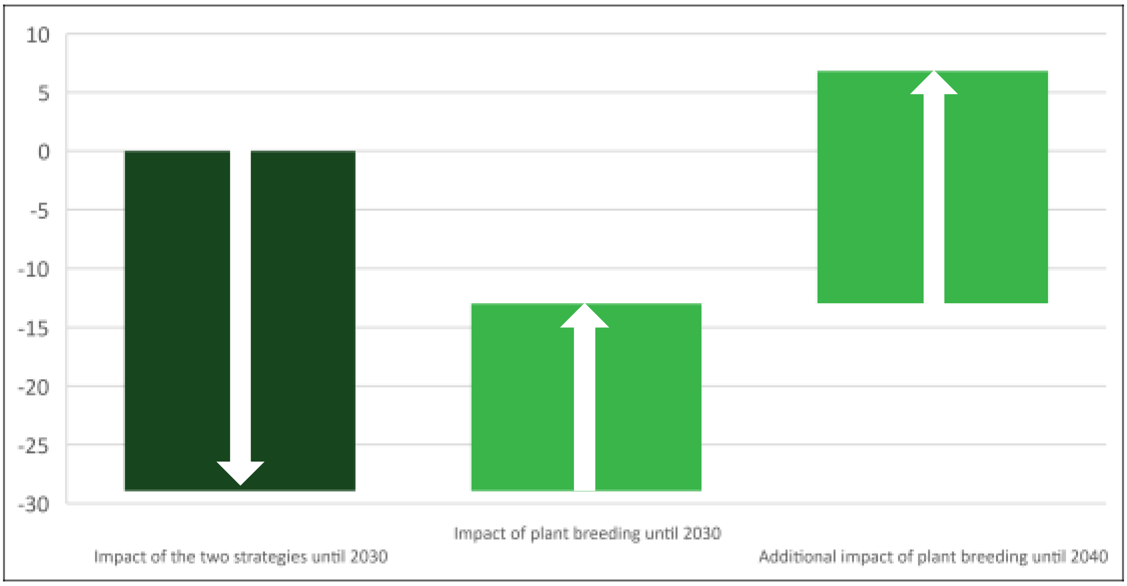
- The full implementation of the two strategies – as defined above – would lead to a GDP loss of almost EUR 29 billion.
- Plant breeding progress until 2030 has the potential to (more than) halve this loss since almost EUR 16 billion could be added to GDP.
- In 2040, the loss attributable to the two strategies would potentially be overcompensated by almost EUR 7 billion due to plant breeding in the next two decades.

Figure 3.50: Level and composition of the additional GDP attributable to major arable crops in 2040 with plant breeding progress between 2020 and 2039 in the EU



Source: Own calculations and figure.

Figure 3.51: Comparing and balancing GDP effects of the two strategies with plant breeding progress until 2040 in the EU (in billion EUR)

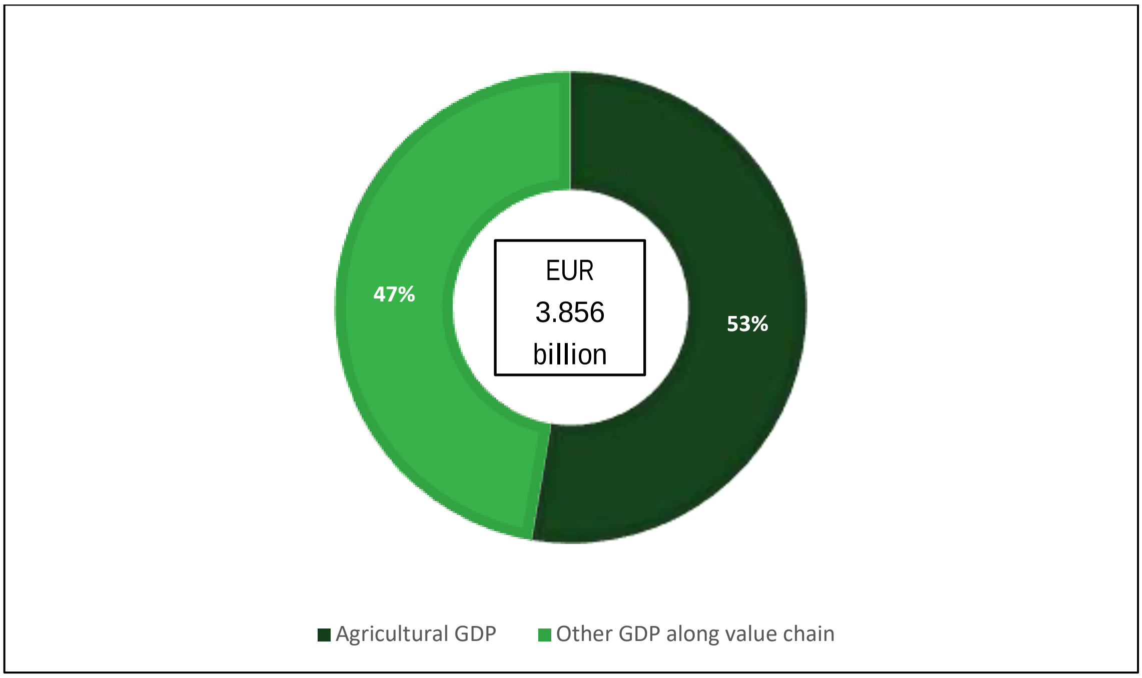


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Germany

For Germany, the impact of plant breeding progress between 2020 and 2039 on the overall GDP in the year 2040 should be seen in the range of approximately EUR 3.9 billion as figure 3.52 describes.

Figure 3.52: Level and composition of the additional GDP attributable to major arable crops in 2040 with plant breeding progress between 2020 and 2039 in Germany



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of France

The corresponding overall impact of plant breeding progress between 2020 and 2039 on the GDP of France in 2040 should be expected to be in the range of EUR 7.0 billion as figure 3.53 visualizes.

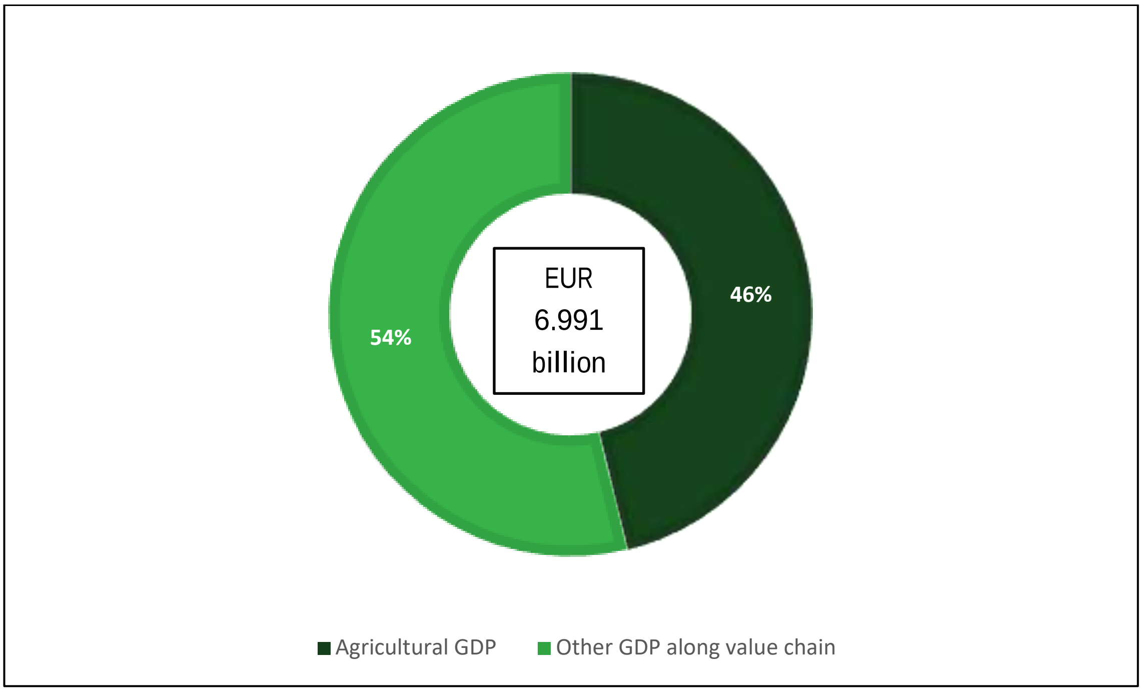
Analysis for the level of EU member states – the case of Italy

In Italy, the overall impact of plant breeding progress between 2020 and 2039 on the GDP in 2040 will be around EUR 1.3 billion. The outcome for this specific EU member state is depicted in figure 3.54.

Analysis for the level of EU member states – the case of Spain

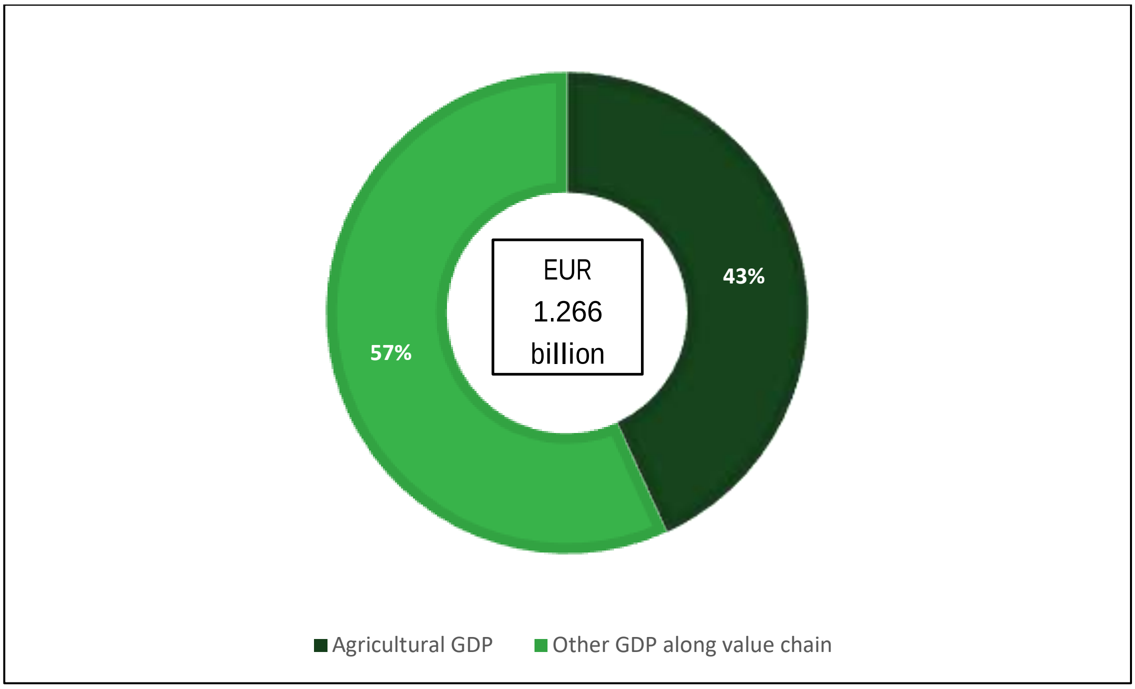
The overall impact of plant breeding progress in the next two decades on the generation of overall GDP in 2040 of Spain should be considered in the range of almost EUR 1.4 billion as figure 3.55 visualizes.

Figure 3.53: Level and composition of the additional GDP attributable to major arable crops in 2040 with plant breeding progress between 2020 and 2039 in France



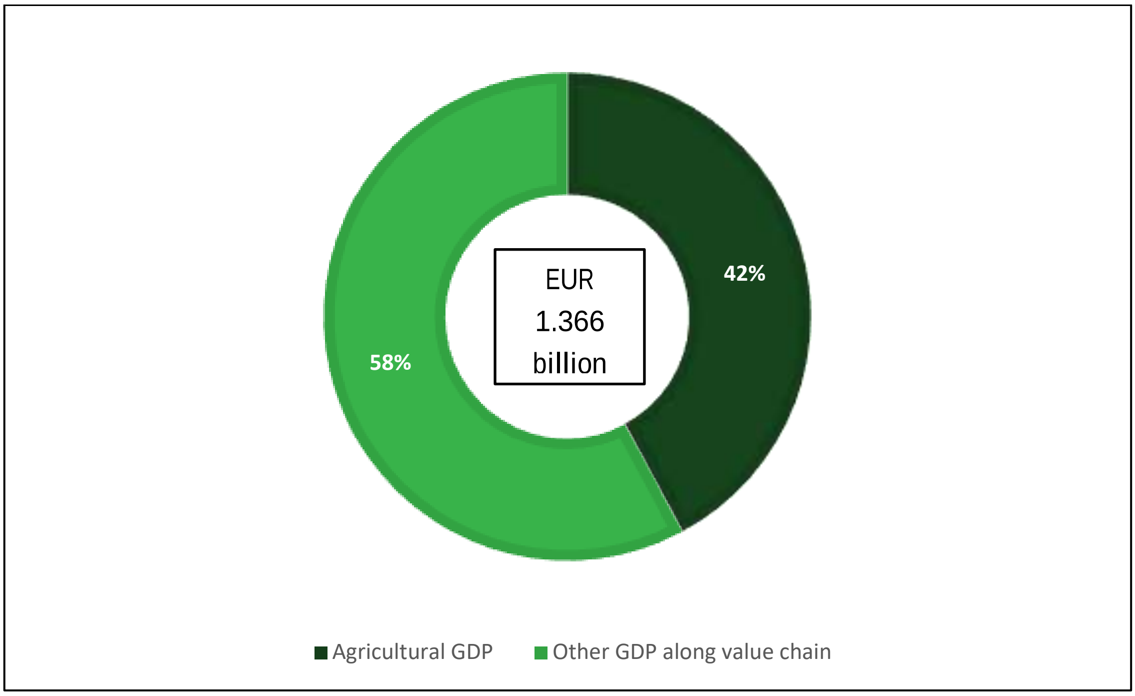
Source: Own calculations and figure.

Figure 3.54: Level and composition of the additional GDP attributable to major arable crops in 2040 with plant breeding progress between 2020 and 2039 in Italy



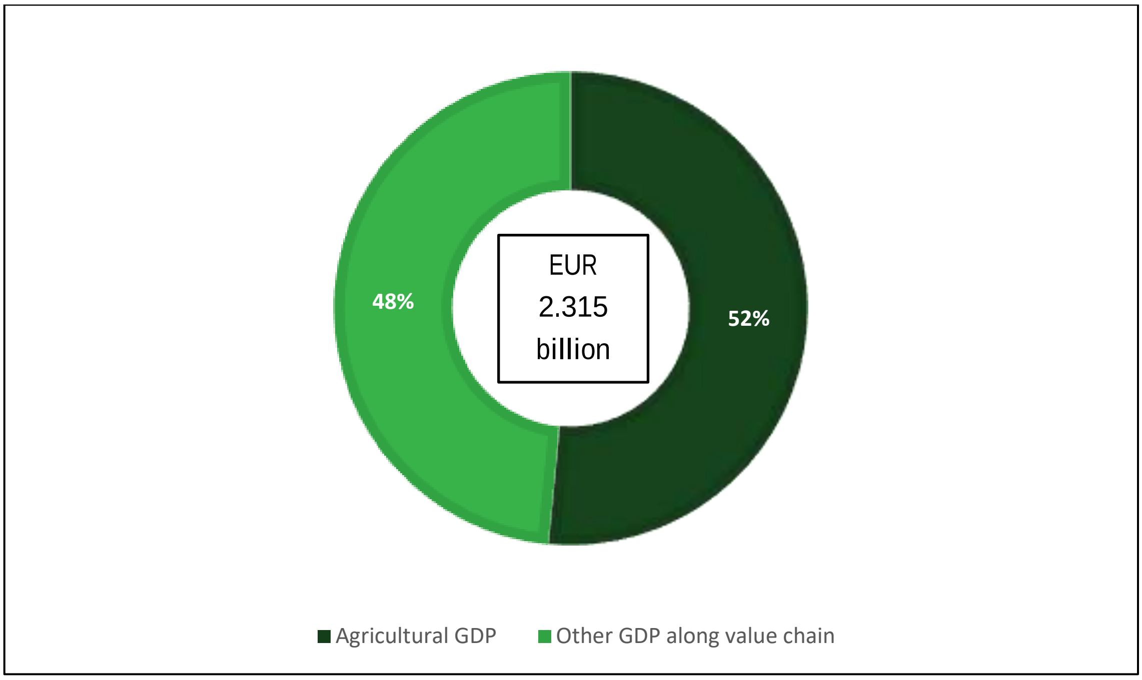
Source: Own calculations and figure.

Figure 3.55: Level and composition of the additional GDP attributable to major arable crops in 2040 with plant breeding progress between 2020 and 2039 in Spain



Source: Own calculations and figure.

Figure 3.56: Level and composition of the additional GDP attributable to major arable crops in 2040 with plant breeding progress between 2020 and 2039 in the UK



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of the UK

Finally, the impact for the UK shall be visualized with the above figure 3.56. For the country, the impact of plant breeding progress between 2020 and 2039 on the GDP in 2040 should be seen in the range of EUR 2.3 billion.

Farm income

Overview on the impacts by EU region and crop

In the context of socio-economic effects of plant breeding, the farm income effect of future genetic crop improvements shall be analysed for labour directly engaged in arable farming and cultivating the crops under consideration. Such crop-specific activities comprise tillage, sowing and drilling, monitoring, applying fertilizers, irrigation, pest management, harvesting, transport of primary and secondary products from the field, and other area-related management efforts.

For calculating the farm income effect, information from EC (2019a) is again used as a basis. However, the data refer to the current situation and must be adjusted to properly simulate the situation in 2040. Production and price changes resulting from the basic scenario in accordance with subchapter 3.1 and, in addition, from implementing the "Farm to Fork" and "Biodiversity" strategies of the EU are considered, but potentially changing governmental transfers are not taken into account. In addition, it is assumed that revenue-cost ratios remain stable, i.e., that structural input-output changes do not materialize in upcoming years. The subsequent results for the 2040 scenario are as displayed in figure 3.57. Annex N provides similar information for the other chosen time horizon, i.e., until 2030.

Figure 3.57: Potential farm income of arable farms in 2040 and income induced by plant breeding progress between 2020 and 2039 in the EU and selected member states (in EUR/AWU)

Indicator/Region	EU	DE	FR	IT	ES	UK
Farm income	19 367	42 440	28 286	23 416	23 309	40 412
Income induced by plant breeding	9 364	11 758	16 017	3 743	2 079	26 681
Other farm income	10 003	30 682	12 270	19 673	21 231	13 731

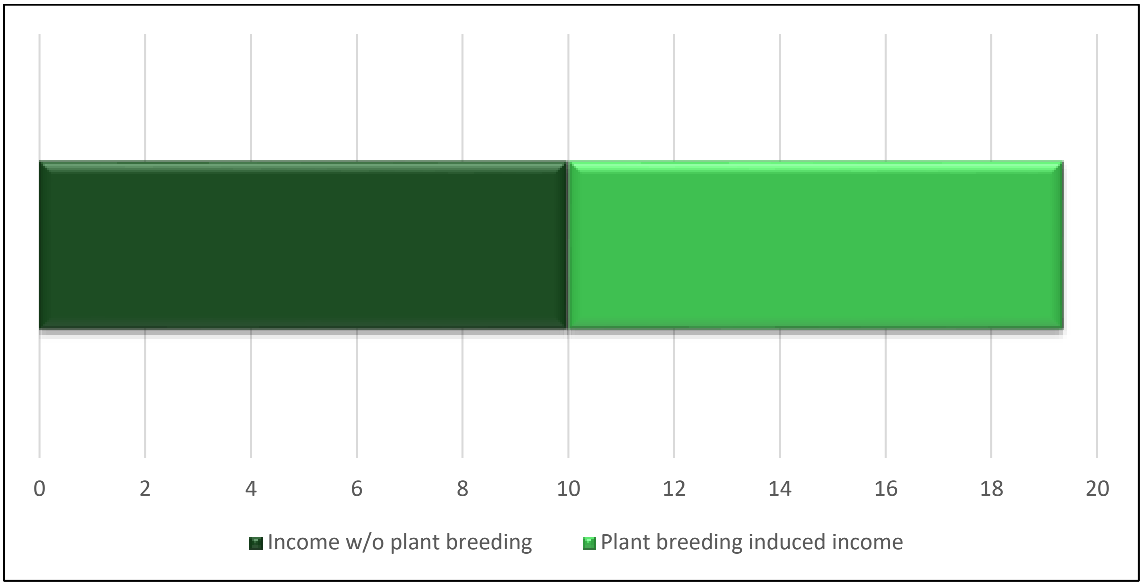
Source: Own calculations and figure.

In general, it becomes apparent that the potential future farm income induced by plant breeding will be substantial. Hence, it can be concluded that without the potential achievements of plant breeding between 2020 and 2039 much more state transfers or additional efficiency gains would be needed by 2040 to compensate for farm income losses.

Analysis for the level of the EU in total

As figure 3.58 depicts, an AWU in EU arable farming will generate an income – again expressed in terms of FNVA – of around EUR 19 400 in 2040. Without the market revenue added by plant breeding between 2020 and 2039, this income in 2040 would shrink by approximately EUR 9 300. In other words: The income of an average arable farm in the EU would decrease by almost 50 percent in 2040 if plant breeding stopped right now.

Figure 3.58: Potential farm income of arable farms in 2040 and income induced by plant breeding progress between 2020 and 2039 in the EU (in thousand EUR/AWU)



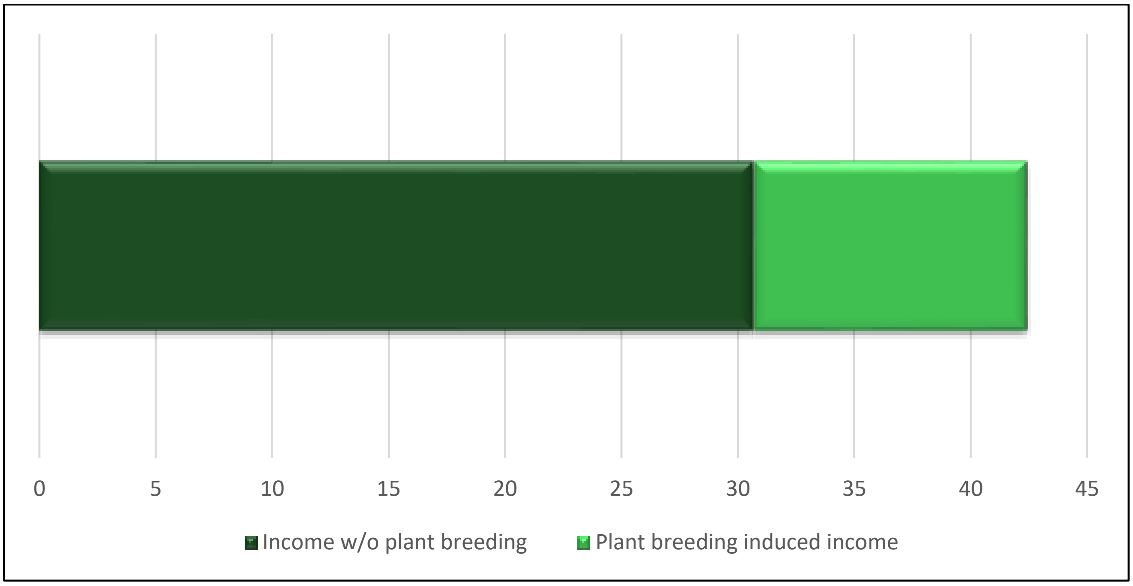
Source: Own calculations and figure.

Comparing this impact at EU level with the effects of the "Farm to Fork" and "Biodiversity" strategies is a challenge as it would require to also consider transfer payments. In fact, a full implementation of the two strategies in a rather short time (until 2030) – as defined above – would require major farm adjustments. The attributable costs – in terms of investments, for instance for using alternative plant protection management approaches, and opportunity costs such as market revenue losses due to setting-aside for non-productive land – are always site-specific, but most likely cannot instantly be covered by many farmers. State support schemes will certainly be needed. Against this background, it is very vague and highly speculative, or in other words: very uncertain, to assume what this could mean for future transfer payments and, hence, farm income. A comparison of the aforementioned effects is therefore not provided at this stage of the analysis. Based on theory of agricultural economics, a working hypothesis, however, is that future plant breeding would also be able to compensate for potential farm income losses that might be attributable to the enforcement of the two strategies.

Analysis for the level of EU member states – the case of Germany

Figure 3.59 depicts the future situation for Germany. Accordingly, it can be stated that an AWU engaged in arable farming of Germany will potentially generate an income of more than EUR 42 400 in 2040. Without the market revenue that will be received due to plant breeding progress between 2020 and 2039, this income would shrink by approximately EUR 11 700. In other words: The income of an average arable farm in Germany without plant breeding progresses in the next two decades would shrink by more than a quarter.

Figure 3.59: Potential farm income of arable farms in 2040 and income induced by plant breeding progress between 2020 and 2039 in Germany (in thousand EUR/AWU)



Source: Own calculations and figure.

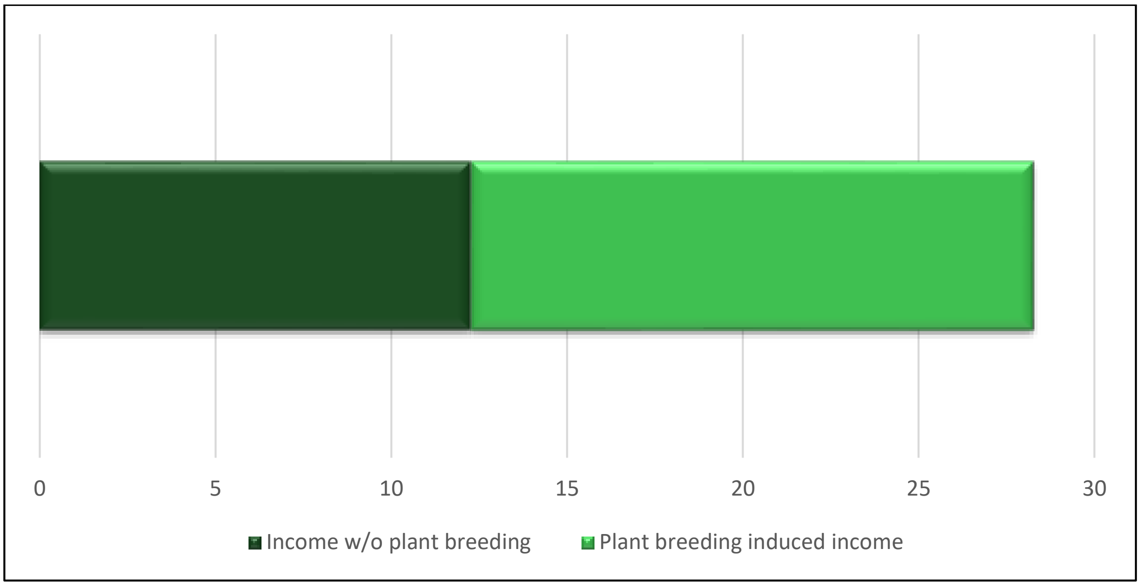
Analysis for the level of EU member states – the case of France

Looking at the case of France, it can be highlighted with figure 3.60 that an AWU engaged in arable farming will potentially generate an income of more than EUR 28 300 in 2040. Without the market revenue generated due to plant breeding progress in the next two decades, this income would shrink by more than EUR 16 000. In other words: The income of an average arable farm in France – without plant breeding achievements between 2020 and 2039 – would shrink by more than 50 percent.

Analysis for the level of EU member states – the case of Italy

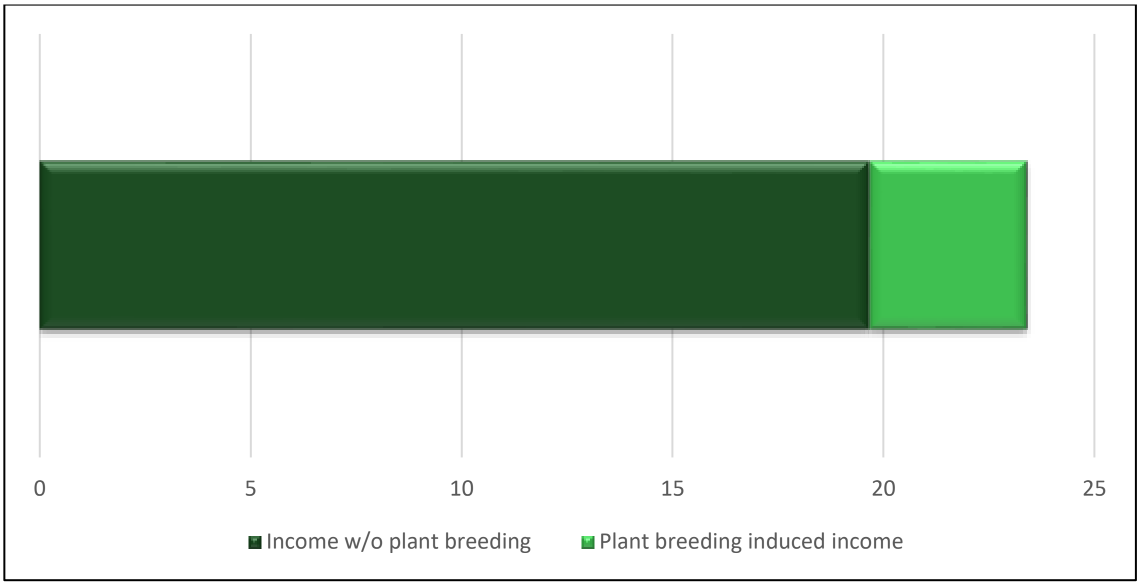
Figure 3.61 displays the potential situation for Italy. Accordingly, it can be stated that an AWU engaged in arable farming will probably generate an income of more than EUR 23 000 in 2040. Without the market revenue that can be received due to plant breeding between 2020 and 2039, this income would shrink by approximately EUR 3 700. Hence, the income of an average arable farm in Italy without plant breeding progress in the next two decades would shrink by more than a sixth.

Figure 3.60: Potential farm income of arable farms in 2040 and income induced by plant breeding progress between 2020 and 2039 in France (in thousand EUR/AWU)



Source: Own calculations and figure.

Figure 3.61: Potential farm income of arable farms in 2040 and income induced by plant breeding progress between 2020 and 2039 in Italy (in thousand EUR/AWU)

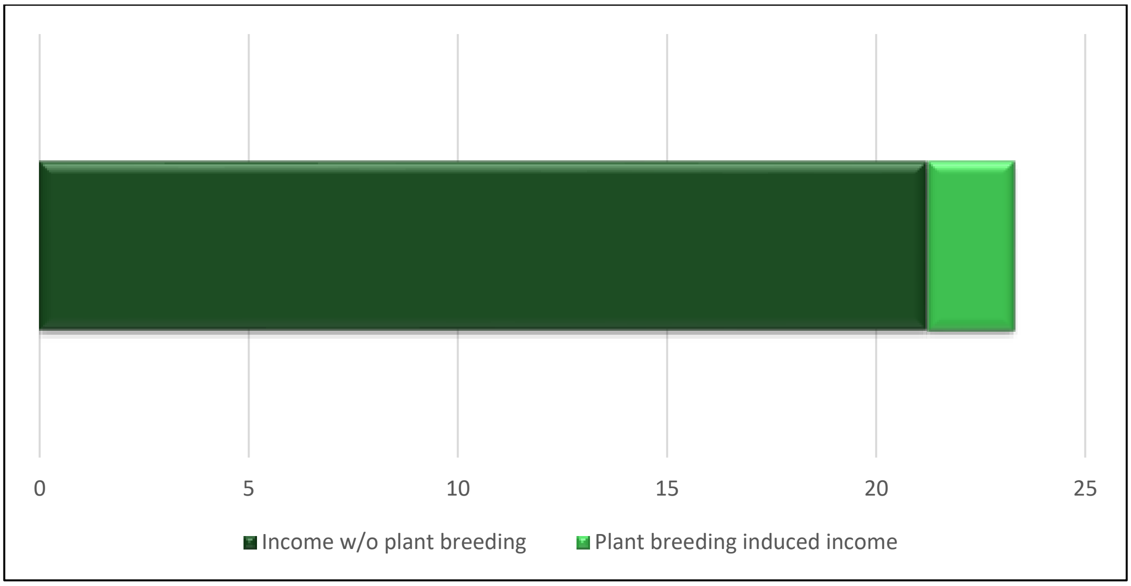


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Spain

Looking at the case of Spain, it can be highlighted with figure 3.62 that an AWU engaged in arable farming will potentially generate an income of more than EUR 23 000. Without the market revenue that will be created because of plant breeding between 2020 and 2039, this income would shrink by about EUR 2 100. In other words, it can be argued that the income of an average arable farm in Spain in 2040 without future plant breeding achievements in the next two decades would shrink by approximately ten percent.

Figure 3.62: Potential farm income of arable farms in 2040 and income induced by plant breeding progress between 2020 and 2039 in Spain (in thousand EUR/AWU)



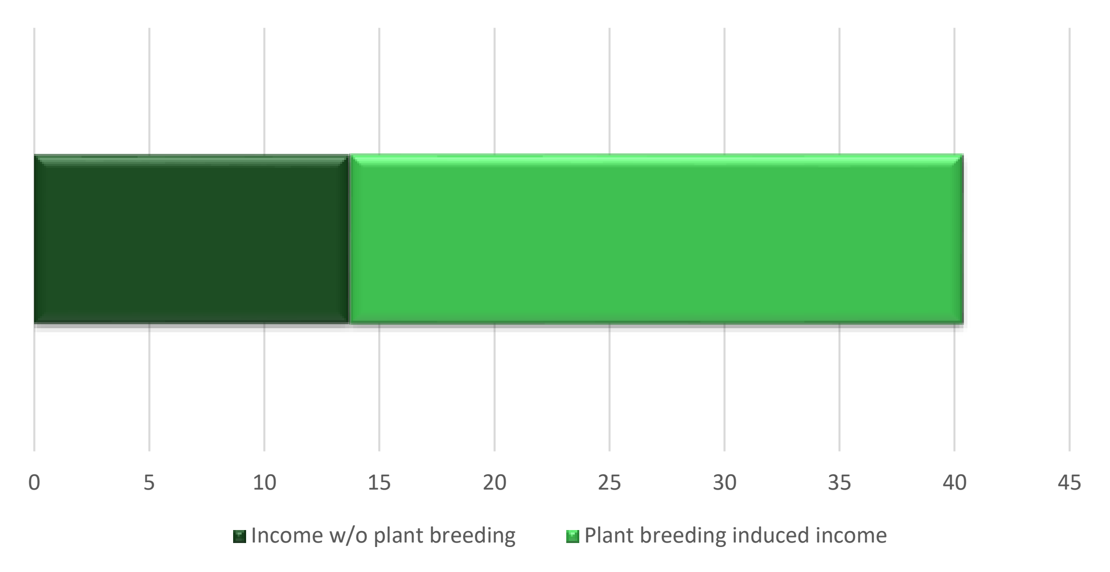
Source: Own calculations and figure.

Analysis for the level of EU member states – the case of the UK

Figure 3.63 finally depicts the potential situation for the UK. Accordingly, it can be stated that an AWU engaged in arable farming of the UK will generate an income of more than EUR 40 000 in 2040. Without the market revenue that will possibly be secured due to plant breeding progress between 2020 and 2039, this income would shrink by approximately EUR 26 600.

This should be considered a huge impact as it would mean to basically expect a farm income decrease by two thirds if plant breeding progress was missing in the next two decades in the former EU member state.

Figure 3.63: Potential farm income of arable farms in 2040 and income induced by plant breeding progress between 2020 and 2039 in the UK (in thousand EUR/AWU)



Source: Own calculations and figure.

Farm and other labour

Overview on the impacts by EU region and crop

Of course, farmers will also try to adapt to this potentially worsening income situation in future. Some would stop working, other would partly move to other income generating options and switch to part-time working in arable farming. The resulting labour effect can be calculated. It is displayed in figure 3.64 per crop and EU region being in the focus of this study. Annex O provides similar information for the other chosen time horizon, i.e., until 2030.

Analysis for the level of the EU in total

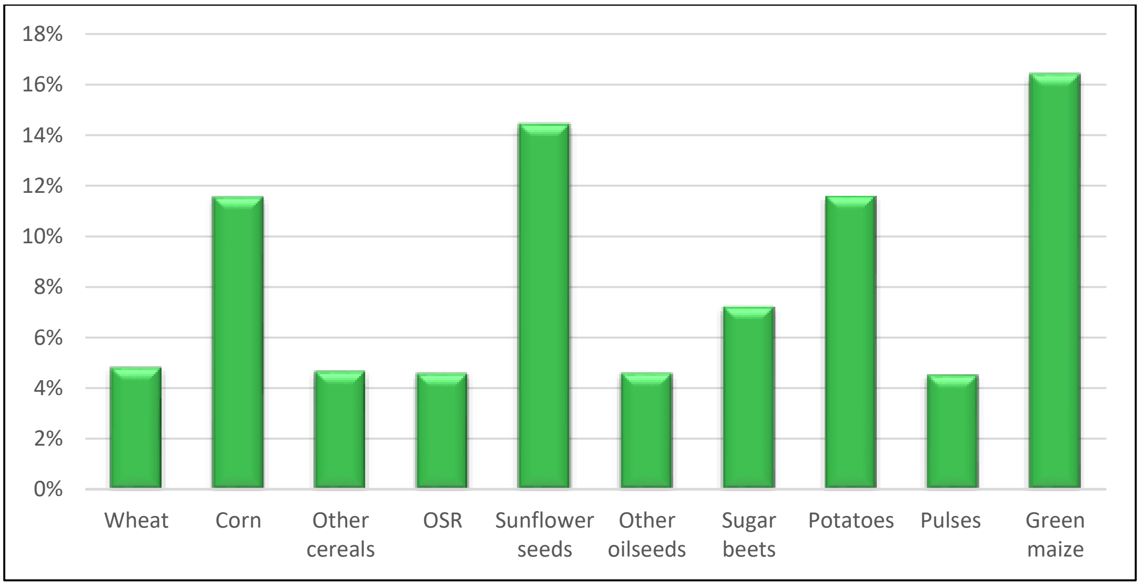
Figure 3.65 displays the effects on labour that will be engaged in arable farming in 2040 for the case of missing plant breeding innovation between 2020 and 2039 in the EU in total. Weighting by acreage, the total effect amounts to 7.1 percent of all labour employed in EU arable farming by then. Assuming an annual increase in labour productivity of 1.0 percent from now on, this would imply that without plant breeding in the next two decades paid or unpaid labour force in arable farming of the EU equal to almost 90 000 AWU would be endangered by 2040. Using once more sophisticated multiplier analysis (see, again annex D) also allows to calculate the overall labour effect and leads to the conclusion that more than 870 000 jobs in storing, processing, packaging, internationally trading and retailing along the value chains would additionally suffer from income losses or unemployment in the EU in total by 2040 if plant breeding progress in the next two decades stopped.

Figure 3.64: Potential farm labour losses attributable to major arable crops in 2040 without plant breeding progress between 2020 and 2039 in the EU and selected member states (in percent)

Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	4.8	3.1	3.5	5.3	2.9	4.3
Corn	11.6	8.8	8.4	5.1	8.7	8.2
Other cereals	4.7	4.4	3.4	3.5	1.6	4.1
OSR	4.6	3.8	7.0	20.6	8.1	8.7
Sunflower seeds	14.5	6.3	7.4	5.0	4.8	N.A.
Other oilseeds	4.6	15.1	6.2	1.6	4.6	19.7
Raw sugar	7.2	6.6	7.5	6.5	6.1	8.1
Potatoes	11.6	5.7	5.6	6.0	6.6	7.2
Pulses	4.5	5.4	5.9	6.9	7.5	5.0
Green maize	16.4	8.5	16.1	3.8	19.6	18.1

Source: Own calculations and figure.

Figure 3.65: Potential farm labour losses attributable to major arable crops in 2040 without plant breeding progress between 2020 and 2039 in the EU



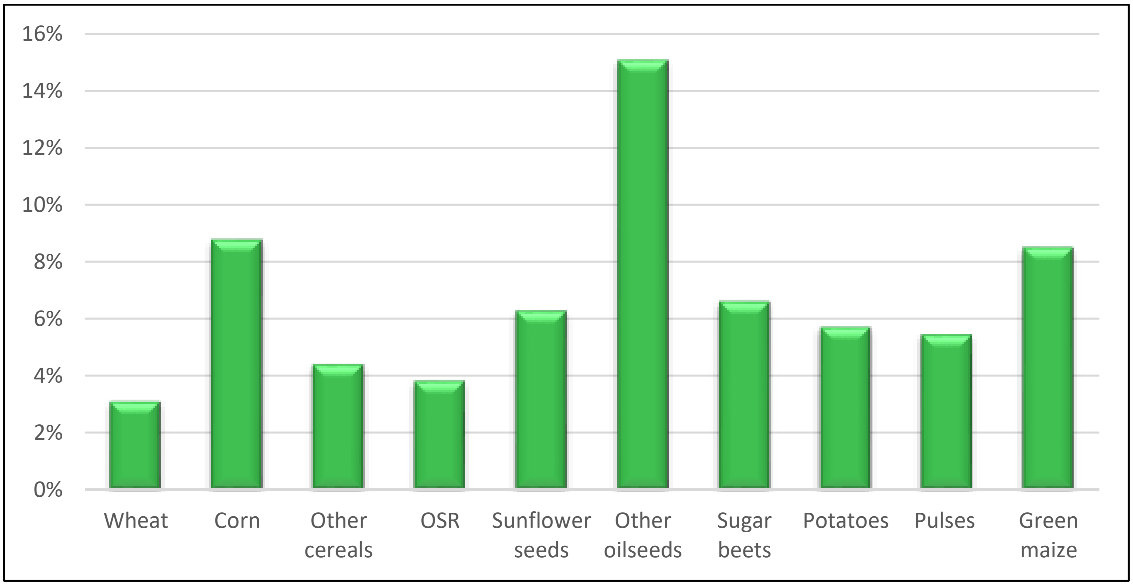
Source: Own calculations and figure.

Comparing this labour market impact at EU level with the effects of the "Farm to Fork" and "Biodiversity" strategies is again a challenge as it would require defining the workload that must be associated with non-productive land, which alone counts for 10 percent of the production effect. Even if this land is non-productive, it does not mean that it will not be cultivated. Flowering strips, managed fallow and other "cultivation" approaches may be substitutes for wheat, corn etc. It is beyond the scope of this study to assess the resulting impacts on farmers' workload. Against this background, it is also here very vague and highly speculative, i.e., very uncertain, to assume what this could mean for future labour engaged on farm. A comparison of the afore-mentioned effects is therefore not provided at this stage of the analysis. However, based on theory of agricultural economics, a working hypothesis can be formulated: Future plant breeding would most probably be able to compensate for potential farm labour losses that might be attributable to the enforcement of the two strategies.

Analysis for the level of EU member states – the case of Germany

Figure 3.66 displays the equivalent impacts of plant breeding on labour for German arable farming in 2040. In Germany, the hectare-weighted average impact of missing plant breeding achievements between 2020 and 2039 would be a decrease in specific labour of 5.3 percent. This would correspond to a loss of more than 5 500 AWU in arable farming and an endangered additional workforce of more than 41 000 AWU along the various agricultural as well as food value chains in this EU member state.

Figure 3.66: Potential farm labour losses attributable to major arable crops in 2040 without plant breeding progress between 2020 and 2039 in Germany

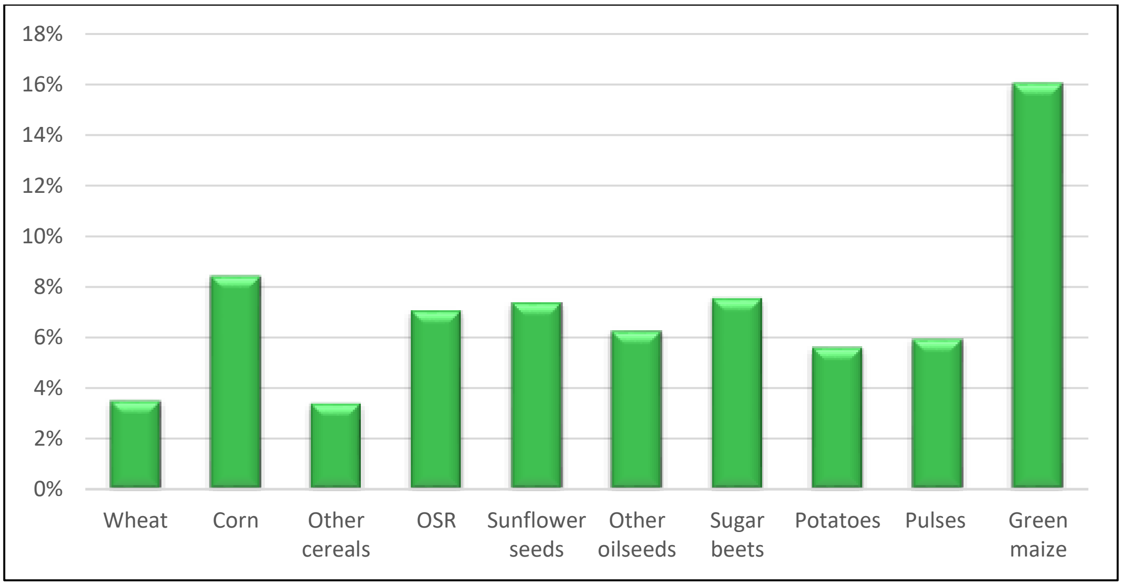


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of France

Looking at figure 3.67, it turns out that also France would experience substantial losses of labour engaged in arable farming by 2040 if plant breeding terminated today. The hectare-weighted average – labour decreasing – impact would be around 6.1 percent. This would correspond to a loss of almost 7 700 AWU in arable farming of the country and an endangered additional workforce of more than 58 000 AWU along the various agricultural as well as food value chains in France.

Figure 3.67: Potential farm labour losses attributable to major arable crops in 2040 without plant breeding progress between 2020 and 2039 in France



Source: Own calculations and figure.

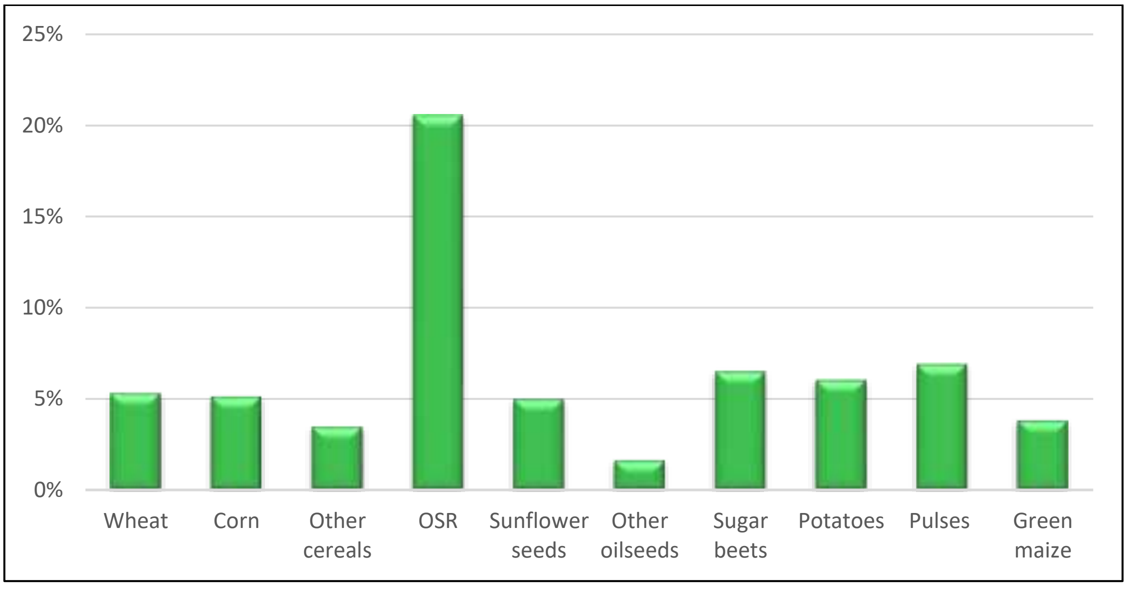
Analysis for the level of EU member states – the case of Italy

Figure 3.68 displays the impacts of plant breeding on labour in arable farming in 2040 for Italy and indicates that also in this EU member state remarkable losses would occur in the absence of plant breeding progress between 2020 and 2039. In Italy, the hectare-weighted average impact would be around 4.7 percent. This would correspond to a loss of almost 5 000 AWU in arable farming and an endangered additional workforce of approximately 42 000 AWU along the various agricultural as well as food value chains in the country.

Analysis for the level of EU member states – the case of Spain

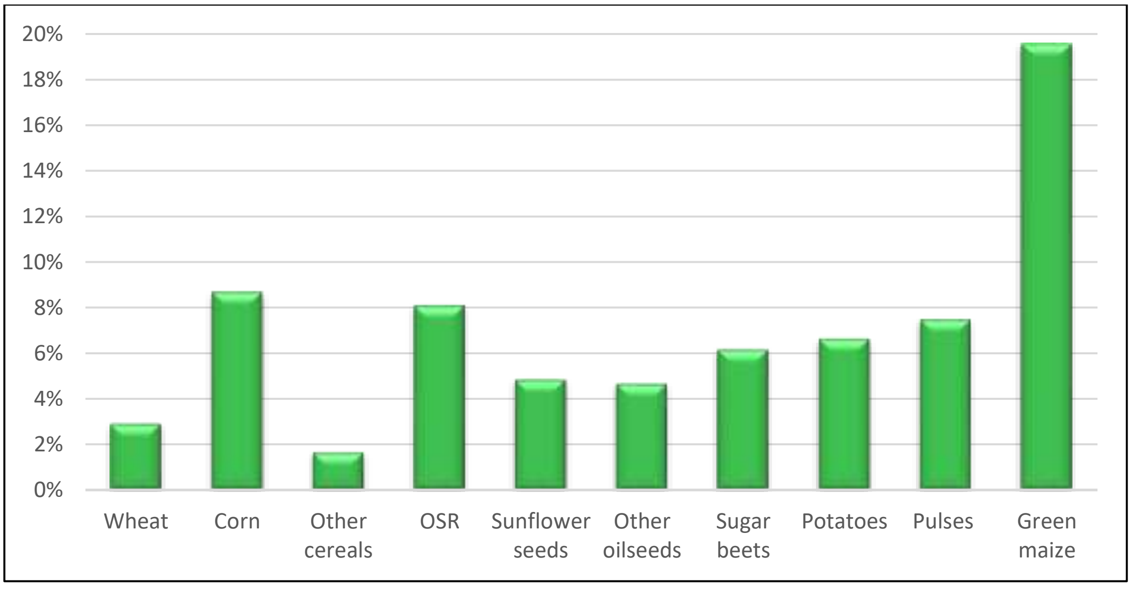
Figure 3.69 shows the results for arable farming in Spain. Weighted by hectare, labour in arable farming in 2040 would be 3.4 percent lower if plant breeding progress in the next two decades was missing. This would correspond to a loss of almost 2 400 AWU, and in addition to that more than 23 000 AWU would be endangered along the various value chains in Spain.

Figure 3.68: Potential farm labour losses attributable to major arable crops in 2040 without plant breeding progress between 2020 and 2039 in Italy



Source: Own calculations and figure.

Figure 3.69: Potential farm labour losses attributable to major arable crops in 2040 without plant breeding progress between 2020 and 2039 in Spain

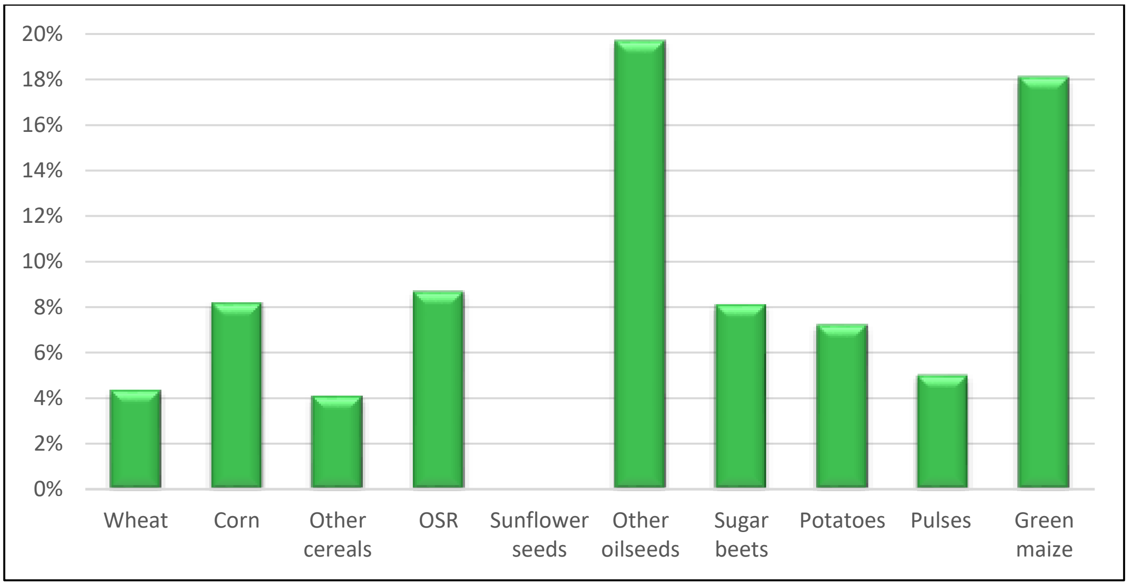


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of the UK

Finally, a look at figure 3.70. It displays the impacts an absence of plant breeding between 2020 and 2039 would have on labour in arable farming in the UK. The hectare-weighted average impact would amount to a decrease in labour of 5.8 percent. This would correspond to a loss of almost 2 000 AWU, and in addition to that more than 15 000 AWU would be endangered along the agricultural and food value chains in the UK.

Figure 3.70: Potential farm labour losses attributable to major arable crops in 2040 without plant breeding progress between 2020 and 2039 in the UK



Source: Own calculations and figure.

3.4 Future environmental effects

Before the tertiary environmental effects are also discussed for the future scenarios in more detail, it shall be repeated that the methodology to derive the various results particularly uses again the models and tools of environmental economics described in annex E[55].

Virtual land trade

Overview on the impacts by EU region and crop

Obviously, a missing of plant breeding activities from now would also reduce the EU-extra exports and increase the EU-extra imports in future (see, again, figure 3.24). This, subsequently, implies a change of the balance of EU net imports of virtual agricultural land. The resulting potentially avoided

55 In addition, an increase of 1.0 percent per annum in global resource use efficiency is implemented.

net virtual land trade in 2040 that can be attributed to the EU in total as well as the selected member states due to successful plant breeding between 2020 and 2039 is visualized in figure 3.71, while annex P provides similar information for the other chosen time horizon, i.e., until 2030 with plant breeding progress between 2020 and 2029.

Figure 3.71: Potentially avoided net virtual land imports attributable to major arable crops in 2040 with plant breeding progress between 2020 and 2039 in the EU and selected member states (in million hectares)

Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	6.824	0.712	1.297	0.274	0.161	0.641
Corn	2.634	0.124	0.412	0.123	0.134	0.001
Other cereals	4.253	0.649	0.481	0.145	0.142	0.289
OSR	3.017	0.520	1.116	0.023	0.040	0.624
Sunflower seeds	2.316	0.004	0.168	0.023	0.070	N.A.
Other oilseeds	0.061	0.003	0.008	0.008	0.001	0.002
Raw sugar	0.356	0.074	0.121	0.006	0.009	0.025
Potatoes	0.162	0.015	0.011	0.002	0.004	0.010
Pulses	0.265	0.043	0.063	0.014	0.038	0.053

Source: Own calculations and figure.

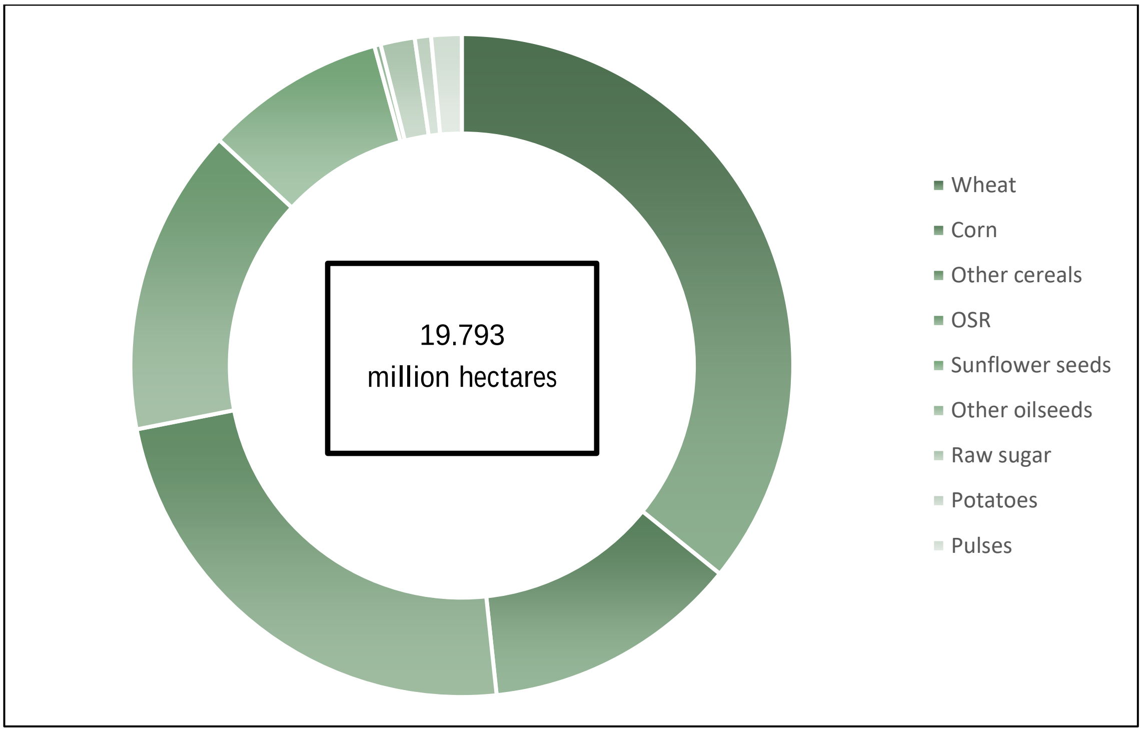
Analysis for the level of the EU in total

Looking at figure 3.72, it can be stated that almost 20 million hectares of arable land would globally be needed in 2040 in addition to what would most likely be used at that time if plant breeding in the EU terminated in 2020.

The regional distribution of these additional EU net imports of virtual agricultural land around the globe in the absence of plant breeding from now on is listed in figure 3.73. Accordingly, more than 5.1 million hectares would come from the CIS, and the MENA region would contribute almost 3.2 million hectares. Almost 2.8 million hectares would need to be additionally occupied in Asia, while more than 2.0 million hectares would be located each in North America, Sub-Sahara Africa, and Oceania. South America would need to contribute almost 1.7 million additional hectares, and the Rest of the World (RoW) would add more than 0.4 million hectares.

The net virtual land trade effect of future plant breeding efforts in the EU can again be compared to the specific impact which would result from a full implementation of the "Farm to Fork" and "Biodiversity" strategies. Figure 3.74 shows the result and firstly indicates that the partial effect of the strategies would be to use more land abroad to satisfy domestic demand in the EU with production losses here due to the strategies. However, figure 3.73 secondly signals that this negative environmental effect can be overcompensated in part due to plant breeding in the next decade and fully with plant breeding progress between 2020 and 2039. The net effect of the two partial future developments, if added, would indicate a land saving of approximately 2.0 million hectares at global scale.

Figure 3.72: Potentially avoided net virtual land imports in 2040 with plant breeding progress between 2020 and 2039 in the EU, by crop



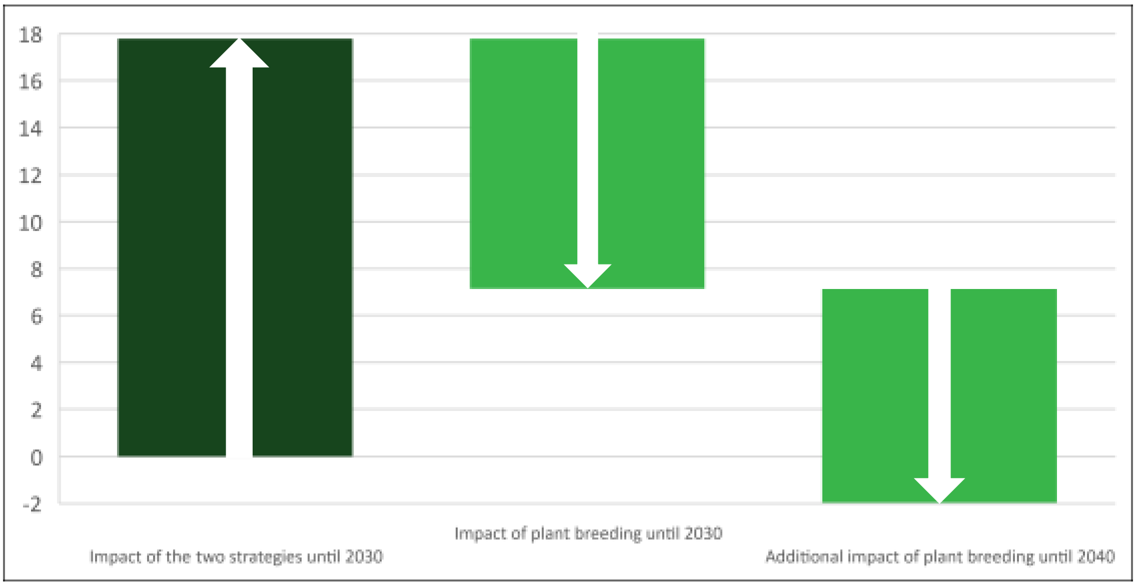
Source: Own calculations and figure.

Figure 3.73: Potentially avoided net virtual land imports in 2040 with plant breeding progress between 2020 and 2039 in the EU, by region (in million hectares)

Region	Value	Region	Value
North America	2.118	Sub-Sahara Africa	2.073
South America	1.680	Oceania	2.381
Asia	2.770	CIS	5.173
MENA	3.156	RoW	0.442

Source: Own calculations and figure.

Figure 3.74: Comparing and balancing partial net virtual land effects of the two strategies with plant breeding progress until 2040 in the EU (in million hectares)



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Germany

Figure 3.75 displays the potentially avoided net virtual land imports of Germany in 2040 due to plant breeding progress between 2020 and 2039 by crop. Accordingly, it can be stated that more than 2.1 million hectares of natural or nature-like habitats across the globe will remain unused for agricultural purposes just by Germany.

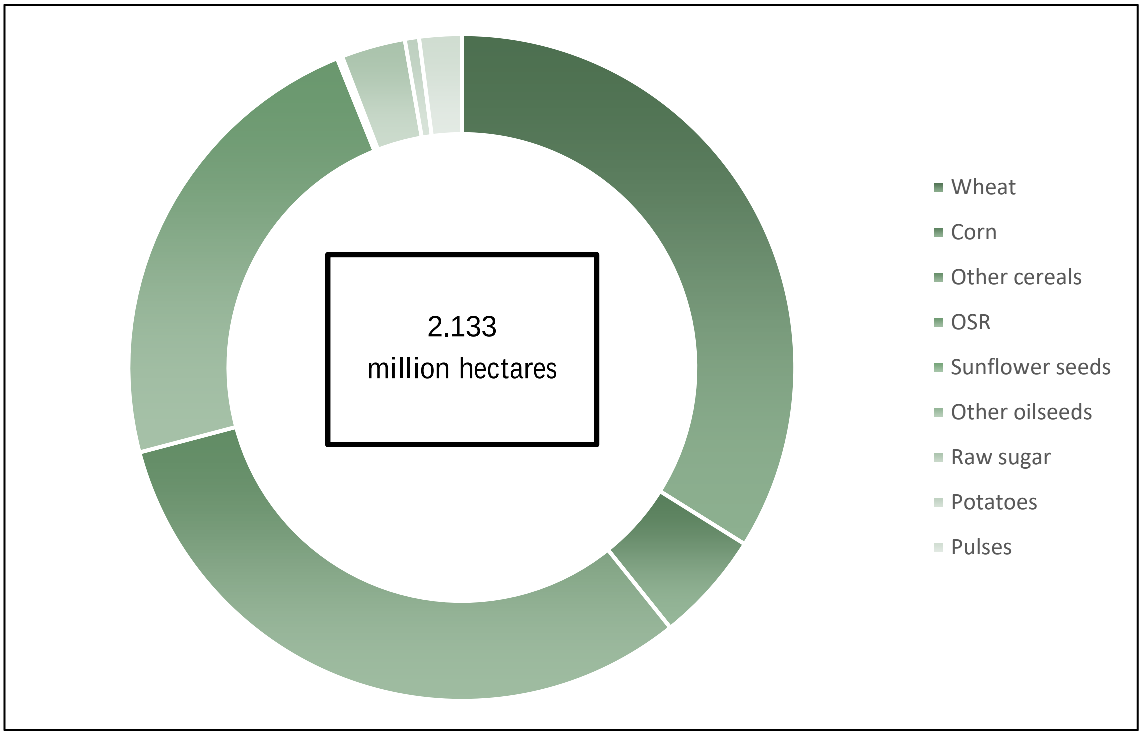
The regional distribution of these German additional net imports of virtual agricultural land by 2040 around the globe in the absence of future plant breeding progress in the country is listed in figure 3.76.

Analysis for the level of EU member states – the case of France

Looking at figure 3.77, it can be stated that the potentially avoided net virtual land imports of France in 2040 due to plant breeding progress in the next two decades are higher than 3.6 million hectares. This is the amount of natural or nature-like habitats across the globe that will remain unused for agricultural purposes due to future plant breeders' innovations in this EU member state.

The regional distribution of these French additional net imports of virtual agricultural land by 2040 around the globe in the absence of future plant breeding progress in the country is listed in figure 3.78.

Figure 3.75: Potentially avoided net virtual land imports in 2040 with plant breeding progress between 2020 and 2039 in Germany, by crop



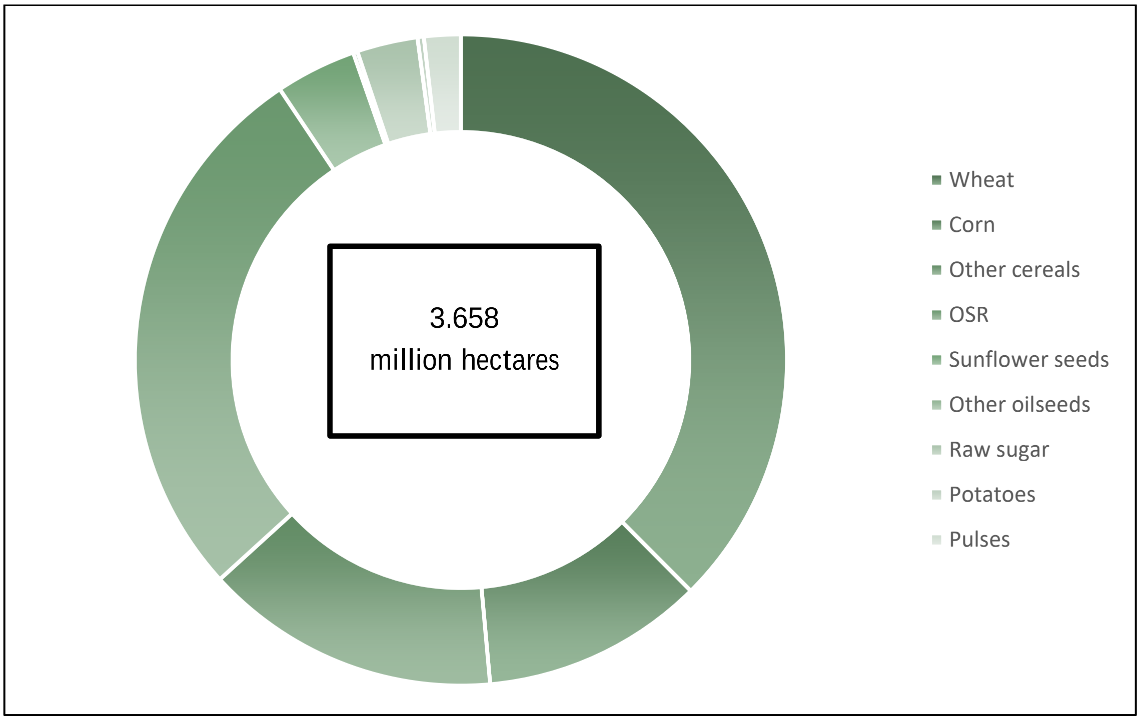
Source: Own calculations and figure.

Figure 3.76: Potentially avoided net virtual land imports in 2040 with plant breeding progress between 2020 and 2039 in Germany, by region (in million hectares)

Region	Value	Region	Value
North America	0.291	Sub-Sahara Africa	0.231
South America	0.171	Oceania	0.367
Asia	0.242	CIS	0.454
MENA	0.367	RoW	0.047

Source: Own calculations and figure.

Figure 3.77: Potentially avoided net virtual land imports in 2040 with plant breeding progress between 2020 and 2039 in France, by crop



Source: Own calculations and figure.

Figure 3.78: Potentially avoided net virtual land imports in 2040 with plant breeding progress between 2020 and 2039 in France, by region (in million hectares)

Region	Value	Region	Value
North America	0.497	Sub-Sahara Africa	0.356
South America	0.261	Oceania	0.547
Asia	0.412	CIS	0.989
MENA	0.518	RoW	0.079

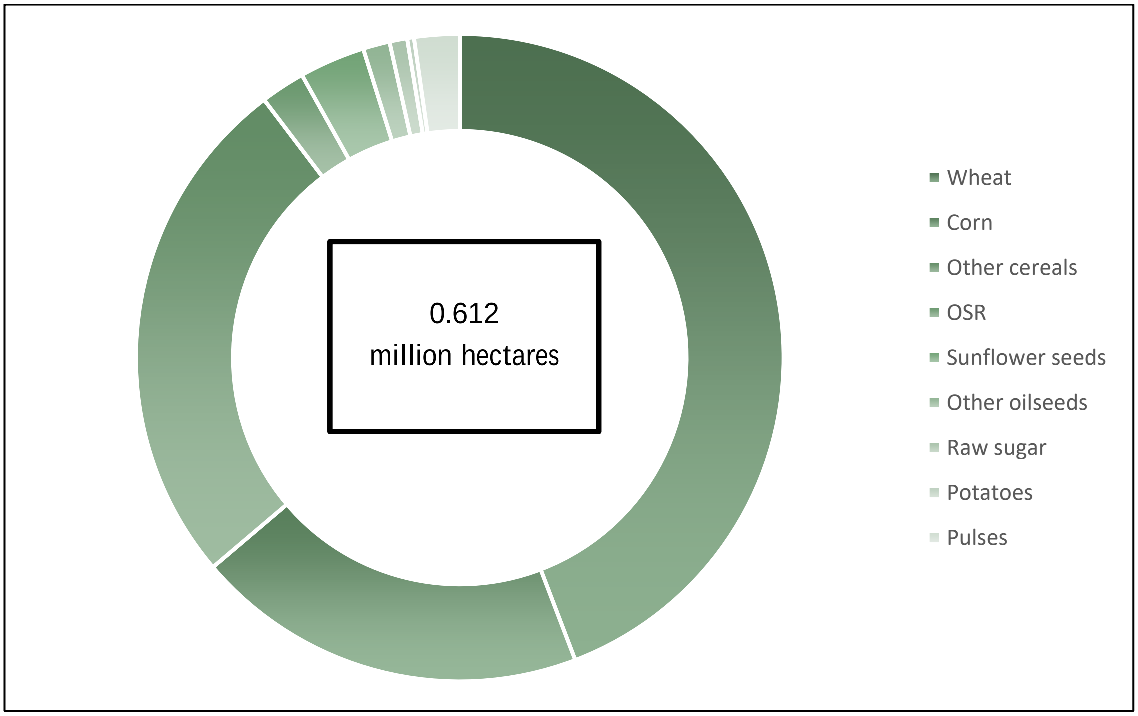
Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Italy

Figure 3.79 visualizes the results for Italy. The avoided net virtual land imports of Italy in 2040 due to plant breeding progress between 2020 and 2039 will be around 600 000 hectares. This is the amount of natural or nature-like habitats across the globe that will not be used for agricultural purposes due to upcoming plant breeders' innovations in Italy.

The regional distribution of these Italian additional net imports of virtual agricultural land by 2040 around the globe in the absence of future plant breeding progress in the country is listed in figure 3.80.

Figure 3.79: Potentially avoided net virtual land imports in 2040 with plant breeding progress between 2020 and 2039 in Italy, by crop



Source: Own calculations and figure.

Figure 3.80: Potentially avoided net virtual land imports in 2040 with plant breeding progress between 2020 and 2039 in Italy, by region (in million hectares)

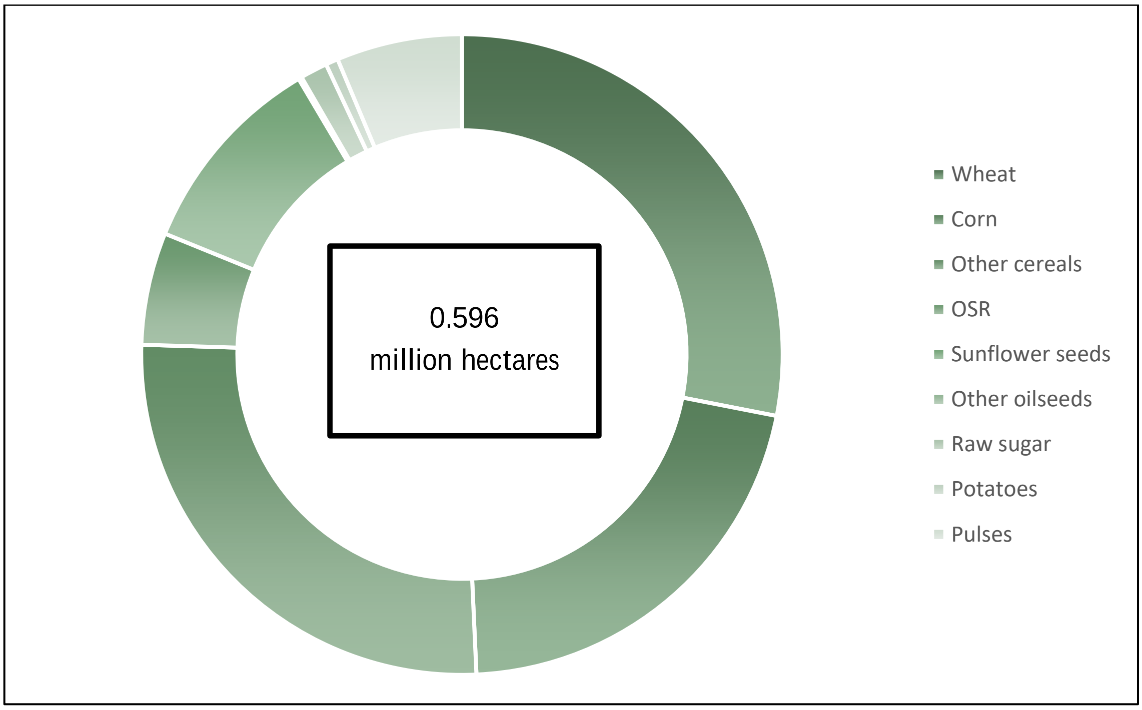
Region	Value	Region	Value
North America	0.055	Sub-Sahara Africa	0.080
South America	0.066	Oceania	0.066
Asia	0.078	CIS	0.140
MENA	0.116	RoW	0.011

Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Spain

Looking at figure 3.81, it can be stated that the avoided net virtual land imports of Spain in 2040 due to plant breeding progress in the next two decades will be around 600 000 hectares. This is the amount of natural or nature-like habitats across the globe that remains unused for agricultural purposes due to future plant breeders' innovations in this EU member state. The regional distribution of these net imports of virtual agricultural land by 2040 around the globe is listed in figure 3.82.

Figure 3.81: Potentially avoided net virtual land imports in 2040 with plant breeding progress between 2020 and 2039 in Spain, by crop



Source: Own calculations and figure.

Figure 3.82: Potentially avoided net virtual land imports in 2040 with plant breeding progress between 2020 and 2039 in Spain, by region (in million hectares)

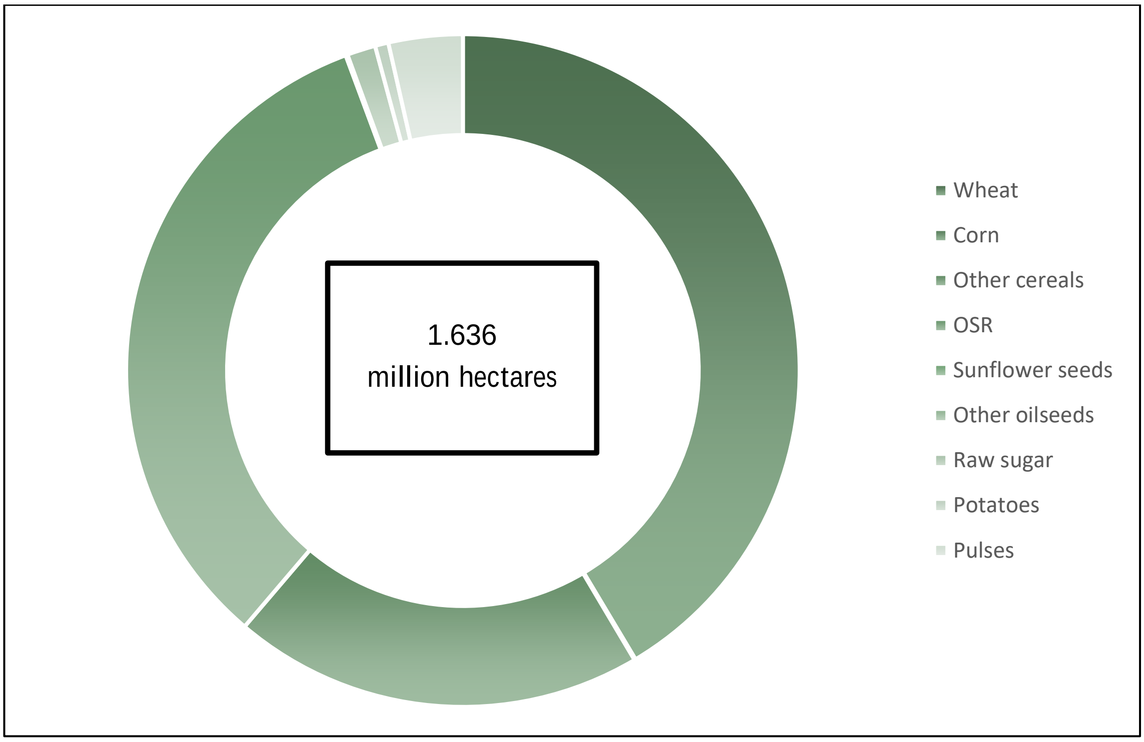
Region	Value	Region	Value
North America	0.068	Sub-Sahara Africa	0.061
South America	0.063	Oceania	0.055
Asia	0.081	CIS	0.162
MENA	0.092	RoW	0.013

Source: Own calculations and figure.

Analysis for the level of EU member states – the case of the UK

Figure 3.83 finally displays the avoided net virtual land imports of the UK in 2040 due to plant breeding progress in the next two decades. More than 1.6 million hectares of natural or nature-like habitats across the globe will remain unused for agricultural purposes due to plant breeding in the UK alone. The regional distribution of these net imports of virtual agricultural land by 2040 around the globe in the absence of future plant breeding progress in the country is listed in figure 3.84.

Figure 3.83: Potentially avoided net virtual land imports in 2040 with plant breeding progress between 2020 and 2039 in the UK, by crop



Source: Own calculations and figure.

Figure 3.84: Potentially avoided net virtual land imports in 2040 with plant breeding progress between 2020 and 2039 in the UK, by region (in million hectares)

Region	Value	Region	Value
North America	0.259	Sub-Sahara Africa	0.158
South America	0.092	Oceania	0.293
Asia	0.165	CIS	0.378
MENA	0.256	RoW	0.035

Source: Own calculations and figure

GHG emissions

Overview on the impacts by EU region

The arable land additionally needed at global scale without plant breeding in the EU in the next two decades will not be available per se but would need to be converted from grassland or other natural or nature-like habitats. Since all this extra land is yet still sequestering a lot of carbon, a substantial part of this carbon would be released into the atmosphere in the form of mainly CO_2 if the land were to be used for farming. The amount to be emitted in such a situation by 2040 is visualized in figure 3.85, while annex Q provides similar information for the other chosen time horizon, i.e., until 2030.

Figure 3.85: Potentially avoided regional CO_2 emissions attributable to major arable crops until 2040 with plant breeding progress between 2020 and 2039 in the EU and selected member states (in million tons)

Region	EU	DE	FR	IT	ES	UK
North America	309	42	73	8	10	38
South America	254	26	39	10	10	14
Asia	820	72	122	23	24	49
MENA	615	72	101	23	18	50
Sub-Sahara Africa	404	45	69	16	12	31
Oceania	269	37	62	7	6	33
CIS	874	77	167	24	27	64
RoW	80	8	14	2	2	6

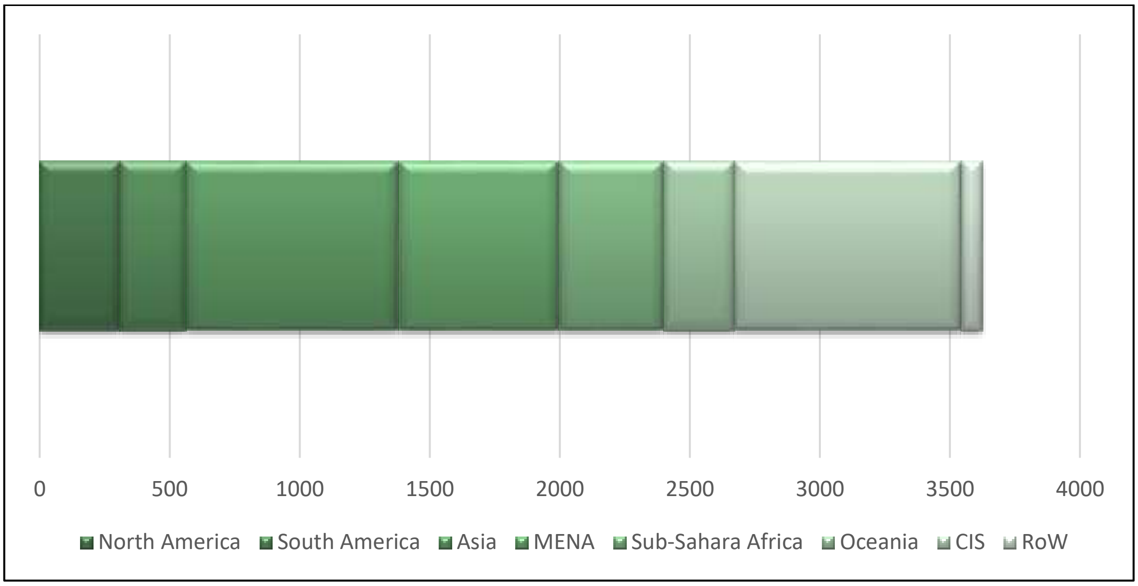
Source: Own calculations and figure.

Analysis for the level of the EU in total

Plant breeding successes in the EU in the next 20 years will help avoid an additional emission of GHG of more than 3.6 billion tons until 2040 as figure 3.86 reveals. This one-time-only effect is three times the current GHG emissions of the EU's energy supply sector per year (EEA, 2019).

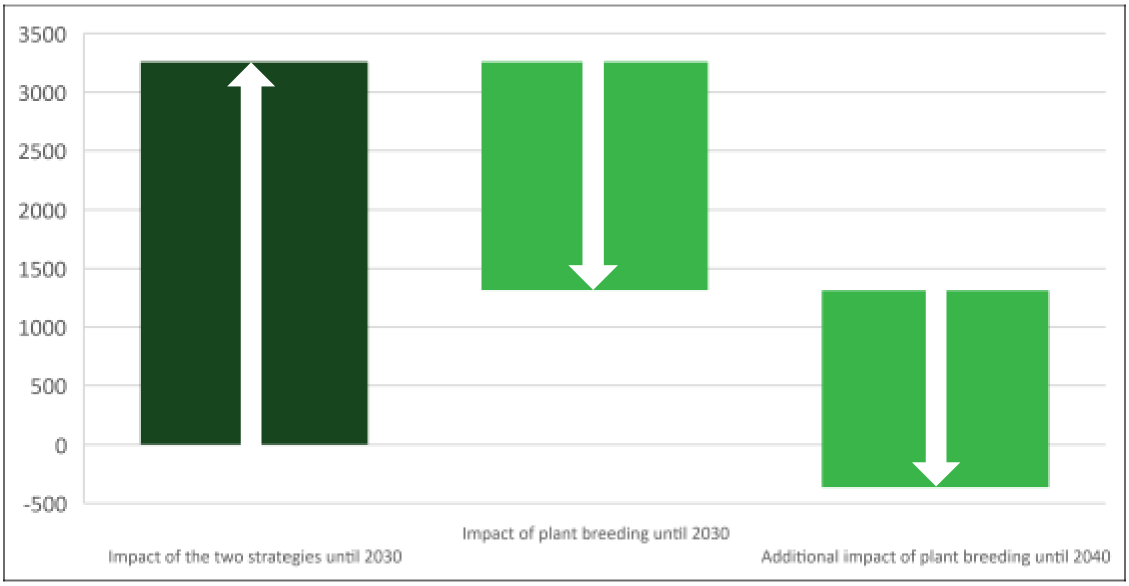
Plant breeding successes in the EU between 2020 and 2039 will also help mitigate GHG emissions due to an enforcement of the "Farm to Fork" and "Biodiversity" strategies as these strategies – as defined above- add to lower production and, hence, increase land use abroad to satisfy domestic demand. The partial impact on CO_2 emissions effects from respective land use changes of the two strategies, on the one hand, and future plant breeding progress in the EU, on the other hand, are visualized in figure 3.87. It turns out, that almost 400 million tons of GHG can be avoided, until 2040 on balance, if the two partial effects are aggregated.

Figure 3.86: Potentially avoided regional CO_2 emissions until 2040 with plant breeding progress between 2020 and 2039 in the EU (in million tons)



Source: Own calculations and figure.

Figure 3.87: Comparing and balancing partial CO_2 emission effects of the two strategies with plant breeding progress until 2040 in the EU (in million tons)

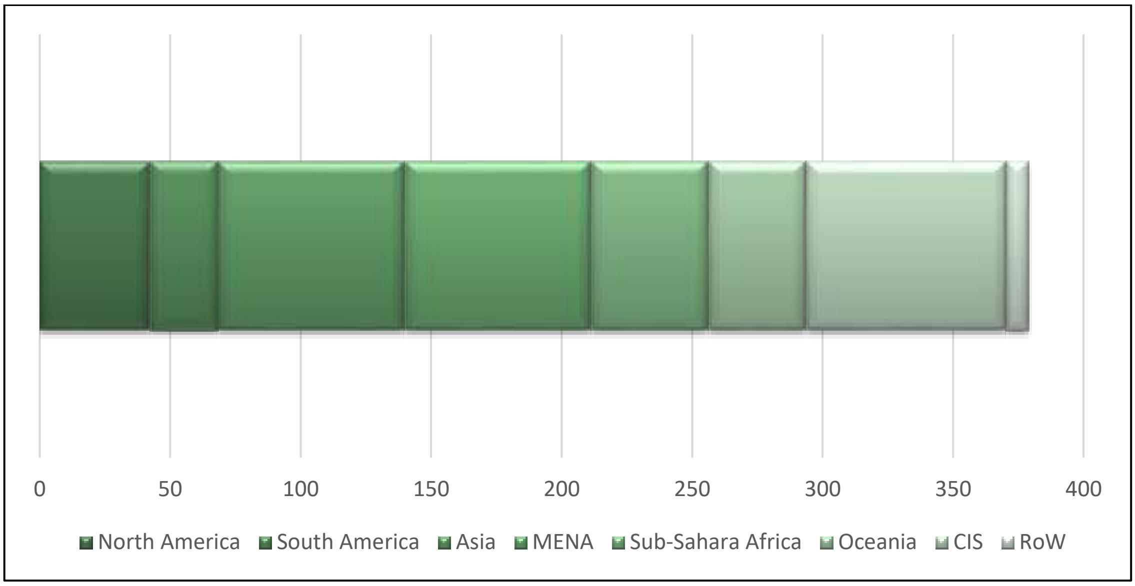


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Germany

Similarly, future plant breeding successes in Germany will help avoid an extra emission of GHG of almost 380 million tons until 2040 as figure 3.88 depicts. This one-time-only effect is considerable and equals more than two thirds of the annual GHG emissions of the EU's agricultural sector (EEA, 2019).

Figure 3.88: Potentially avoided regional CO_2 emissions until 2040 with plant breeding progress between 2020 and 2039 in Germany (in million tons)



Source: Own calculations and figure.

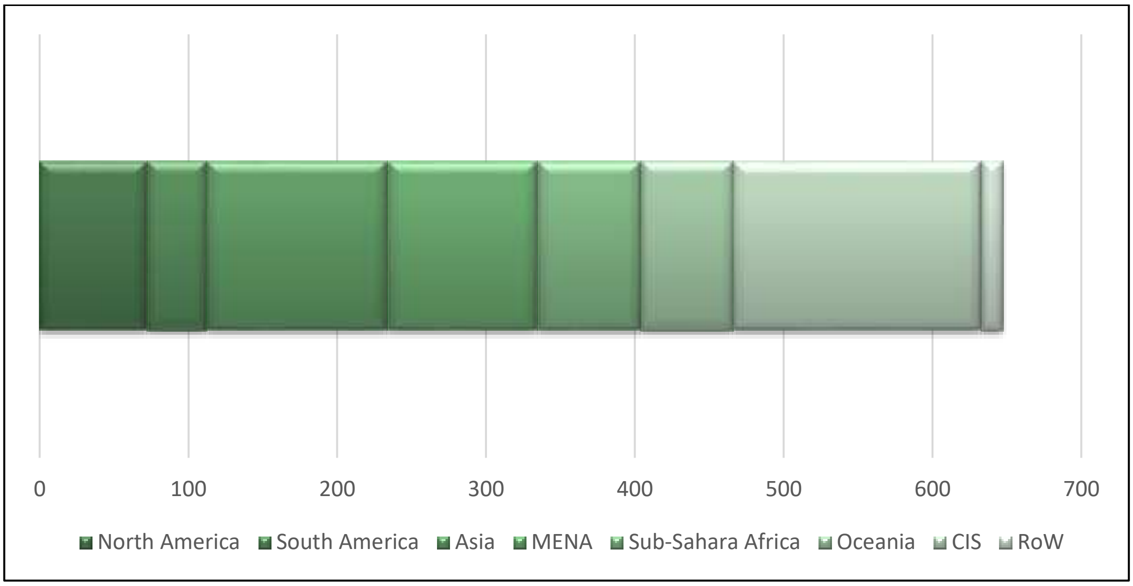
Analysis for the level of EU member states – the case of France

For France, the values are as follows: Plant breeding progress in the next 20 years in this EU member state has the potential to avoid an extra emission of GHG of 650 million tons until 2040 as figure 3.89 shows. This is four times the annual amount the EU's international aviation sector emits (EEA, 2019).

Analysis for the level of EU member states – the case of Italy

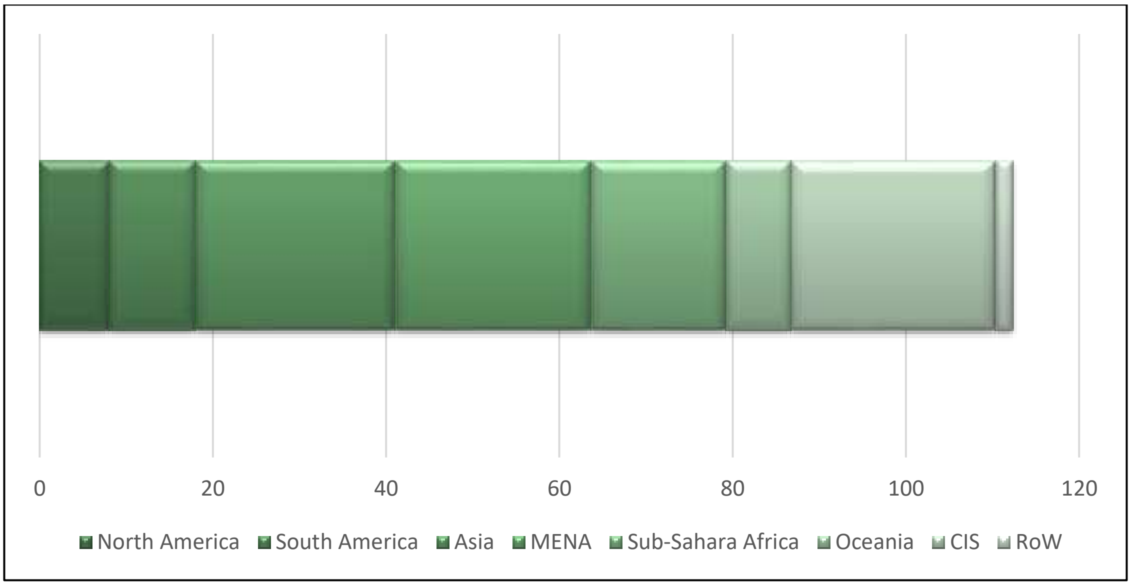
Similarly, plant breeding successes in Italy in the next two decades will potentially avoid an extra emission of GHG of more than 110 million tons until 2040 as figure 3.90 visualizes. This one-time-only effect is approximately as large as the annual GHG emissions of the waste sector of the EU (EEA, 2019).

Figure 3.89: Potentially avoided regional CO_2 emissions until 2040 with plant breeding progress between 2020 and 2039 in France (in million tons)



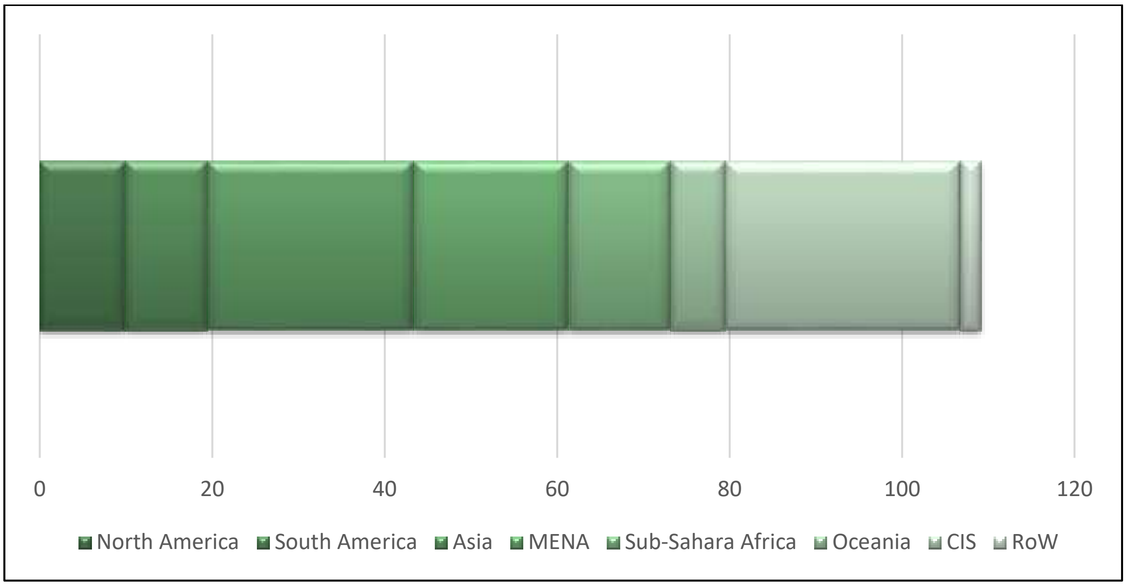
Source: Own calculations and figure.

Figure 3.90: Potentially avoided regional CO_2 emissions until 2040 with plant breeding progress between 2020 and 2039 in Italy (in million tons)



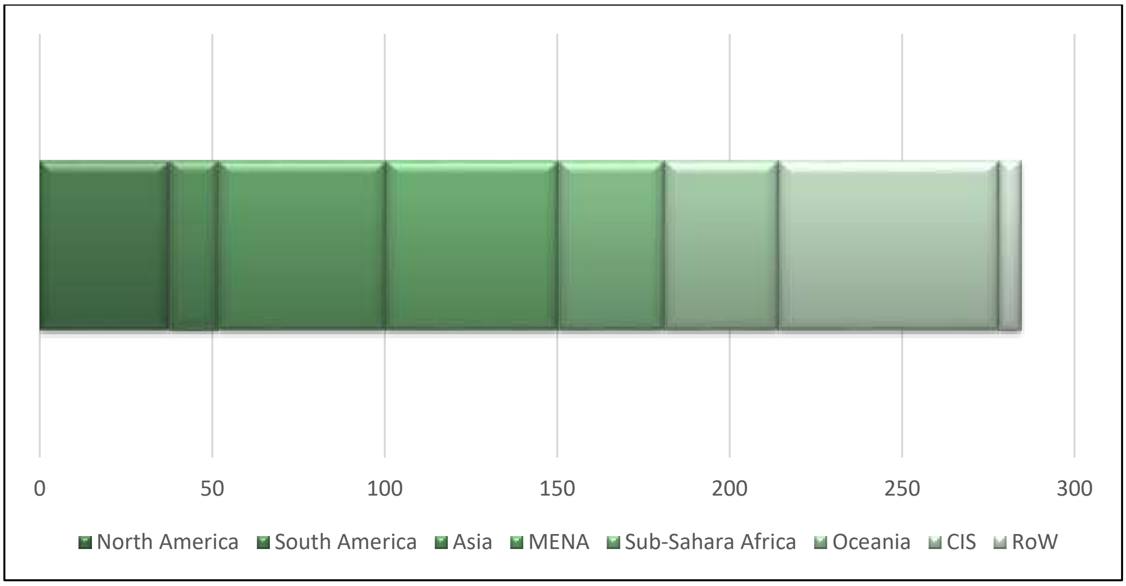
Source: Own calculations and figure.

Figure 3.91: Potentially avoided regional CO_2 emissions until 2040 with plant breeding progress between 2020 and 2039 in Spain (in million tons)



Source: Own calculations and figure.

Figure 3.92: Potentially avoided regional CO_2 emissions until 2040 with plant breeding progress between 2020 and 2039 in the UK (in million tons)



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Spain

Looking at Spain and the above figure 3.91, the same arguments as in the case of Italy can be provided. The one-time-only effect until 2040 that can be associated to plant breeding progress in this EU member state between 2020 and 2039 is around 110 million tons of GHG emissions and, thus, as large as the annual GHG emissions of the waste sector of the EU (EEA, 2019).

Analysis for the level of EU member states – the case of the UK

Finally, the above figure 3.92 shows the results for the UK: Here, plant breeding between 2020 and 2039 has the potential to avoid an extra emission of GHG of 280 million tons until 2040. This one-time-only effect is as large as half the current GHG emissions of the residential sector of the EU (EEA, 2019).

Global biodiversity

Overview on the impacts by EU region

Repeating that future plant breeding efforts in the EU will avoid a conversion of grassland and other natural or nature-like habitats of almost 20 million hectares at global scale (see, again figure 3.72), it is also worth quantifying the associated potential "biodiversity preserving" effect of future genetic crops improvements based on the two methods outlined in annex E. The results of the separate analyses for the 2040 scenario as well as for the EU and selected member states are depicted in figure 3.93, while annex R provides similar information for the other time horizon, i.e., until 2030.

Analysis for the level of the EU in total

Distinguishing the two biodiversity concepts, figure 3.94 visualizes the results for the EU in total. Looking at the figure, the following can be highlighted:

- Based on the GEF-BIO, almost 790 million biodiversity points would be lost by neglecting plant breeding in the EU in the next two decades on top of what will most probably be lost in terms of global species richness anyway due to other reasons until 2040. This is equivalent to the biodiversity currently found on 7.9 million hectares of Brazilian ecosystems and implies that plant breeding for arable crops in the EU between the years 2020 and 2039 will compensate for more than ten years of deforestation in the Amazon region at current pace.

- Applying the NBI concept suggests an even larger potential loss in global biodiversity. It would decline by an additional almost 1 100 million points without genetic crops improvements in the EU between 2020 and 2039. If plant breeders in the EU gave up their jobs today, global biodiversity would be reduced by an equivalent of species richness on an additional 10.9 million hectares of Indonesian rainforest, i.e., by as much as the loss of biodiversity that can be attributed to more than 24 years of cutting rainforests in Indonesia at the current intensity level.

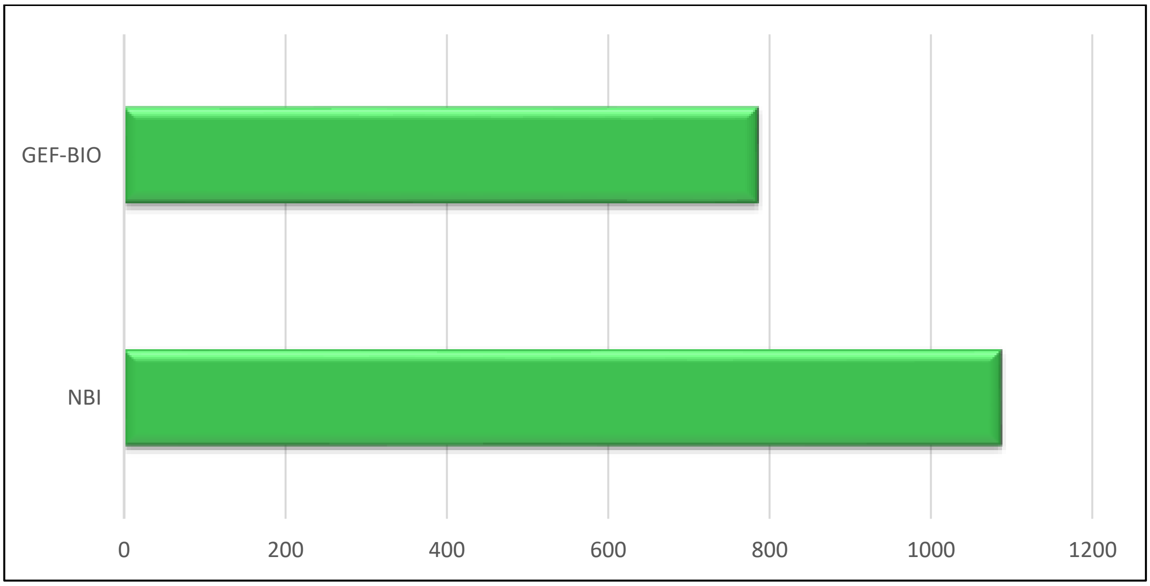
Figure 3.93: Potentially avoided biodiversity loss until 2040 with plant breeding progress between 2020 and 2039 in the EU and selected member states (in million points)

Region	EU	DE	FR	IT	ES	UK
GEF-BIO						
North America	87	12	20	2	3	11
South America	102	10	16	4	4	6
Asia	50	4	7	1	1	3
MENA	6	1	1	0	0	1
Sub-Sahara Africa	12	1	2	0	0	1
Oceania	74	10	17	2	2	9
CIS	440	39	84	12	14	32
RoW	15	2	3	0	0	1
NBI						
North America	85	12	20	2	3	10
South America	146	15	23	6	5	8
Asia	108	9	16	3	3	6
MENA	98	11	16	4	3	8
Sub-Sahara Africa	87	10	15	3	3	7
Oceania	107	15	25	3	2	13
CIS	435	38	83	12	14	32
RoW	23	2	4	1	1	2

Source: Own calculations and figure.

Again, a comparison of the partial effect of the "Farm to Fork" and "Biodiversity" strategies with the corresponding impacts of future plant breeding for major arable crops in the EU makes. Accordingly, it can be highlighted that plant breeding successes in the EU between 2020 and 2039 will also help mitigate negative global biodiversity consequences due to an enforcement of the two strategies as these strategies – as defined above- add to lower production and, hence, increase land use abroad to satisfy domestic demand. The partial biodiversity loss effects from respective land use changes of the two strategies, on the one hand, and future plant breeding progress in the EU, on the other hand, are shown in figure 3.95. It turns out, that in terms of the GEF-BIO (the NBI) almost 80 (110) million points can be avoided, until 2040 on balance, if the two partial effects are aggregated. This is comparable to a loss of biodiversity on 0.8 million hectares of Brazilian ecosystems (1.1 million hectares of Indonesian ecosystems) at current pace.

Figure 3.94: Potentially avoided global biodiversity loss until 2040 with plant breeding progress between 2020 and 2039 in the EU (in million points)



Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Germany

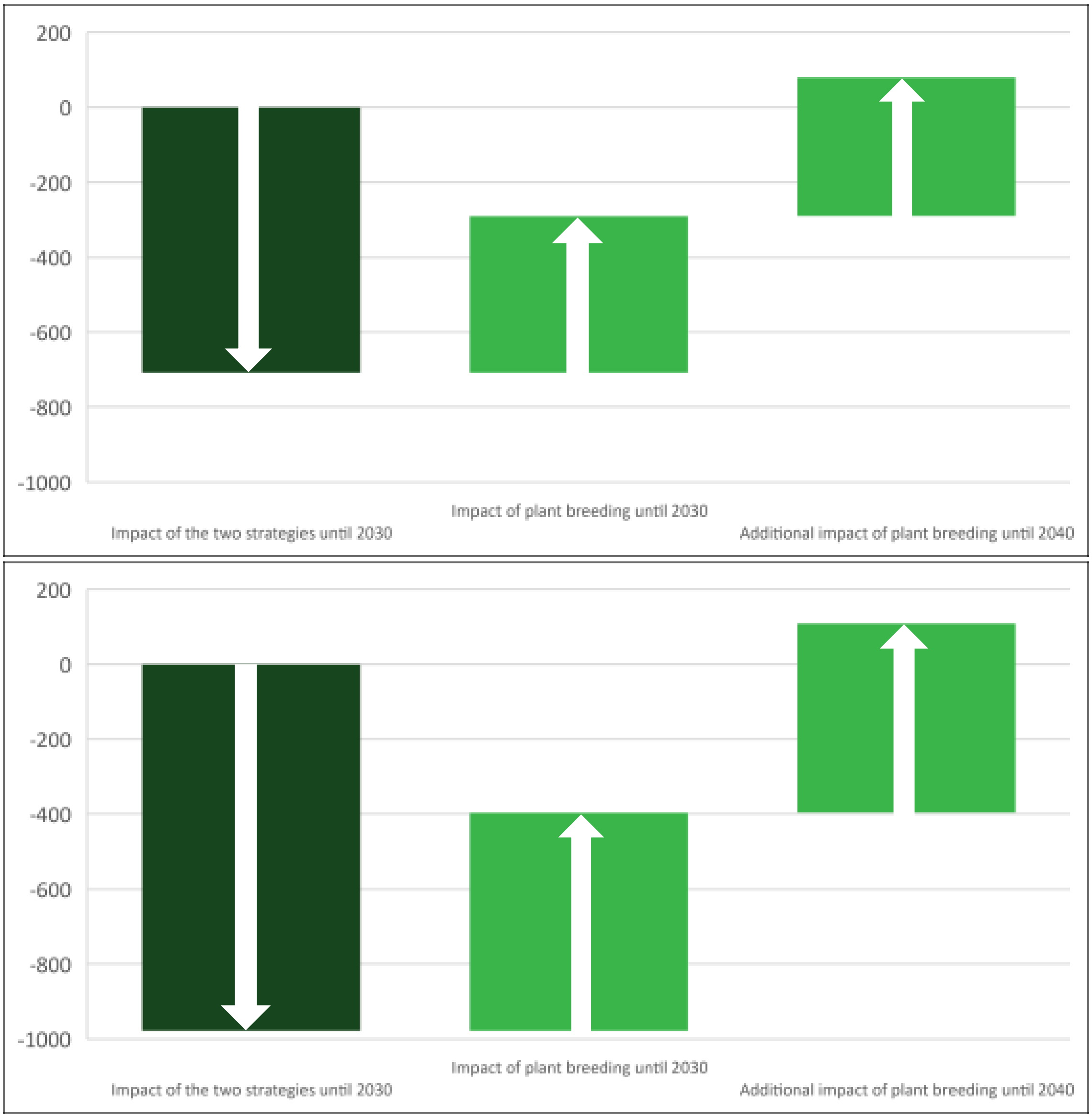
Looking at Germany and figure 3.96, the following can be stated as regards avoided biodiversity losses by 2040 due to plant breeding in the country between 2020 and 2039 based on the GEF-BIO: Almost 80 million biodiversity points would get lost without plant breeding. This is equivalent to the biodiversity found on 0.8 million hectares of rainforest and savannahs in Brazil and implies that plant breeding for arable crops in Germany in the next two decades will compensate for approximately one year of losing natural habitats in the Amazon region at current pace.

The NBI suggests an even larger loss. Global biodiversity would have declined by around 110 million points if plant breeding had terminated in 2020. This is biodiversity found on 1.1 million hectares of Indonesian rainforests. Subsequently, plant breeders in Germany will compensate in the next 20 years for global biodiversity losses similar to two and a half years of deforestation in Indonesia.

Analysis for the level of EU member states – the case of France

In accordance to figure 3.97, the following applies to France with respect to potentially avoided biodiversity losses due to plant breeding in the next two decades using the GEF-BIO approach: More than 150 million biodiversity points would additionally be lost without respective breeding progress. This is equivalent to the biodiversity found on 1.5 million hectares of rainforest and savannahs in Brazil and implies that plant breeding for arable crops in France between 2020 and 2040 will compensate for two years of Brazilian deforestation.

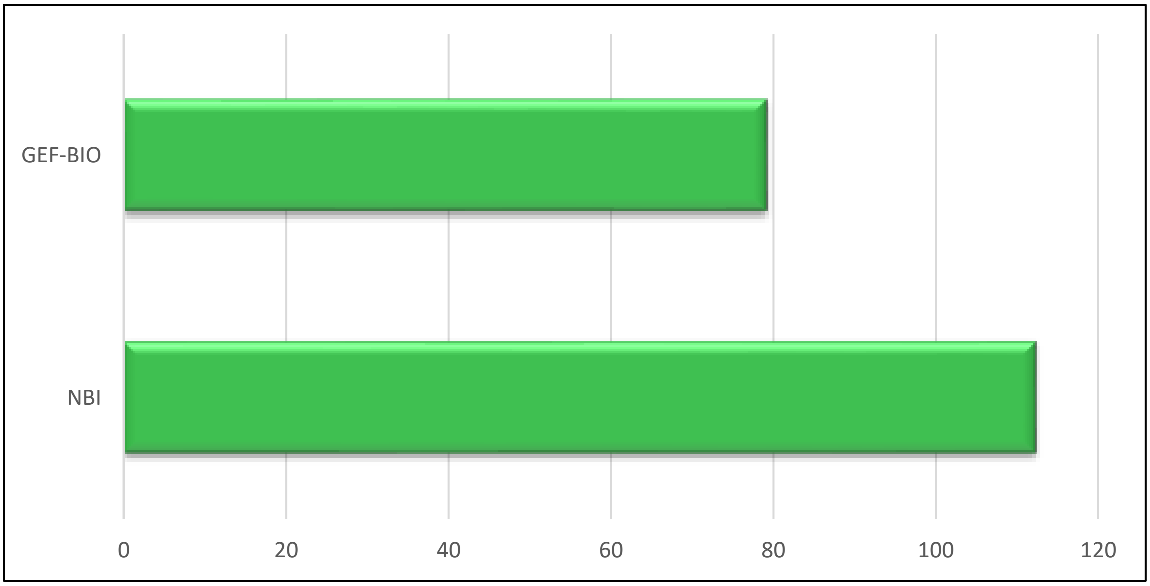
Figure 3.95: Comparing and balancing partial biodiversity effects based on the GEF-BIO (above) and NBI (below) of the two strategies with plant breeding progress until 2040 in the EU (in million points)



Source: Own calculations and figure.

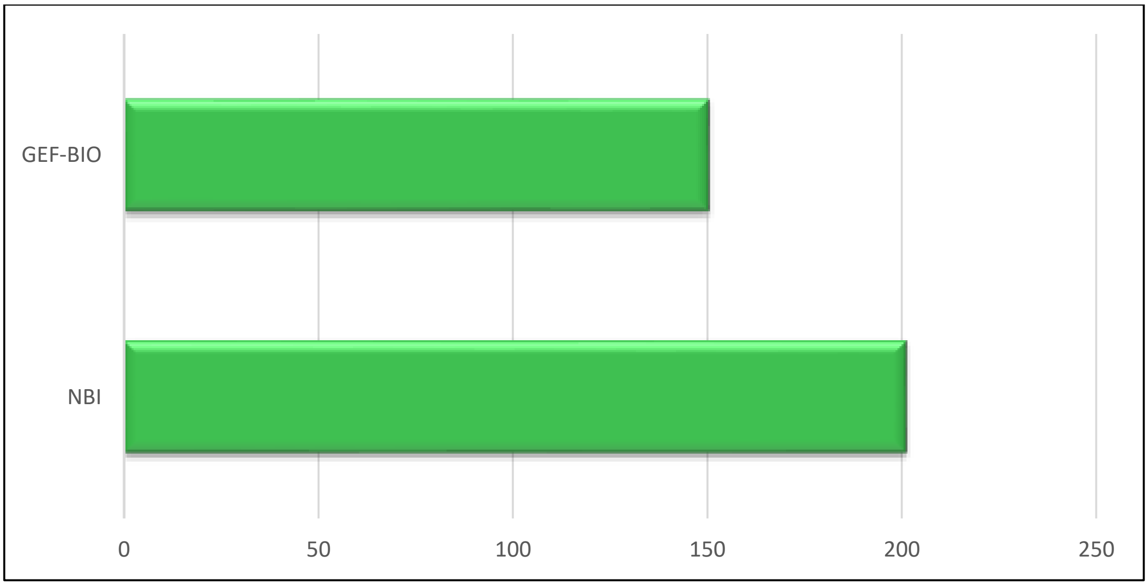
And with respect to the NBI concept, the loss in global biodiversity would be around 200 million points. This is the biodiversity found on 2.0 million hectares of Indonesian rainforests. Hence, plant breeding in France in the next two decades may compensate for global biodiversity losses as large as the losses of more than four years of natural habitats in Indonesia.

Figure 3.96: Potentially avoided global biodiversity loss until 2040 with plant breeding progress between 2020 and 2039 in Germany (in million points)



Source: Own calculations and figure.

Figure 3.97: Potentially avoided global biodiversity loss until 2040 with plant breeding progress between 2020 and 2039 in France (in million points)



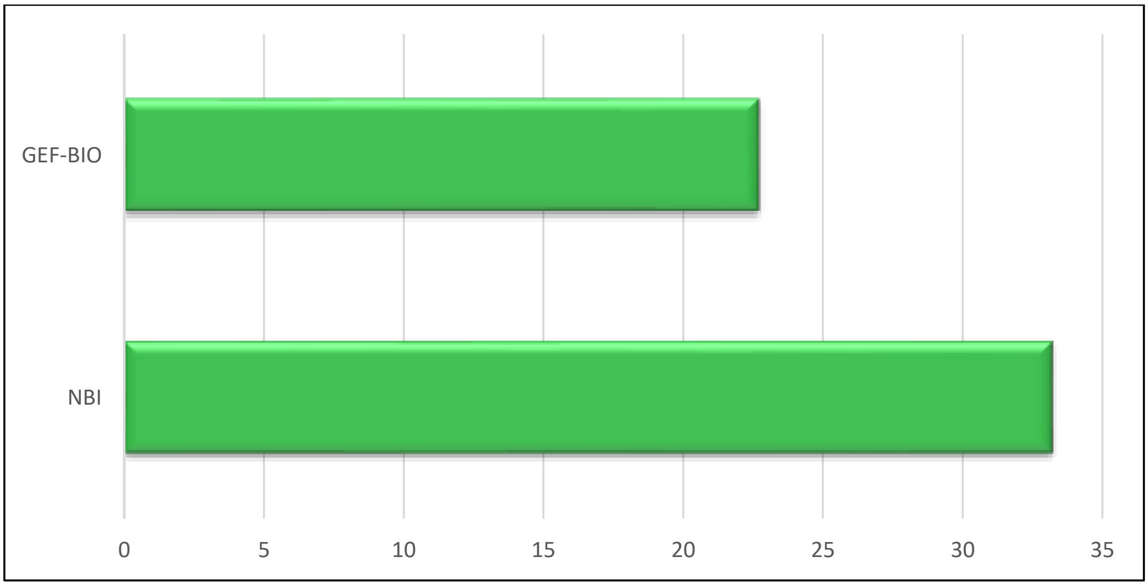
Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Italy

Based on the GEF-BIO, approximately 23 million biodiversity points would additionally be lost by 2040 without plant breeding progress between 2020 and 2039 in Italy as figure 3.98 visualizes. This is equivalent to the biodiversity found on 230 000 hectares of Brazilian natural habitats. Assuming the current cutting rate in the Brazilian Amazon Forest, this implies that plant breeding for arable crops in Italy in the next 20 years will most likely compensate for more than three months of losing natural habitats in the region.

Applying the NBI concept suggests an even larger loss in global biodiversity. It would decline by an additional 33 million points without future Italian plant breeding progress until 2040. This is the biodiversity living on 330 000 hectares of Indonesian rainforests and implies a potentially avoided global biodiversity loss as large as the loss of approximately nine months of deforestation in Indonesia.

Figure 3.98: Potentially avoided global biodiversity loss until 2040 with plant breeding progress between 2020 and 2039 in Italy (in million points)



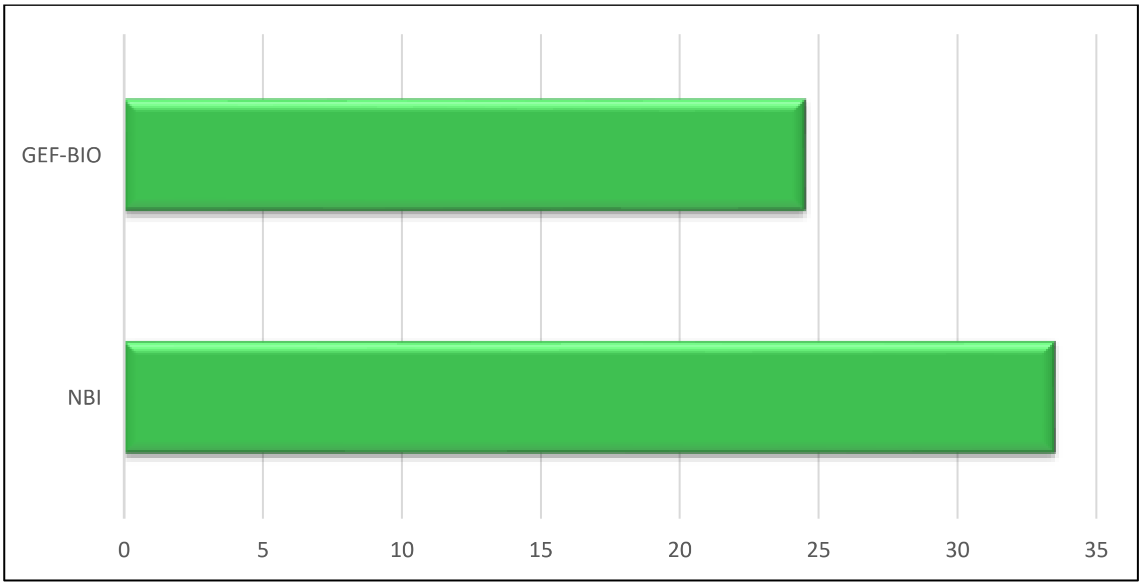
Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Spain

In line with figure 3.99, the following can be stated as regards avoided biodiversity losses by 2040 due to plant breeding in Spain between 2020 and 2039 based on the GEF-BIO: Almost 25 million biodiversity points would get lost without the attributable breeding progress. This is equivalent to the biodiversity found on 250 000 hectares of rainforest and savannahs in Brazil and implies that plant breeding for arable crops in Spain in the next two decades will most likely compensate for approximately four months of losing natural habitats in the Amazon region.

The NBI suggests an even larger loss in global biodiversity. It would decline by an additional more than 33 million points without plant breeding in the next 20 years. This is the biodiversity living on 330 000 hectares of Indonesian rainforest and leads to the conclusion that plant breeders in Spain might compensate in the next 20 years for global biodiversity losses as large as losses of approximately eight months of deforestation in Indonesia.

Figure 3.99: Potentially avoided global biodiversity loss until 2040 with plant breeding progress between 2020 and 2039 in Spain (in million points)



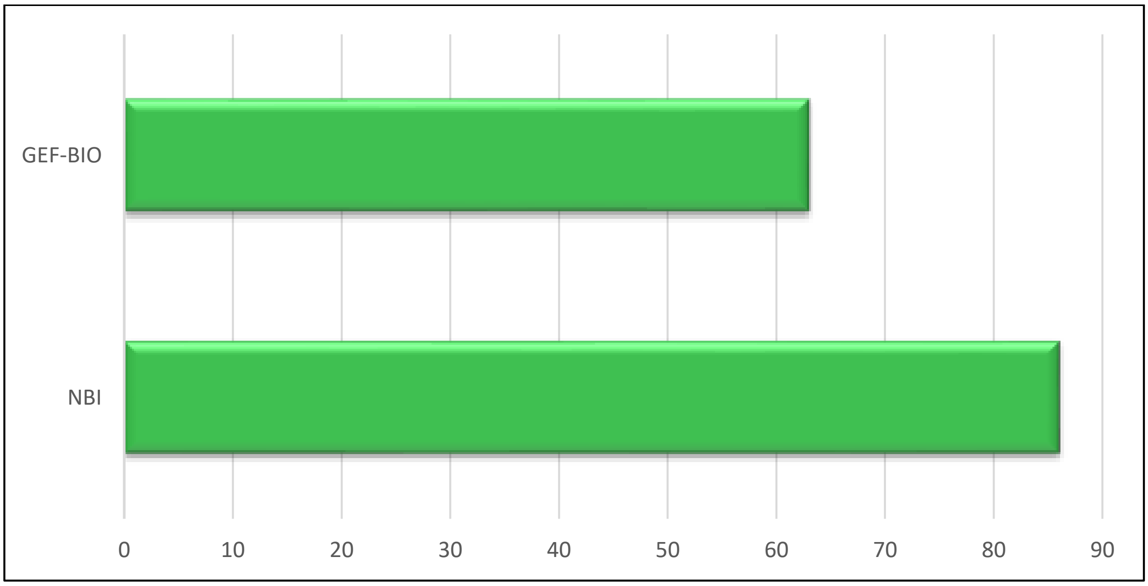
Source: Own calculations and figure.

Analysis for the level of EU member states – the case of the UK

Looking finally at the UK and figure 3.100, it turns out that plant breeding between 2020 and 2039 will help avoid substantial biodiversity losses by 2040. Based on the GEF-BIO, almost 65 million biodiversity points would additionally get lost without breeding progress. This is equivalent to the biodiversity found on more than 0.6 million hectares of rainforest and savannahs in Brazil and implies that plant breeding for arable crops in the UK the next 20 years will compensate for more than three quarters of a year of losing natural habitats in the Amazon region.

The NBI suggests an even larger loss in global biodiversity. It would decline by more than 85 million points. This is biodiversity currently found on more than 0.8 million hectares of Indonesian rainforests and leads to the conclusion that plant breeders in the UK will most probably be able in the upcoming 20 years to compensate for global biodiversity losses similar to almost two years of deforestation in Indonesia.

Figure 3.100: Potentially avoided global biodiversity loss until 2040 with plant breeding progress between 2020 and 2039 in the UK (in million points)



Source: Own calculations and figure.

Water use

What has been analyzed with respect to water use in the past can also be examined for the future scenarios. In the following, again the results for the 2040 scenario are discussed in greater detail. Respective findings as regards the 2030 scenario can be found in annex S. As in the case of the ex-post evaluation, the ex-ante assessment also distinguishes two (gross) water impacts:

- On the one hand, future plant breeding in the EU and its member states will increase domestic production of arable crops (see above), and this certainly requires more water to be used domestically.
- On the other hand, this will allow the EU to export more and/or import less. Both tend to lower production and hence, agricultural water use abroad.

The two separate effects can be aggregated, and this leads to a net water impact in 2040 which is displayed in figure 3.101. It turns out, again, that in all cases, except for green maize, which is not traded, the water use balance will be negative. That means, plant breeding between 2020 and 2039 in the EU and its member states will reduce global water use in 2040 because the additional water needed here in the EU by then will be lower than the water use that will be avoided abroad.

Figure 3.101: Potential global water use balance in 2040 with plant breeding progress between 2020 and 2039 in the EU and selected member states (in billion m³)

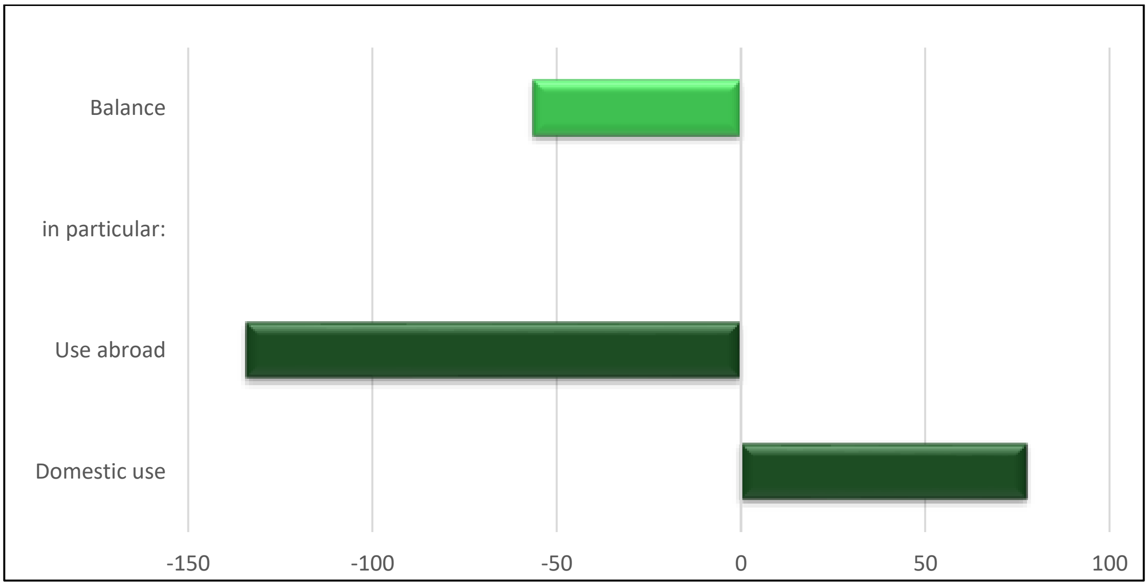
Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	-15.418	-2.251	-5.037	-0.254	0.046	-2.541
Corn	-19.509	-1.012	-3.029	-0.898	-0.739	-0.007
Other cereals	-14.025	-2.183	-1.658	-0.398	-0.162	-1.228
OSR	-3.375	-0.788	-1.517	0.030	-0.015	-0.893
Sunflower seeds	-3.035	0.007	-0.261	-0.010	0.208	N.A.
Other oilseeds	-0.274	0.000	-0.013	-0.080	0.009	-0.009
Raw sugar	-0.645	-0.172	-0.361	-0.010	-0.014	-0.060
Potatoes	-3.684	-0.370	-0.247	-0.032	-0.059	-0.265
Pulses	-2.242	-0.384	-0.565	-0.111	-0.162	-0.495
Green maize	5.724	1.113	0.676	0.095	0.132	0.183

Source: Own calculations and figure.

Analysis for the level of the EU in total

The two underlying gross effects and the resulting net effect for the EU in total are displayed in figure 3.102.

Figure 3.102: Potential global and regional water use balances in 2040 with plant breeding progress between 2020 and 2039 in the EU (in billion m³)

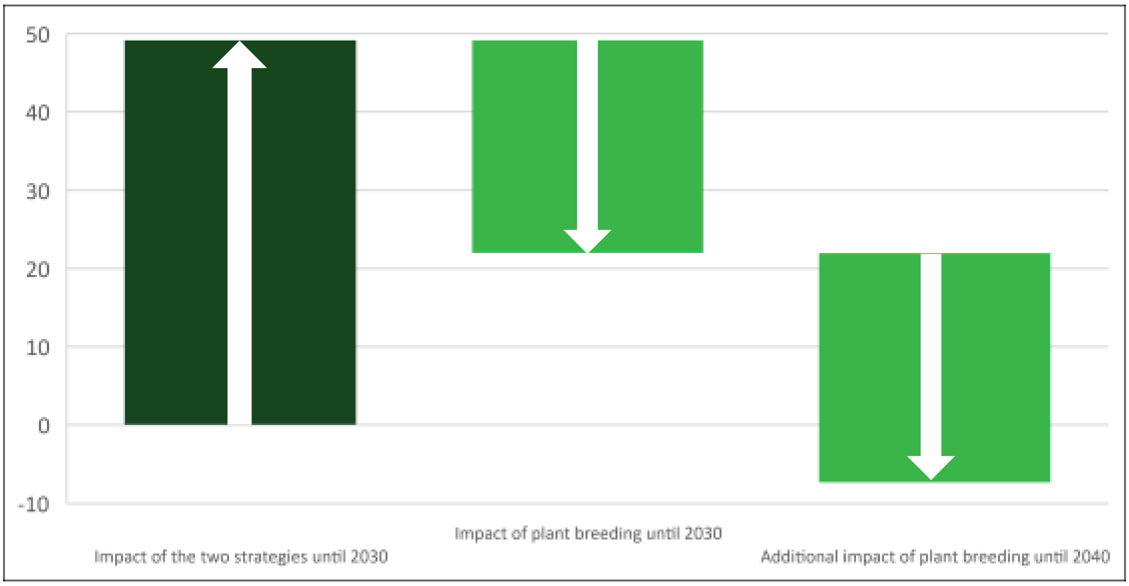


Source: Own calculations and figure.

Due to plant breeding progress in the next two decades, EU arable production in 2040 will be higher than it would potentially be without future genetic crop improvements. The embedded domestic water in this potential additional crop production will amount to 77.8 billion m³. The higher crop production in the EU in 2040, however, will also allow to export more and/or import less. Subsequently, production incentives in foreign countries will shrink and water will be saved abroad due to upcoming plant breeding activities in the EU. In total, 134.3 billion m³ of water will be saved this way in other countries than EU member states. On balance, a net saving of 56.5 billion m³ would occur. This is approximately the amount of water both, Lago Maggiore and Lago di Como together have in terms of volume.

This net saving can again be compared with the corresponding effect of the "Farm to Fork" and "Biodiversity" strategies as these strategies tend to lower EU production of arable crops and with this water use in the EU at the cost of higher water use abroad. Figure 3.103 shows and balances the two partial effects.

Figure 3.103: Comparing and balancing partial water balance effects of the two strategies with plant breeding progress until 2040 in the EU (in billion m³)



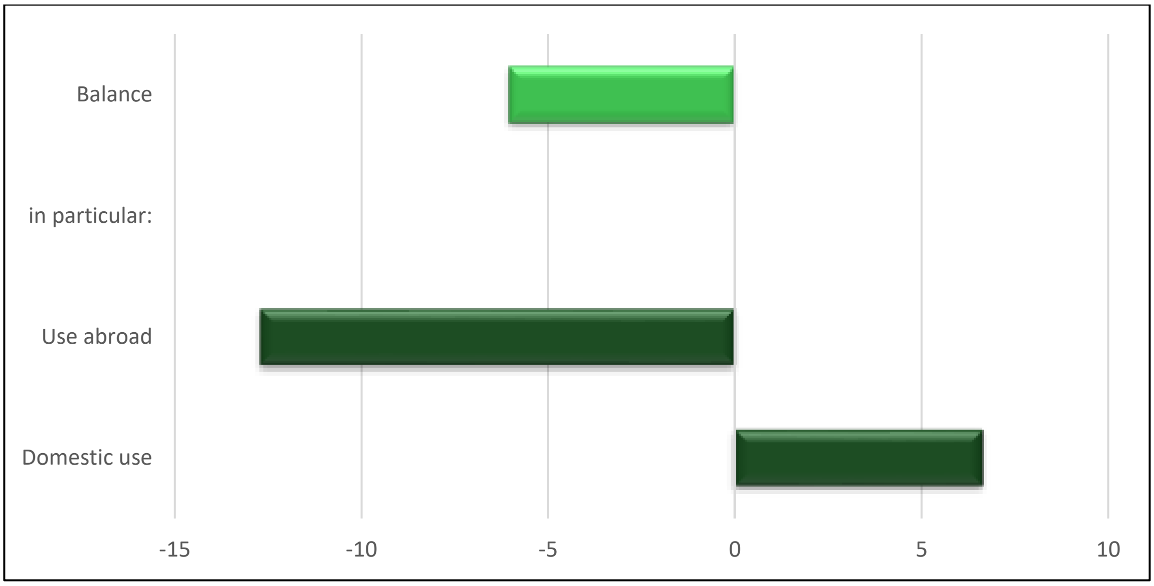
Source: Own calculations and figure.

The full implementation of the two strategies would, on balance, cause an additional global water use of almost 50 billion m³. Already plant breeding progress in the next decade in the EU would be able to half this partial effect, and the partial water saving effect of plant breeding between 2020 and 2039 is greater than the water cost effect of an enforcement of the two strategies as defined above. Hence, a net saving of approximately 7.3 billion m³ would occur if both effects ere aggregated. This is ten times the water volume of Lake Müritz in Germany.

Analysis for the level of EU member states – the case of Germany

Looking at Germany and figure 3.104, it can be stated that due to plant breeding in the next two decades the embedded domestic water in additional German crop production will amount to 6.7 billion m³ in 2040, whereas the saved water abroad will total 12.7 billion m³. Hence, a net saving of 6.0 billion m³ will potentially occur. This is approximately eight times the water Lake Müritz has in terms of volume.

Figure 3.104: Potential global and regional water use balances in 2040 with plant breeding progress between 2020 and 2039 in Germany (in billion m³)



Source: Own calculations and figure.

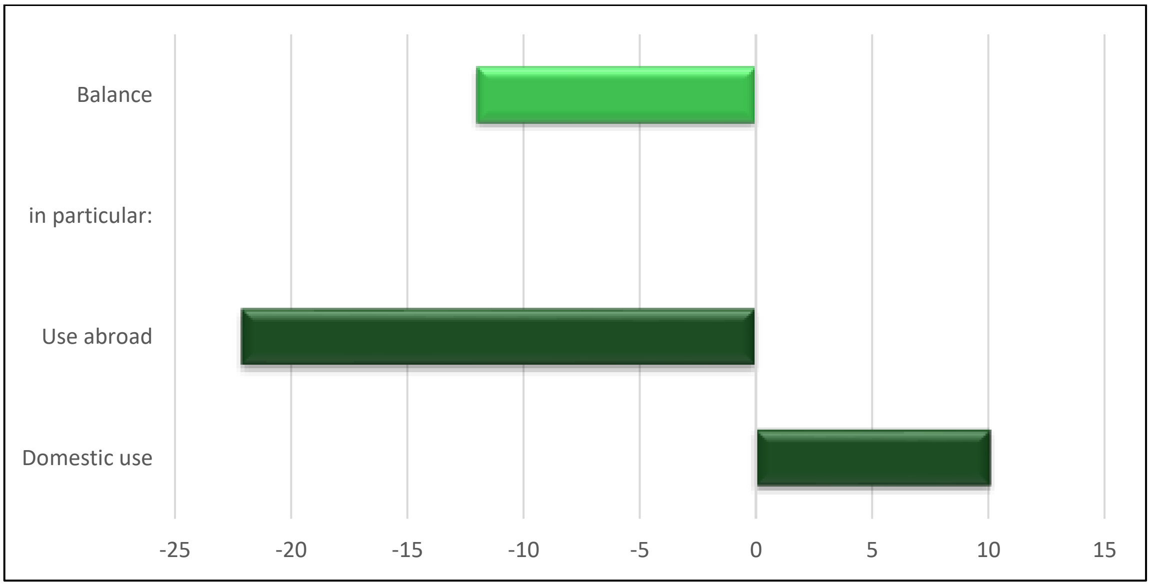
Analysis for the level of EU member states – the case of France

The picture for France is provided with figure 3.105. Accordingly, it can be highlighted that due to plant breeding between 2020 and 2039 the additionally embedded domestic water in extra French crop production will amount to 10.1 billion m³ in 2040, whereas the saved water abroad will total 22.1 billion m³. Hence, a net saving of 12.0 billion m³ occurs. This will be more than eleven times the water Étang de Berre has in terms of volume.

Analysis for the level of EU member states – the case of Italy

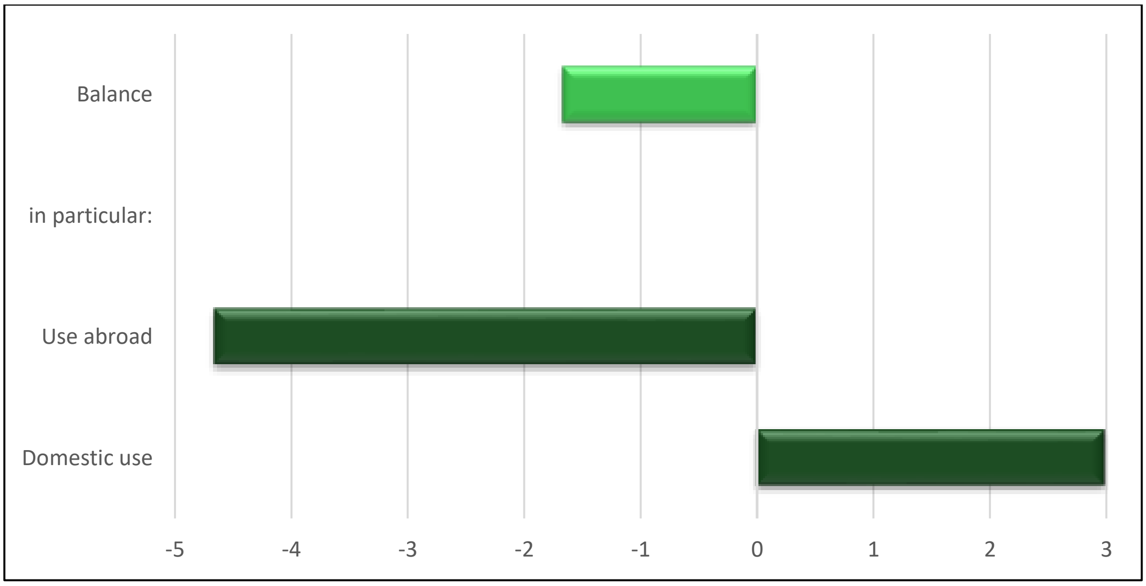
Looking at Italy and figure 3.106, it can be argued that due to plant breeding between 2020 and 2039 the additionally embedded domestic water in extra Italian crop production amounts to 3.0 billion m³ in 2040, whereas the saved water abroad will total 4.7 billion m³. Hence, a net saving of 1.7 billion m³ will occur. This is approximately a fifth of the water Lago di Bolsena has in terms of volume.

Figure 3.105: Potential global and regional water use balances in 2040 with plant breeding progress between 2020 and 2039 in France (in billion m³)



Source: Own calculations and figure.

Figure 3.106: Potential global and regional water use balances in 2040 with plant breeding progress between 2020 and 2039 in Italy (in billion m³)

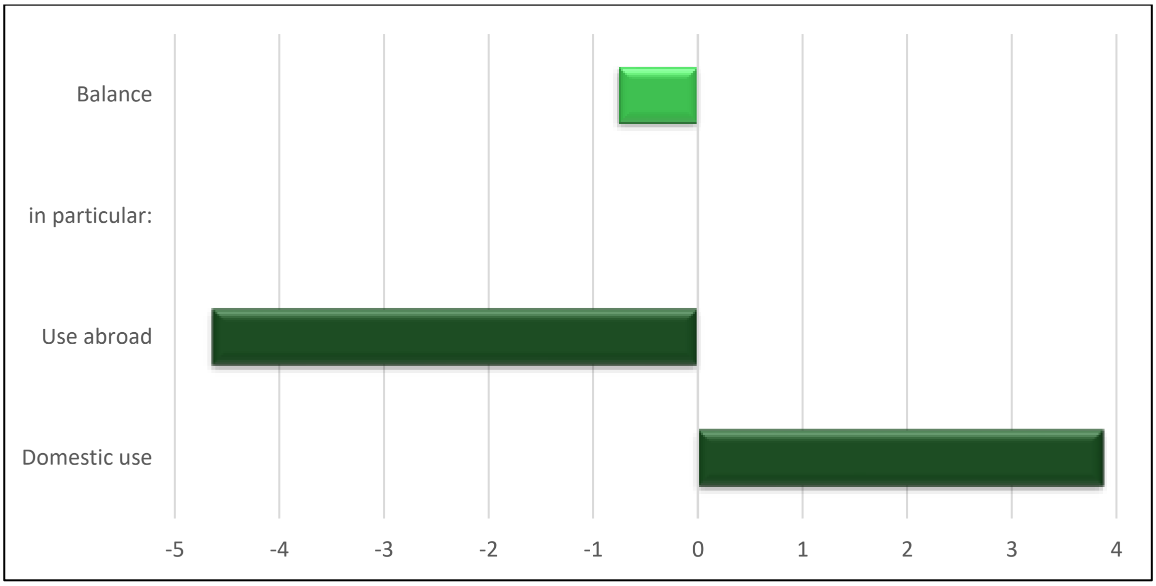


Source: Own calculations and figure.

Analysis for the level of EU member states – the case of Spain

The future balance for Spain can be seen in figure 3.107. Looking at the figure, it can be stated that due to plant breeding in the next two decades the additionally embedded domestic water in extra Spanish crop production will amount to 3.9 billion m³ in 2040, whereas the saved water abroad will total 4.6 billion m³. Hence, a net saving of 0.7 billion m³ will occur. This is approximately the same amount of the water Mar Menor has in terms of volume.

Figure 3.107: Potential global and regional water use balances in 2040 with plant breeding progress between 2020 and 2039 in Spain (in billion m³)



Source: Own calculations and figure.

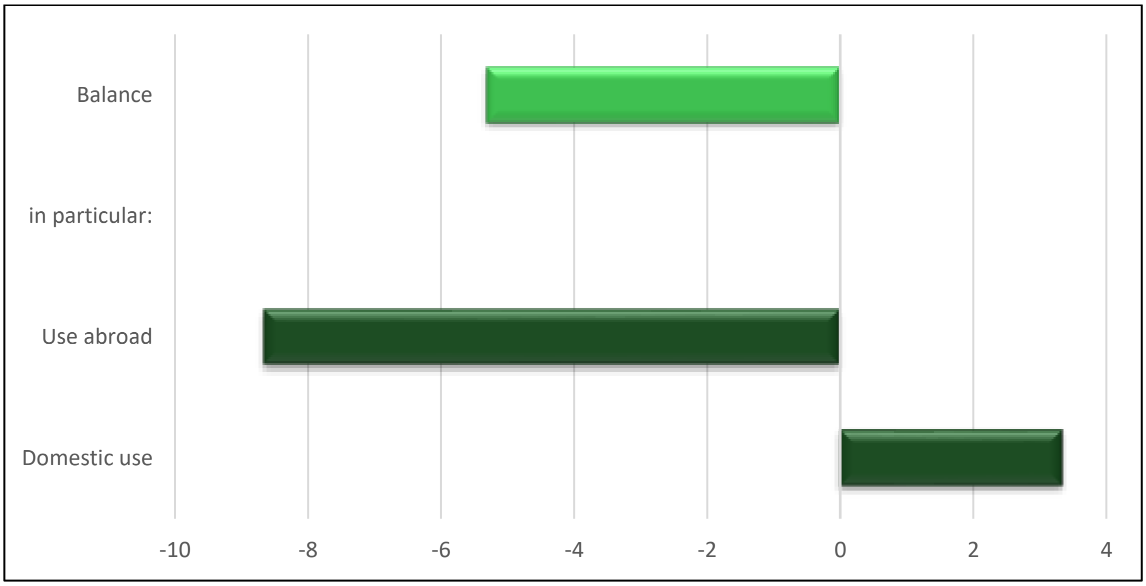
Analysis for the level of EU member states – the case of the UK

Finally looking at the UK and figure 3.108, it can be stated that due to plant breeding between 2020 and 2039 the additionally embedded domestic water in extra crop production of the country will amount to 3.4 billion m³ in 2040, whereas the saved water abroad will total 8.7 billion m³. Hence, a net saving of 5.3 billion m³ will occur. This is 1.5 times the water Lough Neagh has in terms of volume.

Topical summary

The ex-ante assessment of future EU plant breeding progress mirrors what has already been stated based on the ex-post evaluation: Genetic crop improvements will help meet the various socio-economic and environmental challenges our societies face today and will envisage in future. In particular, EU plant breeding will support the enforcement of the "Farm to Fork" and "Biodiversity" strategies.

Figure 3.108: Potential global and regional water use balances in 2040 with plant breeding progress between 2020 and 2039 in the UK (in billion m³)



Source: Own calculations and figure.

4 Case study analyses

The above analysis clearly shows that plant breeding for arable crops in the EU since the turn of the millennium has contributed various values to the agricultural economy and broader society, and it demonstrates that it will continue to do so in the next decades. However, the analysis also indicates that the current intensity of plant breeding progress in the EU with respect to major arable crops cultivated in its member states will most likely not be enough to fully compensate various effects which an implementation of the "Farm to Fork" and "Biodiversity" strategies until 2030 – as defined above – might cause on the production side.

In fact, the EU faces various challenges, which the envisaged implementation of the two strategies aims to meet. In particular, the strategies recognise the need for agricultural and food systems to reduce their environmental and climate footprint and increase their resilience in the face of climate change and biodiversity loss while also acknowledging the vulnerabilities of food and other agricultural supply chains, often precarious working conditions faced by farmers and agricultural workers, and risks to farmers' economic welfare and social livelihoods (Meredith et al., 2020). Hence, the two strategies address some of the most important environmental as well as socio-economic objectives the EU – and above that our world – faces (Schebesta and Candel, 2020).

Achieving the strategies' goal will very much depend on its implementation, i.e., the instruments and measures used, in the very near future and on the mitigation of some partial negative consequences that could result from these strategies if not accompanied by proper policy instruments. So far, no holistic impact assessment of the two strategies has been available, nor have any concrete policy and other intervention schemes been formulated and enforced to achieve the objectives. Nevertheless, it can be argued with respect to production effects that a full implementation of the strategies in the next decade as desired by EU policy makers will cause severe losses of agricultural yields and overall produce. This, ceteris paribus, would certainly lead to some remarkable adverse consequences for the economy and environment.

In chapter 3 of this research, it has been shown that such negative impacts could occur soon in terms of various socio-economic and environmental indicators if certain elements of the two strategies had to be implemented until 2030 as required in the currently formulated strategy texts. Chapter 3 has also shown that plant breeding progress in the next decade (until 2030) at current pace has the potential to partially mitigate some but not all of these consequences. The following can be highlighted in this respect:

- Production and subsequent market supply losses due to the two strategies until 2030 could potentially be halved with plant breeding in the next decade at current pace (see again figure 3.3 and figure 3.18).
- Continually occurring genetic crop improvements in the next ten years, in addition, have the potential to counteract approximately 55 percent of the apparent sectoral income and GDP

shrinkages in 2030 that must be attributed to production and market supply impacts of the two strategies until then (see again figure 3.43 and figure 3.51).

- Negative consequences of the initial production and market supply impacts on the use of global natural resources such as land and related climate and biodiversity issues as well as water that can be attributed to an enforcement of the two strategies until 2030 can be alleviated by 50 to 60 percent, assuming the same progress for the next ten years of plant breeding as in the past (see again figure 3.87, figure 3.95 and figure 3.103).

As it becomes clear that not all negative implications of the two strategies can be compensated this way, the question is: What can possibly fill the still existing gaps in the near future? Plant protection and fertilization shall be reduced according to the two strategies and, thus, might be limited in the provision of needed innovation. Land machinery and other technologies (including embedded digitalisation) has long-lasting investment intervals and may only contribute in the long run. It is, then, again plant breeding that must(!) be considered a potential "game changer"[56]. However, this requires speeding up processes aiming at genetic crop improvements. Mainly two factors may help:

- All available technologies must be used, especially those able to provide genetic crop improvements in a more targeted way and, in addition, a shorter period of time, and

- The overall policy and regulatory framework must encourage and not hinder the therefore necessary investments into future plant breeding.

In the following, the first factor shall be discussed in greater detail while the second determinant will be covered within chapter 5 of this research. Using case study analyses it will now exemplarily be shown how NPBT may lead to desperately needed improvements as regards certain challenges, specific arable crops, and selected EU member states. Altogether, five case studies are included:

- Wheat with fungi resistance in Germany,

- OSR with pod shatter resistance in France,

- Sugar beet with virus resistance in the UK,

- Maize with drought resistance in the EU in total, and

- Grapevine with fungi resistance in Italy.

These five case studies will now be discussed by describing the problem formulation, potential NPBT solutions, and expected results potentially leading to various beneficial impacts of plant breeding.

56 Specific demand side developments may also help to fulfill the objectives of the strategies and fill gaps. However, it is beyond the scope of this study focusing on plant breeding as an innovative production factor to assess such "consumption" developments. Nevertheless, they should not be neglected.

4.1 Wheat with fungi resistance in Germany

Wheat is certainly one of the most relevant staple crops and foods worldwide. Regarding the global population, it is estimated that wheat provides approximately one fifth of dietary calories and protein making the arable crop one of the major components of human diet (Okada et al., 2019; Sánchez-León et al., 2018; Trnka et al., 2019). Due to the global population growth, it is expected that the demand for wheat will considerably rise. Conservative estimations arrive at the conclusion that an increase in global annual demand of more than 40 percent until 2050 should be envisaged (Trnka et al., 2019).

The EU shall be considered a major wheat producer at global scale. According to EC (2021a), almost each ninth ton of global wheat is currently harvested in the EU; and the EU shall also be considered a major trader of the arable crop as its member states altogether have exported (imported) between 13 and 20 percent (6 and 7 percent) of all wheat and products thereof in most recent years (USDA, 2021a). Within the EU, Germany is the second largest wheat producer and contributes, by and large, 20 percent to the overall wheat volume of the EU (Eurostat, 2021b). Only France provides more.

Like most other arable crops, wheat cultivation currently faces and will continue to face immense challenges in the coming decades, especially considering climate change, but also comprising biotic stress factors. In fact, wheat is susceptible to a variety of diseases and pests. Especially fungal infestations do pose a major danger to the harvest and are thought to have a huge impact on the quality and yield of the crop (Figueroa et al, 2017; Zetzsche et al., 2020). Winter wheat particularly reacts to wet conditions and is, thus, especially prone to fungal diseases. Various fungal diseases can substantially affect wheat yield. Among them are the following (N.N., 2021)[57]:

- Powdery mildew is one of the most dangerous leaf diseases in wheat. It is caused by the fungus *Erysiphe graminis*, which overwinters on crop residues and occurs mainly in warm, humid weather in spring. It can cause crop losses of up to 25 percent.
- Leaf drought, triggered by the fungus *Septoria tritici*, is recognisable by the yellowing, later browning, of the leaf blade, on which black spots (fruiting bodies of the fungus) subsequently appear. In Germany, it usually occurs in wetter locations, but is also more widespread in wet springs and summers. It can cause crop losses of up to 30 percent.
- Yellow rust is caused by the fungus *Puccinia striiformis*, which penetrates the leaf veins via the stomata. It is recognisable by linear, orange-yellow areas on the leaf and spreads mainly in cool, damp areas, but is more prevalent in wet, cool summers. It can cause crop losses of up to 50 percent due to the poorer photosynthesis performance of the infested grain.

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57 The source argues from a German perspective. The following yield loss information, thus, particularly refer to this EU member state, but may potentially also be used as a proxy for other countries within the EU.

- One of the most dangerous cereal diseases is caused by the mould *Fusarium graminearum*. The pest attacks the plant via the root, also infects the ears and causes grains to shrivel. In addition, the pathogen produces mycotoxins that are highly toxic to humans and animals (Redman and Noleppa, 2017). It is particularly difficult to be controlled because symptoms only appear after flowering – by then it is often already too late to take countermeasures.

Of course, such fungi-related losses of up to "X" percent would not occur every year and at any place. In fact, the level very much depends on the concrete weather and specific location for instance. However, as a rule of thumb it can be stated that if not managed properly, wheat yield losses of approximately 10 to 15 percent should be envisaged due to the various fungal diseases (see Oerke, 2006).

To prevent fungal infestation, wheat can be treated with fungicides. The number of applications of relevant substances depends a lot on the weather in the specific region. On average and as regards German wheat cultivation, two – sometimes three – applications of fungicides have been needed in past years (JKI, 2021) and are still recommended (Wiegand, 2020). However, since the reduction of PPP has become a societal goal in the German and European context, certainly more diverse measures are needed to address the problem of fungi-based diseases in wheat in the future. Miedaner and Juroszek (2021) suggest that wheat cultivars with multi-disease resistances will become of crucial relevance. Such resistance does not only react to existing and emerging diseases but could also persist under growing heat and water stress induced by climate change.

Certainly, NPBT present such other urgently needed tools to minimise the risk of fungi infestation. The conventional breeding practice of small grain cereals relies on the efficient production of fully homozygous plants with fixed beneficial traits. With its hexaploidy structure, the wheat genome is enormously complex and has so far been a challenge for the introduction of homozygous new characteristics. In 2018 the wheat genome was decoded, and IWGSC (2018) could present a detailed mapping of the entire wheat genome. Only two years later, in 2020, a German-Canadian research team was able to use genomic selection to find genotypes for breeding wheat varieties that are resistant to some fungi and proved that genome-based breeding and selection also work for resistance to fungi[58] and that NPBT can be applied to create better adapted wheat material in a shorter amount of time (Boldt, 2020) [59].

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58 For more examples on how NPBT can target fungi resistance in wheat (and other crops), see the most recent meta-analysis of Zaidi et al. (2020).

59 NPBT were also or are currently successfully applied in wheat regarding other relevant qualitative aspects of the crop. For example, with support of the CRISPR/Cas technology the gluten in seed kernels of wheat could successfully be reduced and the relevant traits could be integrated into elite wheat varieties in the near future. Such low-gluten, transgene-free wheat lines could be an important quality criterion to produce low-gluten foodstuff for gluten-intolerant consumers suffering from coeliac diseases and non-coeliac gluten sensitivity (Sánchez-León et al., 2018). To take a second example, Singh et al. (2018) could successfully use CRISPR/Cas to generate male sterile wheat lines, thus, paving the way for rapid breeding of hybrid wheat varieties. The authors suggest that the specific NPBT could be an especially promising tool for polyploid species such as wheat, making the time-consuming and

Another similar project was started in Germany in 2020: The so-called PILTON project, which is supported by almost 60 plant breeders and aims at developing wheat plants with an improved, multiple, and permanent fungal tolerance through NPBT, namely CRISPR/Cas. During the project, the defence reaction against pathogens is to be strengthened by activating a plant's own regulatory gene. The expectation is that this will subsequently lead to broad and lasting tolerance against a rather broad spectrum of fungal diseases such as brown rust, yellow rust, Septoria, and fusarium. Apart from that, it is also expected to show the potential for reducing the response time of plant breeding (BDP, 2021). However, since the PILTON project started in 2020, concrete results are yet not available and still need some time to materialise. Nevertheless, a best guess can be given to assess the potential value of generating fungi resistance in wheat varieties with NPBT. It is, therefore, assumed that the expected broad and lasting tolerance against a rather broad spectrum of fungal diseases can be achieved and will lead to a considerable decrease of the application of fungicides.

To allow for an exemplified calculation of the impact of this expectation, the following simplified scenario is established: A typical German farmer growing wheat at current yield levels, product prices and input costs will be able to reduce one (two) fungicide application(s) per year with a wheat variety created via the PILTON project (or a similar plant breeding effort). On farm level, this may lead to a remarkable cost reduction which consequently allows for a higher farm income as figure 4.1 displays.

The figure is based on KTBL (2021) data. In the reference system (the status quo), the typical wheat farmer creates a market revenue of approximately 1 200 EUR per hectare, which is assumed not to change when switching from a standard to a fungi-resistant wheat variety created through NPBT. This is because a yield impact is not embedded in the scenario[60]. This switch, however, allows to reduce fungicide application(s), and the related cost decrease – including costs for the fungicide and its application – allows the farmer to generate higher gross and net margins. Looking at the net margin[61], the following can be stated:

- If new wheat varieties created through a NPBT allowed avoiding one fungicide application in comparison to the standard (reference) application scheme, the net margin (the profit which can be used for new investments, structural change and further development of the farm) of 35 EUR per hectare might potentially increase by 55 EUR or more than 150 percent.

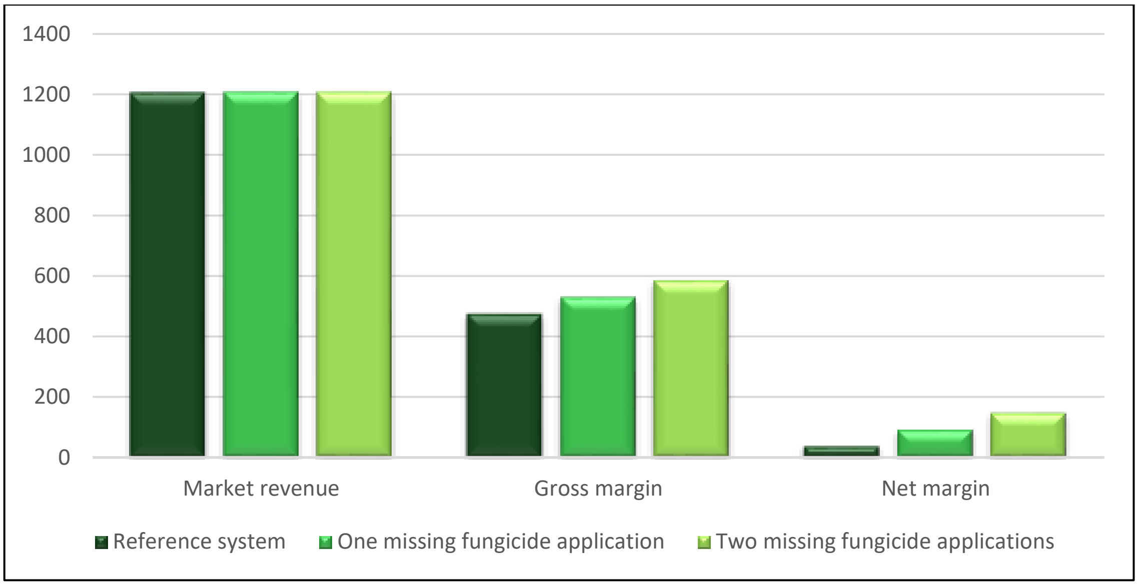
resource-intensive backcrossing redundant. Accordingly, the research findings could be used for a male fertility control system for hybrid seed production and resulting heterosis effects. Since the heterosis effect in wheat has shown an estimated increase of 15 percent of the yield, such potential advantages could be exploited in future breeding programmes (Singh et al., 2018; Okada et al., 2019).

60 Highlighting this is insofar important as Zetzsche et al. (2020) clearly show that breeding for fungal pathogen resistance may also lead to remarkable yield improvements.

61 The net margin is the result of the market revenue minus direct costs for seed, fertilisers, PPP, irrigation, crop insurance, and drying if applicable, as well as minus other variable costs such as variable machinery and labour costs and costs for services, and additionally minus fixed costs including own costs of capital and labour.

- If new varieties allowed reducing the use of fungicides by two applications, an additional profit of 110 EUR per hectare could be achieved. This is 300 percent more than in the reference system.

Figure 4.1: Main economic indicators of wheat production at the level of a typical German farmer without and with a fungi-resistant variety developed through NPBT (in EUR per hectare)



Source: Own calculations and figure.

This alone would certainly improve the competitiveness of the individual wheat producing farmer(s) of – if extrapolatable – the EU wheat sector. If an additional yield impact was embedded (see again the arguments of Oerke (2006) and/or Zetzsche et al, 2020), the market revenue could also increase. Hence, the increase of the margins as visualised in figure 3.1 might be considered a "conservative" assessment of the potential monetary effects of applying a fungi-resistant wheat variety developed through NPBT on farm.

From a societal point of view, and particularly with respect to the enforcement of the "Farm to Fork" and "Biodiversity" strategies aiming at a considerable reduction of PPP, the fact that the application of fungicides can be minimized via a fungi resistant wheat variety developed through NPBT shall be highlighted using another perspective. In this respect, figure 4.2 shows the number of applications of PPP that could potentially be avoided if such a variety was used on 10, 25, 50, and 100 percent of all acreage currently cultivated with wheat in Germany and the EU in total. Accordingly, it can be argued that up to almost six million applications of specific fungicides could be avoided in Germany and up to almost 50 million applications at European scale.

Figure 4.2: Theoretically avoidable number of applications of fungicides in German and EU wheat production with fungi-resistant wheat varieties developed through NPBT (in million applications)

One fungicide application less on ...				Two fungicide applications less on ...			
10 % of acreage	25 % of acreage	50 % of acreage	100 % of acreage	10 % of acreage	25 % of acreage	50 % of acreage	100 % of acreage
In Germany							
0.290	0.725	1.450	2.900	0.580	1.450	2.900	5.801
In the EU in total							
2.401	6.003	12.006	24.001	4.802	12.006	24.011	48.023

Source: Own calculations and figure.

4.2 Oilseed rape with pod shatter resistance in France and the EU

OSR is also a crop with a huge economic impact at global and especially European scale. The main economic importance of OSR as a crop certainly comes from its use for a protein-rich feed, as well as for vegetable oil and biodiesel production. It is mainly grown in temperate regions. Since winter OSR is up to two times more productive than spring OSR, the former is much more widely grown in the EU. Approximately 6.5 million hectares in the EU have produced around 22 million tons of OSR in recent years, compared to a global production of 70 million tons from around 34 million hectares (Steponavičius et al., 2019; Yang et al., 2018). These numbers stress the relevance of the crop for the European and global agricultural market.

The seed of OSR contains special relevance regarding the economic value of the plant. It does not only serve the life cycle of the crop, but it also contains lots of oil and proteins making the crop especially valuable for the different agricultural uses mentioned above. Thus, the silique – also named pod – that contains the seed and the number of siliques per plant, the number of seeds per silique and the seed weight are crucial for the yield outcome. Relevant traits that influence these factors are, thus, of major interest for OSR breeding and production (Yang et al., 2018).

Consequently, a major challenge of OSR production (and breeding) is the natural seed dispersal strategy of the plant that involves the shattering of dry fruits (Braatz et al., 2020). As soon as the fruits become ripe, OSR tends to shed its seed, what is a result of the need for natural seed dissemination. The pods enclose the seeds during their development. As soon as the process of pod dehiscence – also known as pod shattering – begins they break into two parts, the so-called valves. The pod shattering itself happens due to a built-up tension in the pod, which is marked by lignification of cells surrounding the dehiscence zone in the final stage of the pod development. Also, when the silique dries additional physical pressure is created that triggers pod shattering. Thus, by lowering the tension occurring in the pod wall or by widening the dehiscence zone the pod shattering can be reduced (Steponavičius et al., 2019).

The behaviour of pod shattering is rather unusual for a major agricultural crop, but the economic consequences can be immense. Depending on the conditions, the total losses of major seed due to pod shattering can be defined as somewhere between 15 to 70 percent as reported by Steponavičius et al. (2019). Other sources report a preharvest loss that can go in extreme cases up to 25 percent (Braatz et al., 2020). Variations of such losses certainly depend on the variety and the genotype of the crop. Winter OSR is described as more resistant to pod shattering than spring cultivars (Steponavičius et al., 2019). Besides, shattering can happen before or during the harvest, with different results concerning the amount of seed loss (see again Steponavičius et al., 2019):

- On the one hand, seed loss at harvesting of winter OSR under ideal conditions can range from 2 to 5 percent and under adverse conditions from 11 to 25 percent. If harvesting is delayed beyond the optimal time, yield losses of 20 to 25 percent are reported.
- Pre-harvest seed loss, on the other hand, can go up to 2.5 percent with favourable weather conditions. If unfavourable conditions appear, such losses can even increase up to 12 percent.

In any case, shattering of pods of OSR has been described as a major cause of seed yield losses prior to and during harvesting (see also Casswell, 2014; Gan et al, 2008; Østergaard et al., 2021), and avoiding such losses obviously makes sense.

There are different options to address pod shattering from an agricultural point of view. The spraying of pod sealants two weeks before harvest has been reported to reduce natural losses by up to 20 to 70 percent in controlled plots (Steponavičius et al., 2019). During harvest, also the use of plant growth regulators can lead to a reduction of seed loss. Next to chemical options, the use of appropriate harvest management strategies to minimize the impact of negative weather conditions is another relevant tool. Seed loss can also be reduced by well-equipped and adjusted combine harvester reels that have an extended cutter bar table and vertical double-knife active dividers. Even an inappropriate working speed of the combine harvester has been associated with seed loss, stressing the relevance of adequate mechanical treatment (Steponavičius et al., 2019).

Another potentially important tool next to management options that an OSR farmer has is the cultivation of OSR varieties with pod shatter resistance. However, OSR has a comparably low genetic diversity. Due to its amphidiploid nature, it is, hence, rather complicated to increase the genetic variation by cross-breeding or induced mutations (Braatz et al., 2020). Or, as Yang et al. (2018) formulate it: A multilocular (meaning more than two carpels) line of OSR is a much-desired agricultural trait since it has a great potential not only to produce bigger seeds per silique, but also for better shatter resistance and the avoidance of resulting seed loss during mechanical harvest. While a few multilocular lines of OSR have been found in nature, the lack of mutants with stable multilocular traits has so far hampered a broader research in this area. Only very few studies have fully investigated such multilocular traits in OSR and no multilocular trait has been applied to OSR breeding until most recently (Yang et al., 2018).

Yet, progress in the application of NPBT regarding the genetical improvement of OSR seems on the rise. Already Young et al. (2018) reported the successful utilization of CRISPR/Cas for revealing gene functions based on a relevant mutation that led to a higher number of seeds per silique and a higher weight than the wild type. And two years later, the application of CRISPR/Cas in OSR was again successfully started – this time with the aim to address the problem of pod shattering. According to Braatz et al. (2020), the specific research objective is to apply the system for targeted mutagenesis to reduce yield loss in OSR by assessing pod shatter resistance in the genotype of the crop. While field trials, of course, must still be undertaken, the authors already report the observation of an increased shatter resistance of siliques longer than five cm. Thus, the potential of CRISPR/Cas-targeted mutagenesis for a polyploid species like OSR could be successfully demonstrated in the latest past.

Also, the John Innes Centre in the UK is currently working on a new technology for reducing the susceptibility of OSR to pod shattering. Accordingly, germplasm of pod shatter resistant OSR lines has been produced and is now used for field testing. By better controlling pod shattering, the research project aims at reducing seed losses and wastage, improving yields as well as reducing the number of plants which grow as weeds (voluntary seeds) in the following year. The expectation is that achieving the objectives could consequently allow for a reduction of the land area needed for growing OSR. Thus, the application of genome editing techniques to the phenomenon of pod shattering could not only increase yield, but also support the goal of producing more food on less land area (see also Østergaard et al., 2021).

All these scientific undertakings increase expectations for the tackling of pod shattering in OSR based on genetically defined resistance. In the future, the application of such genome-editing methods to the rather complex genome of OSR could consequently broaden the genetic basis of breeding programmes and offer more diversity to plant breeders. The expectations are high as new varieties with reduced susceptibility to pod shatter will help improve yields of OSR in a range of 10 to 25 percent (Østergaard et al., 2021).

To allow again for an exemplified but meaningful calculation of the impact of this expectation, the following simplified scenario for a farmer in France, the major OSR producing EU member state, is established:

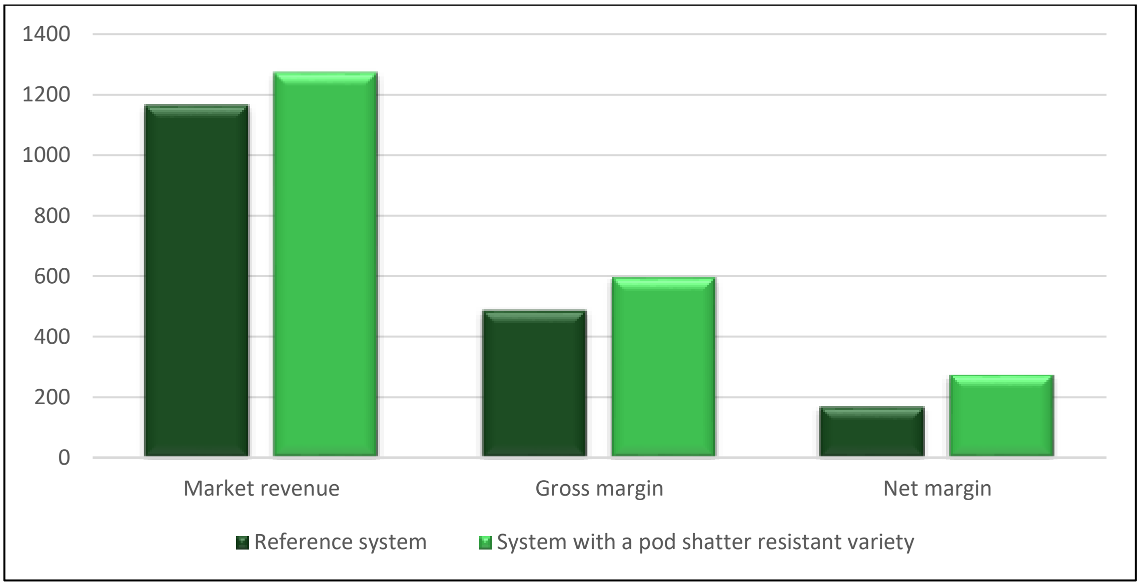
- A typical French farmer growing OSR is described in accordance with Bernat (2016) and Noleppa (2017) and assumed to generate a market revenue of 1 167 EUR per hectare.
- With a new pod shatter-resistant OSR variety engineered through a NPBT, this farmer avoids "usually" occurring yield losses equivalent to an increase of harvestable yield of 9.0 percent[62],

62 The specific postulation is based on the research of Steponavičius et al. (2019). The authors have analysed yield loss changes in OSR production with and without pod sealants applications. The underlying

what is slightly below the expectations of Østergaard et al. (2021) (see above) and shall therefore be considered as a conservative assumption.

On a farm level, this may lead to quite a remarkable market revenue increase which would allow for higher farm income as figure 4.3 depicts. It particularly turns out that the gross margin (covering operational and other variable costs and, thus, being important for economic prosperity of the farm in the short run) increases by more than 100 EUR per hectare or almost 22 percent. And the net margin (additionally covering fixed and own costs and, thus, being important for economic prosperity of the farm in the long run) increases from 167 to 272 EUR per hectare. Hence, the profit rises by more than 63 percent[63].

Figure 4.3: Main economic indicators of OSR production at the level of a typical French farmer without and with a pod shatter-resistant variety developed through NPBT (in EUR per hectare)



Source: Own calculations and figure.

As stated above, breeding for pod shatter resistance in OSR is also associated with the production of more food on less land area (see again Østergaard et al., 2021). Against this background, a yield increase of 9.0 percent as postulated above would lead to the following land savings displayed in figure 4.4 for OSR cultivation in France and the EU, respectively, if the use of the varieties bred with

assumption is that similar relative yield losses or harvestable yield changes can be expected from pod shatter resistance. Hence, costs for pod sealants are not incorporated into own analysis.

63 One may now further assume that – if applicable – costs for pod sealants and/or plant growth regulators prior to harvest, as well as for PPP to combat voluntary seed in the next year can also be avoided by applying a pod shatter-resistant OSR variety. This would further increase the economic benefit at farm level.

NPBT became more and more dominant. If fully implemented, this is almost a tenth of the currently used acreage for OSR in France and the EU and would, thus, certainly help lower the high pressure on existing land-use and, thus, surely support the mitigation of negative GHG emission and biodiversity effects of additional land use (see chapters 2 and 3 of this analysis).

Figure 4.4: Theoretically avoidable land use for OSR production with pod shatter-resistant OSR varieties developed through NPBT in France and the EU (in thousand hectare)

Using pod shatter-resistant OSR in France on ...				Using pod shatter-resistant OSR in the EU on ...			
10 % of acreage	25 % of acreage	50 % of acreage	100 % of acreage	10 % of acreage	25 % of acreage	50 % of acreage	100 % of acreage
11	26	53	105	47	118	236	472

Source: Own calculations and figure.

4.3 Sugar beet with virus resistance in the UK

Sugar crops are among the most important arable crops. While nearly 80 percent of the global raw sugar to be extracted come from sugar cane, the remaining 20 percent originate from sugar beets. Almost every second sugar beet is produced in the EU, and within the EU the UK is a major producer of sugar beets (FAO, 2021). Considering the increasing biofuel production, an increase in the demand for sugar cane as well as sugar beets can be expected (Stevanato, 2018).

To meet this increasing demand, various challenges must be met by sugar crop cultivating farmers as the cultivation of sugar beets – like many other arable crops – is confronted not only with several abiotic but also biotic stress factors that are negatively influencing crop development. Amongst them are plant diseases, weeds, and animal pests. Methods of integrated plant protection and management are, thus, the key for a successful agricultural outcome from sugar beet cultivation (Ladewig et al., 2018).

In this regard, sugar beets are especially prone to viruses, of which two shall be highlighted in the following, because they are especially interesting from a plant breeder's perspective: Beet Necrotic Yellow Vein Virus (BNYVV) and Beet Yellows Virus (BYV).

At a global and also European scale, one of the major constraints in sugar beet production is the rhizomania disease, which is caused by the BNYVV (Galein et al., 2018; Ladewig et al, 2018). The virus is soil-borne and was first discovered in Italy in 1952. The disease was also named "root madness" since it leads to a constriction of the taproot with a proliferation of lateral rootlets. More particularly, characteristic symptoms of the disease are the extensive proliferation of lateral rootlets leading to a root beard appearance (hence the term 'rhizomania') for root madness. Severe disease symptoms are the reduced size of the roots and typical constrictions of the infected taproots sometimes with nodules along the taproot (EFSA, 2020b). Necrosis of vascular is also found (Liebe et al., 2020).

The virus can be found in all sugar beet growing areas of the world. Most affected in the EU, however, are France, the UK and Germany (Galein et al., 2018; Capistrano-Gossmann, 2017; De Biaggi et al., 2010). Since rhizomania is considered the most damaging disease of sugar beet (EFSA, 2020b), the economic consequences of BNYVV are quite impressive. By and large, it is estimated that approximately 50 percent of all sugar beet crops grown worldwide are affected by this disease with an estimated overall loss of 10 percent of the global sugar production based on sugar beets (Biancardi and Lewellen, 2016)[64]. Also, a lower sugar content of minus 60 to 79 percent due to the virus was reported (De Biaggi et al., 2010) as a result of decreased root storability (Strausbaugh et al., 2008). And to make things worse, the disease can also lead to increase sucrose losses in storage (Strausbaugh, 2018) since plant resistance to low temperatures is decreased and freezing during storage causes tissue discoloration. That means further weight loss and a reduction of sugar (Strausbaugh and Eujayl, 2018). Finally, the abnormal proliferation of rootlets renders harvesting more difficult because of an increased amount of soil attached to roots and is furthermore complicating the sugar extraction process at the refinery (EFSA, 2020b).

In the EU, rhizomania is an extremely challenging and growing disease for the sugar beet sector. In 1990, the acreage affected by rhizomania in the EU was "only" approximately 15 percent of the cropped area. However, it increased to 36 percent in 2000 and is expected to have reached 56 percent in 2020 (EFSA, 2020b). Consequently, fighting the virus is a must but also a rather tricky undertaking[65]. It is actually only breeding that has provided meaningful solutions until now (Kuratorium für Versuchswesen und Beratung im Zuckerrübenanbau, 2021).

Indeed, since the mid-1980s rhizomania-resistant varieties have been actively cultivated to address the problem of virus infection (Capistrano-Gossmann, 2017), because the existence of a gene that confers partial resistance towards BNYW was already detected some decades ago. A few more resistance traits could be identified over the years and were broadly introduced into different sugar beet varieties (Stevanato et al., 2018; Pavli et al., 2011). As Galein et al. (2018) put it: The relevant genetic source of those resistance genes found decades ago are still used today throughout most sugar beet producing areas worldwide. Thus, the virus has endured a strong selection pressure since the 1990s.

Over the last decades the loss of resistance against the virus has consequently been observed and has been reported from sugar beet growing areas also in the EU, including the UK (Galein et al., 2018). One reason for such resistance loss can be the simultaneous existence of different types of the virus and resulting reassortments meaning the mixing or redistribution of genetic information

64 Other authors arrive at partly confirming and partly contradicting research findings. It has been reported, for instance, that the BNYVV can lead to a reduction of sugar beet yield by 45 to 50 percent according to conservative estimations (De Biaggi et al., 2010). Other sources even suggest a yield loss of up to 80 percent (Capistrano-Gossmann, 2017; Ladewig et al., 2018).

65 Due to its thick-walled resting spores, the virus can survive in soil for years (Pavli et al., 2011).

between two similar viruses. At the same time, existing resistance traits do lead to a lowering of symptoms in the plant while not offering a total protection from the virus. In consequence, this poses an option to the virus to adapt and to create resistance-breaking strains. As a result, the resistance in the plant loses its effectiveness against resulting new types of the virus (Galein et al., 2018). Thus, it is rather clear that the already ongoing breakdown of resistance with no other response available for farmers than using alternative sugar beet varieties could pose a serious threat to the specific arable crop sector. This is why new solutions by plant breeding have to be offered to the farmers to ensure sustainable solutions for plant protection. In fact, no other effective way to control BNYVV can be detected on the horizon.

De Biaggi et al. (2010) already suggested that assisted selection by molecular markers can significantly reduce the duration and cost to tackle rhizomania in plant breeding programmes. Where classical breeding is rather slow, laborious, and expensive, the use of molecular markers is a very efficient tool to select the desirable traits and design new sugar beet varieties. Subsequently, progress could already be achieved by strengthening the yields in resistant varieties of sugar beets. Nowadays, NPBT provide especially hope with respect to the identification of new sources of resistance in sugar beets, thereby helping to battle resistance-breaking by BNYVV. Research is now focusing on wild relatives of sugar beets for identifying resistance genes and widening the genetic base with gene-resolution mapping (Capistrano-Gossmann, 2017; Stevanato et al., 2018). Indeed, the identification of resistant genes that are present on other loci than those already found could be a crucial next step to breed and release new varieties with more sustainable resistance as regards the BNYVV (De Biaggi et al., 2010; Ladewig et al. 2018; Stevanato et al., 2018).

Various other molecular approaches to tackle sugar beet viruses are currently in the pipeline. An interesting application refers to the BYV, another major virus affecting sugar beets. Infections with BYV lead to yellowish discoloration of the older leaves and subsequently reddish necrosis may occur (Hossain et al., 2020). As such, the BYV also appears in all beet-growing areas throughout the world, and an early infection can thereby decrease yield by up to 50 percent[66] and increase impurity levels, while late infection has little effect (N.N., 2021). In opposite to the soil borne BNYVV, the BYV can be transmitted by insects and particularly by more than 20 different aphid species (Hossain et al., 2020), the most prevalent types being the green peach aphid and the black bean aphid (N.N., 2021). Aphids pick up the virus by feeding on infected plants and spread the disease to new plant hosts by feeding on the new host. Thereby, most of the virus transmission occurs within six to twelve hours after the feeding, although the aphids can retain the virus for a few days.

Until recently, a proper method to control the virus has been to control its host – namely the aphids. As large aphid flights occur in spring, one easy method of control would be planting after the spring flight, that means late in the growing season. However, this shortens the time for yield development. Hence, the application of PPP has been broadly used. In particular, the application of neonicotinoids

66 Interestingly, rhizomania-infected or BNYVV-infected plants are often also infected with BYV (McGrann et al., 2009). Mixed infections of BNYVV and the BYV are reported to cause yield losses as great as 83 percent (Stevens, 2005; Stevens and Asher, 2005).

helped control aphids in the past and saved the sugar beet crop from BYV manifestation (see Noleppa and Hahn, 2013). However, since 2018, neonicotinoids have also been banned in sugar beets by the EU (if no region-specific emergency approval applies).

This is the reason why another interesting application of NPBT shall be highlighted here. A new molecular approach developed by John Innes Centre (2021) in the UK aims at replacing neonicotinoid applications by using a so-called ultra-RNA approach that tries to capture the shape of the viral RNAs (introduced into the sugar beet through aphids) inside plants and use this knowledge to design specific artificial small interfering RNAs to target and degrade the virus. The expectation is that this process of replacing or substituting neonicotinoids in sugar beet cultivation could compensate for yield losses post the ban on neonicotinoids and be undertaken without environmental damage associated with chemical interventions, that means without future insecticide applications to sugar beets.

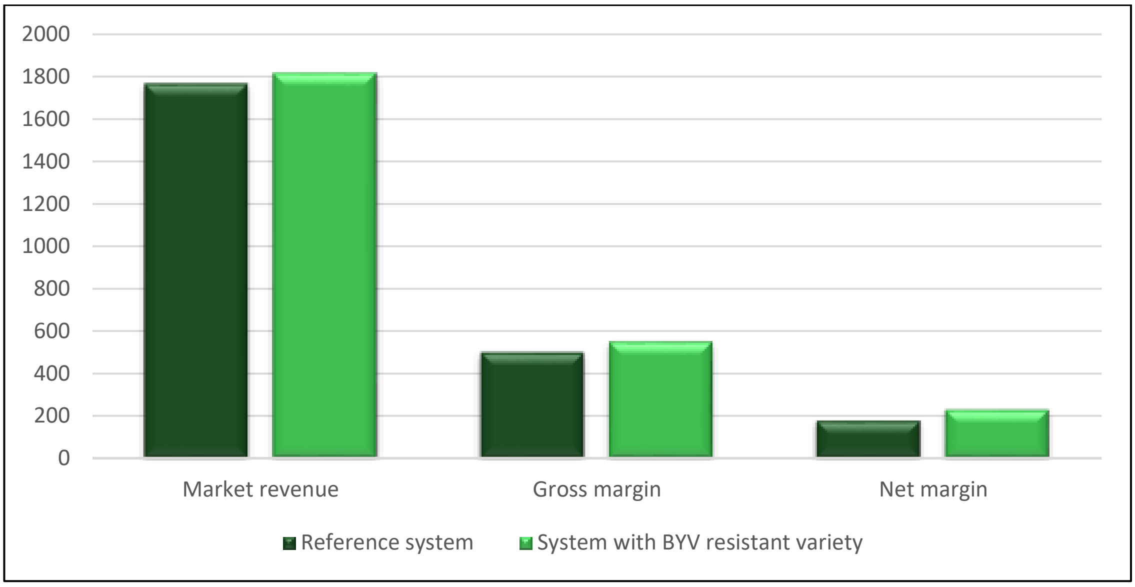
On farm level, the successful meeting of that expectation might create income improvements for sugar beet farmers in the UK as figure 4.5 depicts. The reference system – sugar beet production without the application of neonicotinoids but yield losses attributable to the ban on the specific PPP – is thereby confronted with an alternative (future) production system in which a BYV-resistant sugar beet variety developed through NPBT is used to assure a yield level alternatively achievable with neonicotinoids[67]. This, ceteris paribus, increases market revenues. Accordingly, the following results of this scenario approach shall be highlighted:

- A typical UK farmer growing sugar beets without neonicotinoids is described with Redman (2019) and can be assumed to generate a market revenue of 1 767 GBP per hectare.
- With a new BYV-resistant sugar beet variety bred through a NPBT, this farmer would potentially increase market revenue compensating for yield losses due to the ban on neonicotinoids currently worth 51 GBP per hectare (see again Redman, 2019).
- This would potentially increase the gross margin from 498 to 549 GBP per hectare, i.e., by approximately 10 percent.
- Further incorporating fixed costs in accordance with EC (2019a), a net margin increase from 174 to 225 GBP per hectare would occur. This is equivalent to a 29 percent higher profit.

On an exemplified base, the calculation shows that expectations of the impact of novel genome editing techniques on the sustainability and the competitiveness of sugar beets as an agricultural crop could be high. In fact, some predict an exponential increase in the efficiency of sugar beet breeding (Stevanato et al., 2018) along with contributions towards more environmentally friendly agricultural production (Vogel et al., 2018) – here in terms of PPP use for instance.

67 Noleppa and Hahn (2013) argue that yield losses in European sugar beet production in the absence of neonicotinoids may be around 2.8 percent.

Figure 4.5: Main economic indicators of sugar beet production at the level of a typical UK farmer without and with a BYV-resistant variety developed through NPBT (in GBP per hectare)



Source: Own calculations and figure.

4.4 Maize with drought resistance in the EU

The production of maize, in the context of this study: corn and green maize, is not only particularly relevant for food and feed, but also for the bioeconomy using the crop for energy and other purposes. Hence, maize as a primary cereal crop is certainly one of the most important crops due to its extensive use on a global scale (Liu and Quin, 2021) and in the EU.

A major problem for the cultivation of maize is drought. Drought is a problem at all stages of plant growth, but especially flowering and grain filling are threatened by drought conditions. To make things worse, the challenge of dry soil for the cultivation of maize is predicted to accelerate through climate change. Certain scenarios predict a decline of around 20 percent regarding the area suitable for maize production for the time beyond 2040 (Niles et al., 2020). In fact, climate change is considered to trigger a great adaptation stress for farmers in the maize sector as local drought events have been found to lead, on average, to yield and/or production losses of more than 30 percent (Li et al., 2019).

Although the percentage mentioned above is referring to the North American region, droughts should also be considered a European issue. According to Cammalleri et al. (2020), droughts triggered by global warming will happen more frequently, last longer and will become more intense in the EU and especially in its southern and western parts. Apparently, in 2100 drought losses could be five times higher compared to today, with the strongest increases projected in the Mediterranean and Atlantic regions of the EU. Such predictions should carefully be taken into account, because already now, yield losses in maize (here: corn) that can be associated with extreme weather events (such as droughts) can be around 4.0 tons per hectare in Spain and France (Ben-Ari et al., 2016). This is one third respectively half of the average harvestable yield (see FAO, 2021).

Irrigation may help to avoid such losses, but it is a rather expensive management option. Another option is targeted breeding. However, while conventional breeding strategies have certainly led to significantly increased maize yields over the past decades, they have not been able yet to provide the urgently needed enhancements regarding drought stress tolerance (Liu and Quin, 2021). In fact, all attempts with conventional plant breeding methods are considered as not sufficient to speed up the process of adapting seeds to the changing conditions of the climate (Niles et al., 2020). Against this background and also considering the expediting of climate change effects in agriculture, like drought, plant breeding based on NPBT is increasingly focusing on that specific objective of drought resistance and, in addition, on the reduction of the time necessary for developing new maize varieties.

Drought resistance in maize is embedded in a complex genetic architecture and subject to regulatory mechanisms in the plant. In the first years post the millennium, the identification and validation of candidate genes affecting grain yields and the morpho-physiological traits in drought-stressed maize via the reporting of quantitative trait loci was still described as "time-consuming and resource-demanding" (Tuberosa et al., 2002). Due to the extremely complex genetic basis of yield, improving and stabilizing crop performance under drought-stressed conditions is a slow, laborious and mostly empirical process when applying conventional breeding methods.

Nearly two decades later, as Liu and Quin (2021) formulate, some light has already been shed on the genome of the crop and the alleles that contribute to relevant traits of better drought resistance. With molecular breeding systems, including genome-wide marker-assisted selection and gene-editing technologies, hundreds of genetic variants in maize that are associated with drought-traits could be dissected. Still, the identification of the causal gene or variant poses a remaining challenge, and the exact candidates continue to be precisely identified (Liu and Qin, 2021; Jia et al., 2021).

Castiglioni et al. (2008), already stated that the opportunity exists for the drought-tolerant trait to be added to a growing set of germplasm and for trait options that mitigate environmental stress on the corn plant and provide the crop with better prospects to reach its yield potential in any environment. Subsequently, the authors concluded that biotechnology could support large-scale analyses of candidate gene functions in crops to assess the impact of certain genes on yields under given abiotic stress factors such as droughts. And indeed, a few years later Shi et al. (2017) successfully applied the CRISPR/Cas technology in maize to demonstrate that single endogenous genes can be modified to create novel variants that have a significantly positive effect on a complex trait like drought tolerance. Thus, CRISPR/Cas does already add to the precision breeding toolbox that focuses on the resistance of maize towards abiotic stress factors (see also Njuguna et al., 2017). A better understanding of the molecular regulatory mechanisms of drought response will certainly provide an urgently needed improved information base for upcoming maize breeding efforts. Such acquired knowledge could particularly support the development of new maize varieties that can adapt to and withstand the challenges presented by future water scarcity (Liu and Qin, 2021). Against this situation, the application of NPBT for maize breeding presents a huge chance in the next years – not least by reducing time and resources for maize crop breeding.

It is currently not an easy task to determine a potential yield-saving effect of drought-tolerant maize developed through NPBT. According to Liu and Qin (2021), the survival rate of maize across different genetic resources when confronted with severe drought stress is very diverse and ranges from 2 to 83 percent (see also Wang et al., 2016), This indicates a great genetic diversity in the maize germplasm and, hence, a huge potential is still to be leveraged.

Against this background, let us consider in the following a potential NPBT-based maize variety with respective drought resistance which does not result in yield losses in the case of at least a moderate drought[68] at European scale. Leng and Hall (2019) have analysed that such drought events are on the rise and will happen more frequently in the future. The authors also provide data which allow to calculate the yield and subsequent economic impacts in case of a drought for a particularly affected farmer at national scale. Accordingly, the following can be summarised for the case of a moderate drought affecting an average farmer in the EU: If affected, this average farmer will envisage a shrinking of the yield of maize (compared to a situation without a moderate drought) of approximately 3.0 percent.

Using these findings as an assumption for the modelling, figure 4.6 displays the economic consequences of avoiding such yield losses of an affected EU farmer growing corn and green maize due to the drought resistance of a variety potentially to be developed through a NPBT. Thereby, the reference system describes the situation with drought effects on yield, and the scenario describes the situation with a drought-resistant variety. Based on KTBL (2021), the following can be argued:

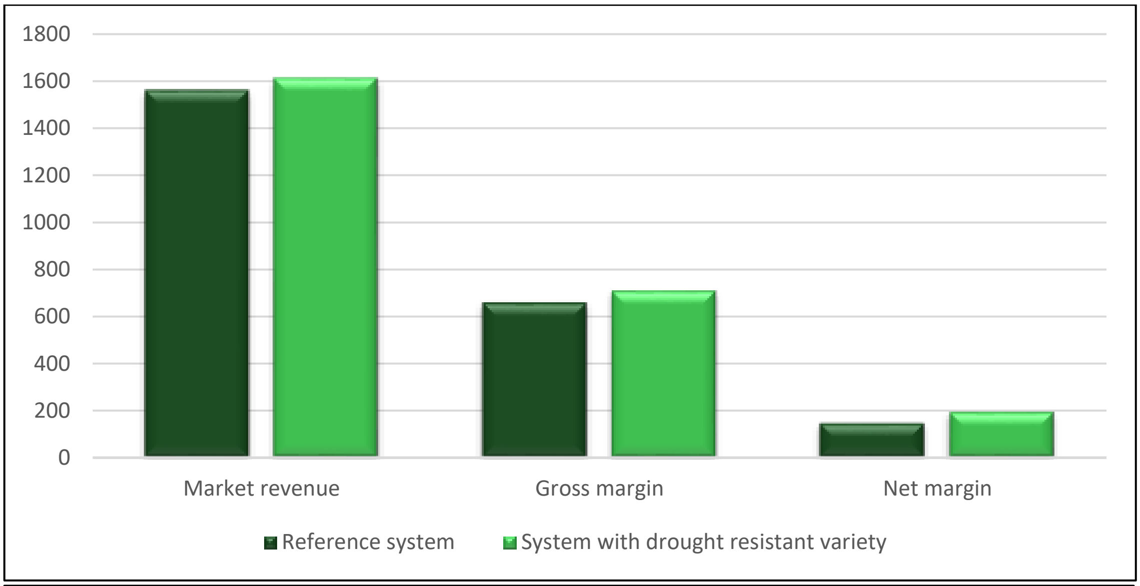
- A corn producing farmer would experience a market revenue loss of 48 EUR per hectare in case of a moderate drought without the availability of a drought resistant maize variety. With such a potential variety developed through NPBT, the farmer would be able to avoid a gross (net) margin loss of 6.8 (25.3) percent.
- Similarly, an average green maize-cultivating farmer in the EU would envisage a market revenue loss of 61 EUR per hectare leading to a gross (net) margin loss of 5.7 (25.9) percent.

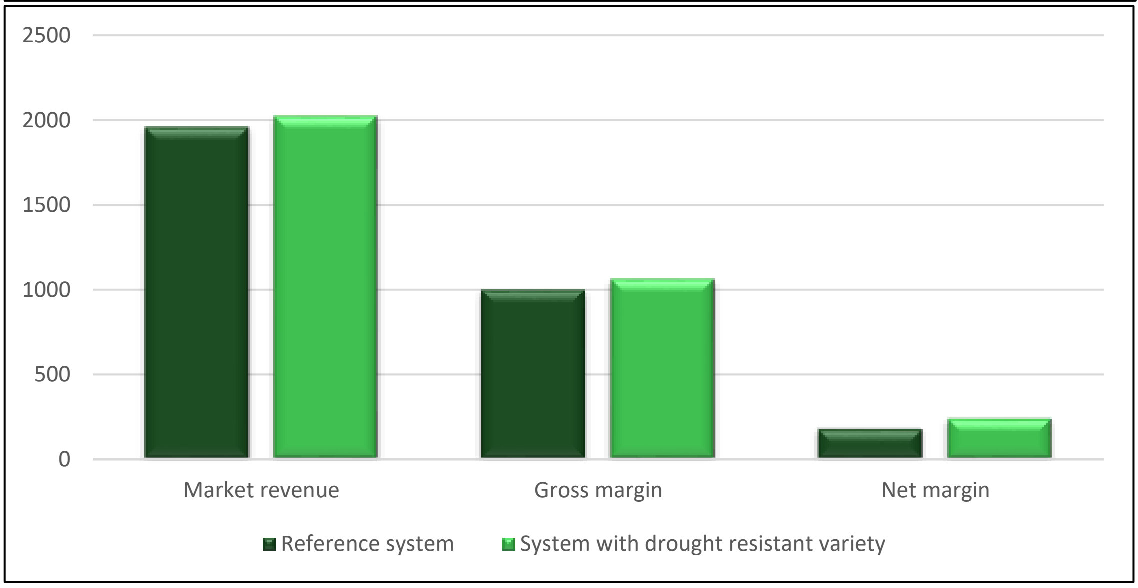
Droughts are usually local weather events but may occasionally also hit larger regions and even entire countries. Hence, it is very speculative to analyse such country-wide or even EU-wide

68 Moderate droughts can be distinguished from severe, extreme, and exceptional droughts. The specific definition depends on several drought indices which have been established by science (see Leng and Hall, 2019). By and large, a moderate drought should be considered a drought event leading to less than "average" drought-related implications. Impacts of severe, extreme, and extraordinary droughts are – by definition – respectively higher.

consequences. However, the impacts of droughts on the national production scale should not be underestimated. Leng and Hall (2019) state that the likelihood that farmers are frequently hit by a moderate drought is high at national scale and can be assumed to appear well above 50 percent[69].

Figure 4.6: Main economic indicators of corn (above) and green maize (below) production at the level of a typical EU farmer without and with a drought-resistant variety developed through NPBT (in EUR per hectare)





Source: Own calculations and figure.

69 If we assume that 50 percent of all maize acreage in the EU is frequently hit by a moderate drought, the avoiding of 3.0 percent yield losses may potentially be used to not cultivate almost 250 000 hectares with corn and green maize while still satisfying domestic demand. This would surely also lead to considerably decrease the continuously high pressure on scarce arable land.

4.5 Grapevine with fungi resistance in Italy

Grape as an agricultural crop plays an essential role for a large number of products, like jam, juice, jelly, raisins, vinegar, grape seed extracts, grape seed oil, the fruit itself, and – last but not least – wine. Besides, grapes provide valuable fibre, nutrients, and antioxidants for which they are today an integral part of a healthy diet in modern societies (Malnoy et al., 2016; Wang et al., 2018). Grapevine does cover around 7.0 million hectares in global production (Wan et al., 2020), and more than 40 percent of this area is in the EU (FAO, 2021). Within the EU, Italy – next to France and Spain – is a large grapevine producer in terms of area. Almost 0.7 million hectares, i.e., each tenth hectare of the entire global grapevine acreage can be found in this EU member state. Consequently, grape does have a great economic value for the global production of perennial crops in general as well as for winemakers in the EU and selected member states in particular.

The quality of grapes and their yield are directly affected by abiotic as well as biotic stress factors. Especially fungal diseases pose a key challenge to the grapevine industry. A relatively high humidity and/or moisture in combination with rather cool temperatures favour the development of fungal diseases of grapes, which affect the leaves, shoots, stems, and fruit. Thus, fungal diseases can render fruit unusable and can very easily cause severe losses in yield. Indeed, crop losses can be devastating ranging from 5 to 80 percent depending on the disease load in a vineyard, weather, and cultivar susceptibility.

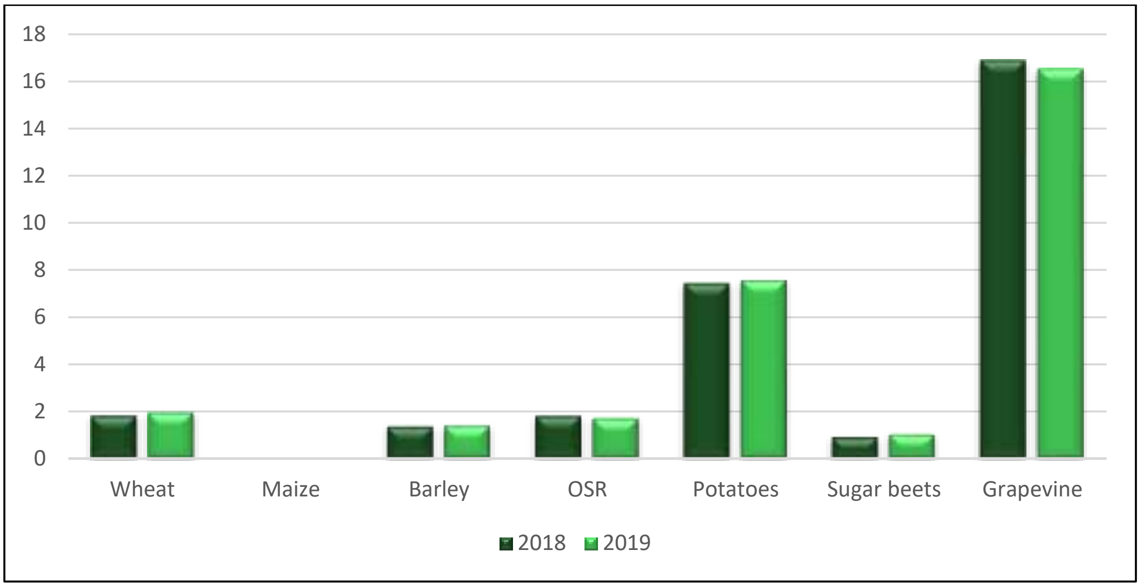
In this respect, black rot, white rot, powdery mildew, downy mildew, and grey mould are the most common and potentially devastating fungal diseases of grapevine (Srobarova and Kakalikova, 2007). Among them, two of the currently most challenging fungi diseases relevant for grapevine are powdery mildew (Wan et al., 2020; Malnoy et al., 2016) and downy mildew. According to Bois et al. (2017), the frequency and severity of these two grapevine diseases are especially high in Europe, and the specific diseases are obviously also highly adaptable to a broad spectrum of changing climate what could make upcoming management of the diseases a challenge.

So far, fungi and especially mildew disease management in grapevine cultivation in the EU has mostly concentrated on chemical control options. Since numerous multiplication cycles of the fungi may occur during a season, several applications per year, starting at shoot-growth, continuing with immediate pre-bloom and post-bloom, and also taking into consideration disease risks as determined by weather conditions and forecasting models are advised to maintain continuous protection of the crop and fruit (Buonassisi et al., 2017). This may end up with biweekly applications of fungicides, because otherwise serious effects with respect to the final grape yield and quality must be anticipated[70]. Against this background, it has been estimated that in the EU alone 68 000 tons of fungicides have been applied annually in recent years just to control grapevine diseases. This would amount to more than 50 percent of all fungicides used in EU agriculture (Eurostat, 2021f). In fact,

70 Mildew diseases in grapevine can devastate up to 75 percent of the crop in one season while also weaken newly born shoots causing serious economic losses (Buonassisi et al., 2017).

compared to many other agricultural crops, especially those being in the focus of this study, the number of fungicides applied to grapevine is enormous as figure 4.7 visualises.

Figure 4.7: Number of applications of fungicides per season in various arable crops and grapevine



Source: Own figure based on JKI (2021).

While powdery mildew and other fungal diseases can currently still be controlled in the field with frequent applications of fungicides, it is obvious that considering a rapid emergence of new fungal strains and the effects of fungicides on the environment, alternative and more sustainable strategies will have to be found for tackling the problem in the future. Against this situation, one of the key interests in current plant breeding research is to understand what kind of mechanisms grape has and can potentially be developed to resist such biotic stress impacts like fungal diseases (Wang et al., 2018).

The ambition to create a fungi-resistant grapevine variety has already been followed-up by conventional breeding programmes. However, a key difference for the grapevine sector when compared to other crop sectors lies in the protection of its traditional grapevine varieties that bring the specific character and resulting economic value to famous wines. Traditional crossing and selection schemes lead to a new genetic identity of the traditional varieties changing their character to an extent where a new variety is created. Such new varieties could not be equally qualified as, for instance, Appellation d'Origine Protégée (AOP)-wines or Denominazione di origine controllata (DOC)-wines consequently losing such relevant economic and quality criteria (Bruins and Morgante, 2021). Furthermore, the knowledge that has been gathered by winemakers over centuries would no longer be directly applicable to those new varieties bringing additional challenges for the wine producing industry. Therefore, plant breeding is facing different challenges in the grapevine sector: The preservation of traditional genotypes is key for the preservation of the relevant brand and has to go hand in hand with the modification and/or inclusion of genetic traits with desired or undesired characteristics.

This is where the application of NPBT could bring additional advantages when compared to traditional crossbreeding. In accordance with Bruins and Morgante (2021), potential advantages in general are that (a) resistant varieties could be generated in a shorter amount of time, (b) the amount of DNA that is brought in from, for instance, resistant wild types could be limited to the resistant genes themselves, and (c) the genetic identity of relevant elite wines would not be changed while traditional grapevine varieties would still be able to achieve a high level of fungi-resistance within their otherwise unaltered DNA.

A more particular advantage of the application of the CRISPR/Cas technology, for instance, lies in its ability to not only deploy resistant genes but also to simply inactivate those genes that are specifically creating susceptibility to certain pathogens. With respect to the powdery mildew fungus, a respective susceptibility gene has already been identified and progress has been achieved:

- Malnoy et al. (2016) could successfully apply CRISPR/Cas for silencing a susceptible gene in grapevine varieties, thereby increasing the resistance of the crop towards powdery mildew.
- In addition, Wang et al. (2018) could efficiently generate biallelic mutant lines in the first generation of grape transformants showing that desired genetic changes can successfully be passed over to the next generation.
- Also Wan et al. (2020) could show targeted mutations in grapevine cultivars which lead to enhanced resistance to powdery mildew.

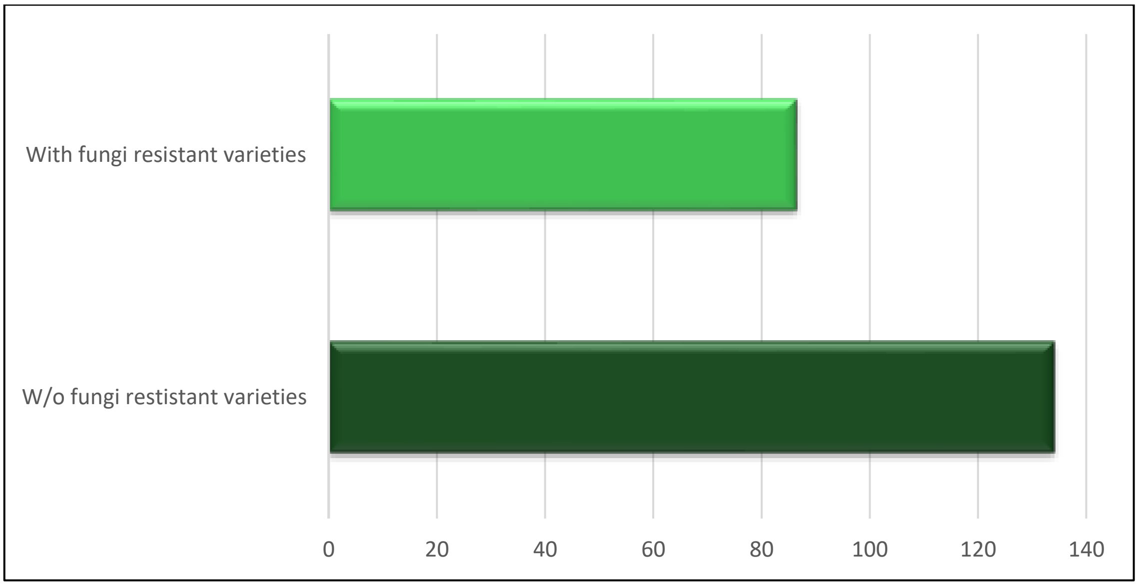
These findings add further relevance to grape gene functional research and molecular breeding in the grapevine sector and could provide interesting new options to increase the resistance of traditional grapevine varieties against biotic stress factors in the future while keeping their individual characteristics for the production of traditional elite wines.

Following Bruins and Morgante (2021), expectations are high. NPBT are considered to be able to reduce fungicide applications in grapevine without negatively impacting yield. Potentially, the number of treatments could go from 10 to 20 (see again figure 4.7) for traditional varieties down to 2 to 3 for the resistant ones. This would save production costs. For a normal year it is suggested that (fungicide-related) costs could be reduced by 60 to 80 percent.

This expectation will now be used to showcase the potential impact of applying NPBT in grapevine at the consumer level. Therefore, a bottle of Italian wine as preferred by the consumer is defined. Using data from Marone et al. (2017), it can be stated that such an "average" bottle from Italy embeds costs of 6.03 EUR (ranging from 4.20 to 11.21 EUR) [71]. Exactly one third of these costs can be attributed to grape production on field. That is 2.01 EUR per bottle (see again Marone et al., 2017). The costs for controlling fungi diseases are usually between 20 percent (Malnoy et al., 2016) and 30 percent (KTBL, 2020) of total production costs. Assuming 25 percent of total costs on field belonging to fungicides and the application of respective PPP, this would mean to take into account approximately 0.50 EUR per bottle of Italian wine. If 60 to 80 percent, or on average 70 percent, of these specific costs could be avoided by using fungi-resistant grapevine varieties developed through NPBT, this would mean to reduce costs per bottle by 0.35 EUR or almost 6.0 percent.

Another impact might even be more important – also from a consumer perspective. It has been stated above that approximately 68 000 tons of fungicides are annually still used in the EU to combat fungi in grapevine production. If really 70 percent of these PPP were able to potentially be avoided in future via fungi-resistant grapevine varieties being the result of successful applications of NPBT, this number could go down to 20 400 tons of fungicides. The effect on the overall fungicide use in the EU would be substantial as figure 4.8 depicts.

Figure 4.8: Use of fungicides in EU agriculture with and without fungi-resistant grapevine varieties developed through NPBT (in thousand tons)



Source: Own figure based on JKI (2021).

By and large, it can be stated that such a single shift – induced through modern plant breeding methods – would create a substantial benefit not only in terms of the economy but the environment as well: More than one third of all fungicides yet used in the EU could be obviated.

71 The authors compare different kinds of bottled wine and also calculate an average for "the total".

Excursus on the time effect of NPBT

The case studies on potential impacts of resistant varieties developed through NPBT illustrate on an exemplified base that specific genetic crop improvements may lead to remarkable benefits at farm and also societal level if successfully implemented. However, it is not the individual case that should count but the overall potential these technologies have to contribute to plant breeding progress in general. Examples should not only refer to plants that are more resistant to certain diseases and certain environmental conditions or climate change, but also to improved agronomic and nutritional traits, a reduced use of agricultural inputs such as PPP and fertilizers – and faster plant breeding (see also EC, 2021).

In the case study-related sub-chapters above it has been mentioned several times that NPBT are able to speed up trait introduction during the variety development process. With respect to major arable crops, conventional breeding methods need ten to twelve years to generate a new variety that can be released and subsequently be used on field (see, for instance, Boldt, 2020; Chen et al., 2019; Kaiser et al., 2020; Zaidi et al., 2020). This is because in conventional plant breeding genetic mutations occur (induced) randomly and need to be selected through backcrossing over several generations and years. Especially trait mapping and early generation selection are time-consuming processes that may take some years to complete but can be shortened with for instance CRISPR/Cas. In particular, the insertion of mutations at a specifically desired site in the genome creates a huge time advantage (Jarasch, 2019). The challenge is to precisely define the potential time to be saved through NPBT even though Zaidi et al. (2020) argue that this saving will be substantial.

Let us take a conservative approach and assume that NPBT will save two years of the time that is necessary to develop and release a new variety. Then, not ten to twelve (or on average eleven) years as mentioned above but "only" nine years would be needed to release a variety embedding a new characteristic. This would speed up plant breeding progress per time unit by 18 percent. In the future, hence, not only 1.16 percent of plant breeding-induced yield growth would be possible per year (see again figure 2.24) but 1.34 percent per annum. If this was implemented starting in 2030 (in nine years) and continued for ten consecutive years, the accumulated plant breeding-induced yield progress on fields in 2040 would not be 26.3 percent (see again figure 3.10) but 28.9 percent.

The additional 2.6 percent might not sound impressive at first glance. However, for reaching the ambitious goals of, for instance the "Farm to Fork" and "Biodiversity" strategies at European scale or the Sustainable Development Goals at global scale each percentage point counts. Not using such an option for additional progress would mean to miss opportunities. This may be related to an economic performance (as in the case studies above) but should much more be seen as a huge pro also in terms of other societal goals, as for instance this 2.6 percent of potentially additional harvest would be enough to provide food for almost 20 million more humans, to avoid GHG emissions of roundabout 350 million tons (which is as much as the annual GHG emissions of France) and save biodiversity currently still living in about 2.0 million hectares of average global natural or nature-like habitats. With these drastic illustrations in mind, the particular importance of the time-saving impact of NPBT becomes obvious.

5 Recommendations for private and public decision-making

In the introductory remarks of this research, it has been argued that global demand for agricultural products in total will most likely grow in the range of 2.0 percent and more per annum in the next few decades. Major reasons behind this potential development are population growth and an increase of income that results in dietary shifts. In addition, an acceleration of the demand for agricultural raw materials to be used more frequently and intensively as input in various industrial and energy producing processes must be considered. This alone implies that agricultural production and foremost productivity must considerably increase – however, not at the expense of environmental goods.

In fact, economic development must sustainably be linked with environmental protection. This multi-layered perspective has undoubtedly become a common understanding, and joint efforts to achieve economic prosperity, social progress and environmental protection are needed for turning former trade-offs into future mutual wins. Provided that the EU sees itself as a responsible actor that accepts the global and regional challenges involved herein and wants to play its part in meeting these challenges, it follows that economic, social, and environmental considerations must be taken into account in a balanced way when making decisions. This decision-making concerns not only policy makers but also private business – in the EU and elsewhere around the globe.

Plant breeders should be aware that their efforts have helped and can continuously help create synergies and avoid trade-offs embedded in multiple objective settings. This study clearly shows that along with socio-economic benefits also environmental advantages are provided through successfully innovated genetic crop improvements in the EU. In other words: Plant breeding counts and must be seen as a highly effective measure for adapting to new challenges and mitigating negative consequences which may arise while addressing these challenges. However, one question remains: Is plant breeding able to even do more than it already contributed for achieving relevant societal goals in the past?

It certainly should. Plant breeding, nutrition and health are major factors to be addressed for making full use of a crop's potential which can further be lifted by proper land machinery. However, the usable innovation potential that lies in these factors is different. Already now, the share of plant breeding in innovation for arable crops cultivated in the EU is greater than the innovation share of all other mentioned factors together (see chapter 2 of this report). In the future, this share might be even greater since (a) societal pressure might create disadvantageous framework conditions for further investments into and, hence, innovations coming from plant health and plant nutrition while (b) capital-intensive technologies have long-lasting depreciation intervals and cannot be substituted continuously and at short notice. Subsequently, increasing crop productivity through the development of superior plant varieties may play not only a more accentuated but even substantiated role when compared to the adaptation of other improved land and crop management practices in the EU.

This makes plant breeding an extremely important area of research and development (R&D) and, of course, business. Plant breeders must take responsibility by investing even more (than before) into innovation as the rate of improvement of genetic potential has to be increased beyond the current rate and pace. This is a key variable for assuring global food availability in times of – among others – growing world population and climate change (Voss-Fels et al., 2019). Consequently, these investments do not only have to target higher and stable harvestable yields but also other characteristics of a plant.

Increasing yields are certainly still one of if not the most important breeding objective(s) with respect to all arable crops cultivated in the EU. This makes sense – given the afore-mentioned gap between a global demand growth of (well above) 2.0 percent per annum and an average EU yield growth of around 1.2 percent per year as in the recent past. Hence, the rate of genetic yield improvement must basically double to meet future demand (Voss-Fels et al., 2019). However, harvestable yields are also a result of the amount of yield losses prior to or during harvest (see chapter 4 of this report). Accordingly, objectives with respect to yield stability – mainly in terms of breeding for various resistances – must gain importance. A soaring resistance to pests and diseases and an increased tolerance to droughts, cold spells, and heavy rains are consequently emerging objectives plant breeders already have in mind and will increasingly have to consider.

Moreover, plant breeders must cope with various other societal and consumer preferences: Crops should use less resources in terms of nutrients and water, for instance, and they should also add value in terms of certain quality characteristics such as protein and/or oil content, micronutrient content, and colour or taste. In other words: Future plant breeding has simultaneously to aim at yield increases, pest and disease resistance, other agronomic traits, product quality, crop adaptation and genetic diversity (see also Qaim, 2019). In addition, it should more often target also orphan crops. This analysis, for instance, has shown that EU plant breeding progress in the past two decades has been remarkably lower in the case of pulses and other oilseeds than in the case of other big cash crops. However, both groups of crops are considered to play a more pronounced role in human food consumption in the future due to expected dietary shifts (De Ron et al., 2017) and also in view of agricultural biodiversity and crop rotation.

It becomes clear that yield and many other complex characteristics of a plant have to be targeted in a successful manner by plant breeders in the near future. This will also help meet specific objectives of the EU. Frans Timmermans, Executive Vice-President of the European Commission, said: *"At the heart of the Green Deal the "Biodiversity" and "Farm to Fork" strategies point to a new and better balance of nature, food systems and biodiversity; to protect our people's health and well-being, and at the same time to increase the EU's competitiveness and resilience. These strategies are a crucial part of the great transition we are embarking upon."* (EC, 2020d). If this better balance of environmental, social, and economic issues was already to be achieved by 2030 – as the two strategies suggest – and if this was to come along with no or at least minimised trade-offs, a lot more and faster implementation of innovation than in the past would be needed in the arable crop sector.

Plant breeders in the private but also public science sector are certainly willing and have the tools to do so. In fact, many genetic resources and breeding tools are presently available. Accordingly, conventional breeding has provided and will continue to successfully provide crop improvements. In addition, NPBT allow to address new challenges of agriculture and the environment. With this increasingly sophisticated toolset, plant breeders will certainly be able to push forward genetic gains to develop crops that can withstand the impacts of climate change while reducing the environmental impact of agriculture, supporting global food security, and offering other economic benefits (Conrow and Cremer, 2021). Yet, the success of NPBT is not guaranteed at the science level alone – it is also influenced by social acceptance and policy decisions (Lassoued et al., 2018).

This is where the role of policy makers and regulators comes in. Indeed, EU plant breeders are currently facing a very challenging policy and regulatory framework in the area of NPBT as these methods are caught up in the rather restrictive legislation the EU has deployed as a consequence of controversial discussions and debates (see also Voss-Fels et al., 2019). To encourage plant breeders to further (and even more) invest into the development of new and better seed varieties and the therefore needed sophisticated breeding technologies, appropriate policy decisions and, in addition, public support are a must. In fact, the obviously high societal rates of return that plant breeding investments can generate (see also Lotze-Campen et al, 2015) should be broader acknowledged and politically supported. Such policy support should include strengthening R&D as well as fundamental research in plant breeding and making evidence-based policy decisions.

One option to do so is higher and/or more targeted financial support. The EUR 10 billion dedicated along with the two strategies to R&D might help regarding the funding of basic plant breeding research. The funds could partially be used for public and public-private R&D in plant breeding as a major driver of future mutual benefits. For instance, fundamental research in plant sciences and testing in field trials of novel crop varieties could be (co-)financed. Ongoing and increased investment from the public (and private) sector is necessary not only to maintain but also to enlarge the existing capacities for further crop improvements (Voss-Fels et al, 2019). In this respect, the "Farm to Fork" strategy does already acknowledge that latest research and subsequent innovative techniques, including biotechnology, may play a more important role in increasing sustainability (Purnhagen et al., 2021). However, what is still missing are concrete policies and measures for this specific strategic aim of advanced R&D to become tangible reality.

Another option for policy support is public awareness raising. This study is also meant to increase such an awareness by providing evidence for the multiple benefits of plant breeding in agriculture and beyond based on reproducible findings and scientific facts. In particular, the results of this study should help to better inform and facilitate an unbiased public debate on the importance of genetic crop improvements for specific socio-economic and environmental objectives. As such, this study should be considered a contribution supporting and motivating this public debate. However, further and foremost interdisciplinary research and evidence-based information campaigns need to follow and should be supported by policy makers and other public decision-makers including scientists. According to Williams et al. (2021), the public (in a high-income country) has got a limited knowledge and awareness of standard practices applied in the agricultural sector and research in this area. A better understanding of the science behind plant breeding may help increase public perception and knowledge about its usefulness also in meeting future societal challenges.

Finally, a proportionate and result-focussed regulatory framework is needed to establish clear and sustainable rules for the European plant breeding sector. Instead of delaying or even hindering European plant breeders to spend the necessary resources on urgently needed future economic productivity increase and environmental resource use efficiency growth, such a legal setting should encourage them. Indeed, current EU legislation seems to increase time and cost of variety development (Zaidi et al., 2020). Specifically, the current regulatory framework of the EU handling NPBT in the same way as genetically modified organisms (GMO)[72] results in disincentives for investments into NPBT as approval and marketing costs become very high. It negatively impacts public and private research on NPBT (EC, 2021b) and almost obstructs the development and efficient use of these methods (Qaim, 2020). Thus, it makes plant breeding with such sophisticated technologies a costly option in terms of money and time, creating uncertainty and delaying investments (Lassoued et al., 2018; Purnhagen and Wesseler, 2019; EC, 2021b).

NPBT constitute a diverse group of techniques, each of which can be used in various ways to achieve different results and products. Therefore, safety considerations depend on the individual technique, how it is used and the characteristics of the resulting product and cannot be made on all techniques in total. Moreover, expert opinions consider that genetically and phenotypically similar products deriving from the use of different techniques are not expected to present significantly different risks. EFSA (2020a) particularly did not identify new hazards linked to targeted mutagenesis and cisgenesis as compared with conventional breeding and established genomic techniques. EU policy makers and regulators should take this into consideration when discussing potential future regulatory options.

To conclude, we have shown that plant breeding in the EU has made and will continue making important contributions towards sustainable agriculture covering all pillars of sustainability – the economy, the social sphere, and the environment. Meeting the sustainability criteria is also a major impetus that comes from the "Farm to Fork" and "Biodiversity" strategies. In this respect, plant breeding and the two strategies can be considered congenial partners that depend on each other and can reinforce each other's positive effects. Among the objectives of the two strategies are not only a few which can be considered benefits that plant breeding may help provide[73]; much more, this study could show that this perspective needs to be turned the other way around: Without

72 In 2018, the Court of Justice of the EU ruled that CRISPR/Cas-based plant breeding is not immediately exempted from existing EU regulation of GMO. This decision places plants engineered via NPBT under GMO regulations (see Wesseler et al., 2019).

73 Also, EC (2021b) states that plant products obtained from NPBT have the potential to meaningfully contribute to the objectives of the "Farm to Fork" and "Biodiversity" strategies, hence, the EU's Green Deal. In addition, such products may also contribute to various Sustainable Development Goals (EC, 2021b).

accelerating plant breeding in the EU in the future, the objectives of the “Farm to Fork” and “Biodiversity” strategies and, hence, the European Green Deal can hardly be achieved.

To credit this great importance, European plant breeders must be increasingly recognized by policy makers, regulators, and the society as supporters of sustainable development in agriculture and beyond. Policy makers should foster innovations in general, but explicitly plant breeding innovations, while regulators should count on a science-based approach and particularly on the scientific prove regarding the safety and usefulness of novel plant breeding methods. And while discussing particular societal objectives, society at large should look more holistically and fact-based on plant varieties developed through conventional as well as latest breeding methods, thereby acknowledging the various positive societal impacts these varieties cause.

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Annex A: Description of the total factor productivity calculation approach

This study, similarly to HFFA Research (2016), counts on the peer-reviewed TFP calculation approach developed by Lotze-Campen et al. (2015) and proven to be genuine since it allows to abstract from land as a production factor. Thus, it allows to directly compare TFP growth rates with changing yields per hectare to simplify the calculation process and to approximately determine TFP for specific crops. Accordingly, a hectare-related TFP change rate can be calculated as follows:

(1) $dTFP/TFP = dQ/Q - (DI/I) * SI - (dL/L) * SL$

with: Q= index of production (i.e., yield),

I = index of all intermediate inputs used (e.g., fertilisers, PPP, machinery, and seeds),

L = index of labour input, and

S = expenditure shares of the specific production factors (excluding land).

Looking at equation (1), it becomes apparent that weighted change rates with respect to the various input factors (other than land) need to be subtracted from yield changes to come up with meaningful TFP growth rates. Developments in factor use consequently need to be incorporated into the analysis.

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Annex C: List of references for definition of plant breeding shares in innovation-induced productivity growth

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Annex D: Methodological particularities of the embedded models of agricultural economics

Modelling market developments

For this analysis, a partial equilibrium model was used. It is based on an already existing own multi market model (MMM) (see, Lüttringhaus and Cartsburg, 2018) and fed with current data. It was also further modified and calibrated to fit the reference scenario and time horizon of this study.

In the context of this research, a MMM is understood as a multi-market, multi-regional market model. This model type is a common standard in the economic analysis of agricultural processes. Such models are especially useful for the consideration of alternative production, demand, and policy scenarios (Sadoulet and de Janvry, 1995; Saunders and Wreford, 2005) and the analysis of the resulting quantities supplied and demanded (Francois und Reinert, 1997).

By means of the specific MMM, changes can be calculated not only for the EU in total, but also for the selected EU member states and other world regions. This means that interactions between single markets and individual regions can be quantified simultaneously. The applied MMM therefore distinguishes between the EU as well as Germany, France, Italy, Spain, and the UK (and the rest of the EU). Main trading partner regions are also considered: North America, South America, Asia, MENA, Sub-Sahara Africa, Oceania, CIS, and RoW. Crop-wise wheat, corn, other cereals, OSR, sunflower seeds, other oilseeds, sugar crops, potatoes, and pulses are distinguished.

The accordingly specified MMM is a comparative static partial equilibrium model. Two equilibria can be compared: a reference equilibrium and an alternative (shocked) equilibrium. In this context, partial means that only certain selected markets and not the entire economy and all its sectors are depicted. One important model assumption thereby is that domestic and foreign goods are perfect substitutes.

International trade is modelled as the difference between supply and demand in every region and all markets. The model is then closed by the assumption of a market equilibrium. For this, the RoW is defined as described above and the trade flows are calibrated so that the global supply (of all regions, including RoW) equal global demand on all markets. In other words: All markets clear at equilibrium prices. Market reactions to changes per region are quantified by means of elasticities. Thus, this model consists in essence of a rather complex system of equations which must be solved simultaneously. A shock to the market(s) resulting from a move from the reference system to one of the alternative (shock) scenarios is the result of an iterative process that solves the system of equations.

The concrete model used here is based on the USDA's modelling framework "Static World Policy Simulation" (see e.g. Roningen, 1986; 2004; Roningen et al., 1991), which has been used in other studies as well (Saunders and Driver, 2016; Blandford, 2015; Jechlitschka et al., 2007). Accordingly, the model makes use of isoelastic Cobb-Douglas functions (for details see Chiang und Wainwright, 2005). Cobb-Douglas supply and demand functions have a long tradition in agricultural economic analysis (see, e.g., Ledebur, 2001). Markets are linked with each other by means of cross-price elasticities. The result is a consistent system of equations which meets the homogeneity and symmetry conditions for proper modelling (Chiang und Wainwright, 2005).

In the context of this study, the change in supply is modelled by a pivotal adjustment, i.e., by a multiplicative link of shift factors (changing the intercept). This is a time-proven procedure in equilibrium modelling (see, e.g., Kazlauskiene and Meyers, 1993; 2003; Cagatay et al., 2003). The advantage of the specific approach is that shocks to the system may be quantified in a straightforward fashion as a relative change rate.

This well-structured MMM is fairly data intensive. Therefore, particular care has been taken in choosing reliable data and consistent other information. Most data are from public sources. Random shocks are accounted for by using three-year averages of the most recent information available. Accordingly, prices are, for the most part, based on various dashboards from EC (2021a) supplemented by IndexMundi (2021) data. Data on supply quantities are from Eurostat (2021b) as well as from FAO (2021). Information on demand has been obtained from FAO (2021). Elasticities are gathered partly from the World Food Model (FAO, 2003) and the FASOMGHG model (see Adams et al., 2005; Beach et al., 2010), but most of all from Roningen (2016).

Modelling further socio-economic changes with multiplier analysis

This study's goal is not solely to conduct an economic impact analysis on the agricultural market level, i.e., the sector level. It additionally aims at assessing the included benefits for the rural sector and the entire economy. These benefits are attributed to farm input suppliers as well as downstream food and other industries depending on farmers' decisions. Changes affecting primary agricultural markets almost immediately impact interlinked upstream and downstream sectors of an economy. This is because changing production also requires adaption in processing, packaging, manufacturing, trading, retailing, etc. Against this background, GDP and labour effects are of particular interest.

Multiplier analyses permit the assessment of such effects. Multipliers are parameters, which reflect the transmission of a particular sector change into an economy-wide change. They have often been applied in agricultural economic analyses (see e.g., Breisinger et al., 2010; Mattas et al., 2009; Schwarz, 2010). Relevant multipliers for the analysis provided here have been taken from a comprehensive meta-analysis on such parameters. More particularly, most recently calculated output and workforce multipliers for EU arable farming and specific (groups of) crops published by Fuentes-Saguar et al. (2017) are used as these multipliers – by and large – are supported by Cingiz et al. (2021).

Annex E: Methodological particularities of the embedded models of environmental economics

Modelling virtual net land trade

The virtual agricultural land trade approach used here is based on the concept of virtual inputs initially developed by Allan (1993; 1994). The basic idea is as follows: Essentially, any good being produced requires inputs. The inputs used in the production of a good are then considered a virtual part of this good. Hence, when a good is traded internationally the virtual input is traded simultaneously. By analogy, we define virtual land as the amount of land that is required to produce one unit of a given agricultural good. In essence, this means that the import of agricultural goods adds land to the domestic resource base, while the export contributes to reduce it.

Eurostat (2020) data have been used to analyse the EU's virtual agricultural land trade. International agricultural trade volume flows, i.e., export and import tonnages, which are based on the Standard International Trade Classification (SITC) are point of departure for the particular analysis. The SITC categories distinguish various degrees of processing meaning that goods from identical raw materials (e.g., wheat) may end up in different classifications (e.g., wheat flour, feed preparations, pasta, etc.). However, they can as well always be attributed to their raw material again.

Nevertheless, the conversion of agricultural trade data into land trade information is a rather complex methodological issue. Calculating virtual land trade from agricultural trade statistics requires several intermediate steps to be performed for each SITC category:

- First, it is essential to re-convert traded agricultural goods back into their respective raw material using consistent technical parameters and suitable conversion factors. Here, technical parameters from FAO (2012) have been obtained for proper conversion.
- The resulting "primary" trade volumes (in terms of agricultural raw products) have then to be related to annual regional yields. The respective yield information is taken from FAO (2021) and allows to compute region-specified land used for exports or imports.
- Finally, it is necessary to calculate the net imports respectively net exports of virtual land for every single SITC category, therefore for every internationally traded agricultural commodity, and for each trading partner of the EU.

Using this gradual approach SITC by SITC category, it is possible to sort the traded agricultural goods into different crop groups of agricultural raw materials including wheat, corn, other cereals, OSR, sunflower seeds, other oilseeds, sugar beets, potatoes, and pulses. Green maize, however, is not considered to be traded internationally. Applications of the self-developed methodological concept used here can also be found in Kern et al. (2012) and Lotze-Campen et al. (2015). Meier et al. (2014) as well as UNEP (2015) also use it as a reference system for own research.

Modelling resulting GHG emissions

All other things being equal and given the fact that worldwide – except in the EU (see Searchinger et al., 2008) – more and more land is being used for agricultural purposes, an extra amount of virtual land the EU would need has to come from additional land use changes elsewhere and particularly from converting natural or nature-like habitats into acreage. However, such habitats (which are not used for farming) serve as an important carbon sink. They sequester carbon that is still not released as CO_2.

Knowing where and how much land would be converted allows the calculation of GHG effects. Regional carbon release factors per converted hectare are used for calculating these effects and are obtained from Tyner et al. (2010). Other sources for carbon release factors, such as Searchinger and Heimlich (2008), Heiderer et al. (2010), Laborde (2011) and Marelli et al. (2011), are not used since they tend to postulate higher release fractions of carbon and thus may overestimate the GHG emissions from land use changes.

Modelling global biodiversity losses

The conversion of natural habitats into agricultural land also leads to a loss of biodiversity. Although measuring biodiversity and its changes is a challenging task, a variety of methods have been developed and a considerable number of biodiversity indicators has been published. All of them appear to have pros and cons. Hence, a generally accepted science-based indicator of mapping biodiversity and the loss thereof is still not in sight. This study applies a pragmatic approach. Two rather dissimilar, but already frequently used indicators are applied to cope with the inherent uncertainty.

First, the Global Environment Facility Benefits Index of Biodiversity (GEF-BIO) is used (see e.g., UNEP, 2009; Wright, 2011). It captures the status quo of biodiversity as well as its changes per country. Thus, it allows not only for a pure accounting of species, but also for mapping a regional distribution of species and their loss. The indicator is consistent with the targets of the Convention on Biological Diversity (CBD) and was originally developed by Dev Pandey et al. (2006). It is a tested composite index of relative biodiversity and based on the species represented in a country, their threat status, and the diversity of habitats. Moreover, the index is easy to handle. It is standardised on the {0; 100}-interval. Brazil is defined as the country with maximum biodiversity. Its natural habitats are rated 100. On the other end is Nauru, an island nation in the Pacific Ocean. Other countries are rated between these extremes. Accordingly, 100 biodiversity points lost while converting land somewhere are comparable with species richness that can be found on one hectare of natural habitats in Brazil.

Second, the National Biodiversity Index (NBI) is applied. This index was developed by the CBD itself (CBD, 2001). It continues to be used in the Global Biodiversity Outlook Reports of CBD. The NBI is based on estimates of a country's richness and endemism in four terrestrial vertebrate classes and vascular plants, which are attributed the same weight in the index. Multiplied by 100, original NBI values range from 100 (the maximum value is assigned to Indonesia) to 0 (the minimum value is allocated to Greenland). Accordingly, 100 biodiversity points lost while converting land somewhere are thus comparable with species richness that can be found on one hectare of natural habitats in Indonesia.

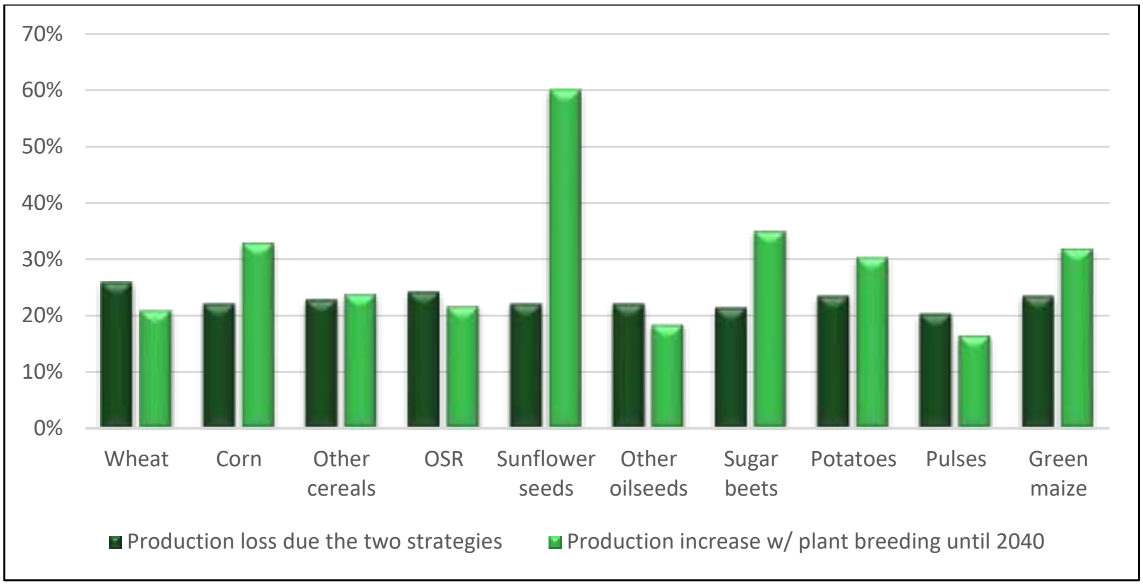
Modelling changes in the use of (virtual) global water resources

Calculating impacts of plant breeding on virtual agricultural water use requires linking production and associated trade change data (already used for detecting changes in the use of global land resources for virtual net trade balances, see above) with information on regional water footprint data for EU and global agriculture. Such water footprint data are given by unit of production and reported in Mekonnen and Hoekstra (2011a; b) for every crop being in the focus of this study and each trading partner of the EU.

Thus, the combination (multiplying) of changing regional trade (import vs. export) volumes with water footprint data – extensively described in Noleppa and Cartsburg (2015) – leads to a statement on how much agricultural water is or will be used domestically and abroad in alternative scenarios (here: with or without plant breeding of the EU).

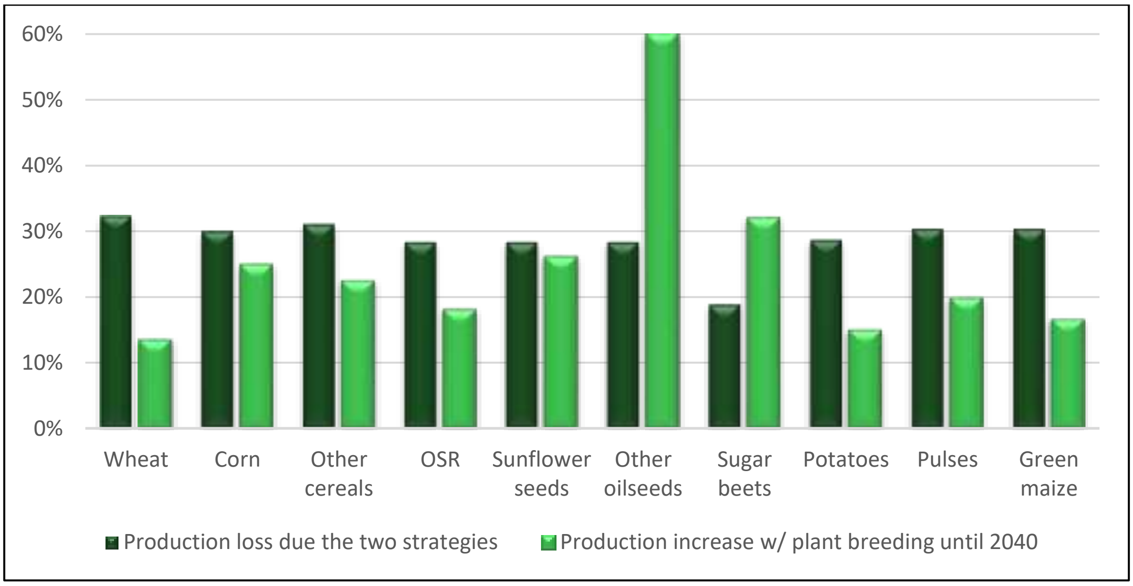
Annex F: Importance of plant breeding for meeting the "Farm to Fork" and "Biodiversity" strategies scenario until 2040

Figure F.1: Production effects in 2040 of the "Farm to Fork" and "Biodiversity" strategies vs. with plant breeding progress between 2020 and 2039 in the EU



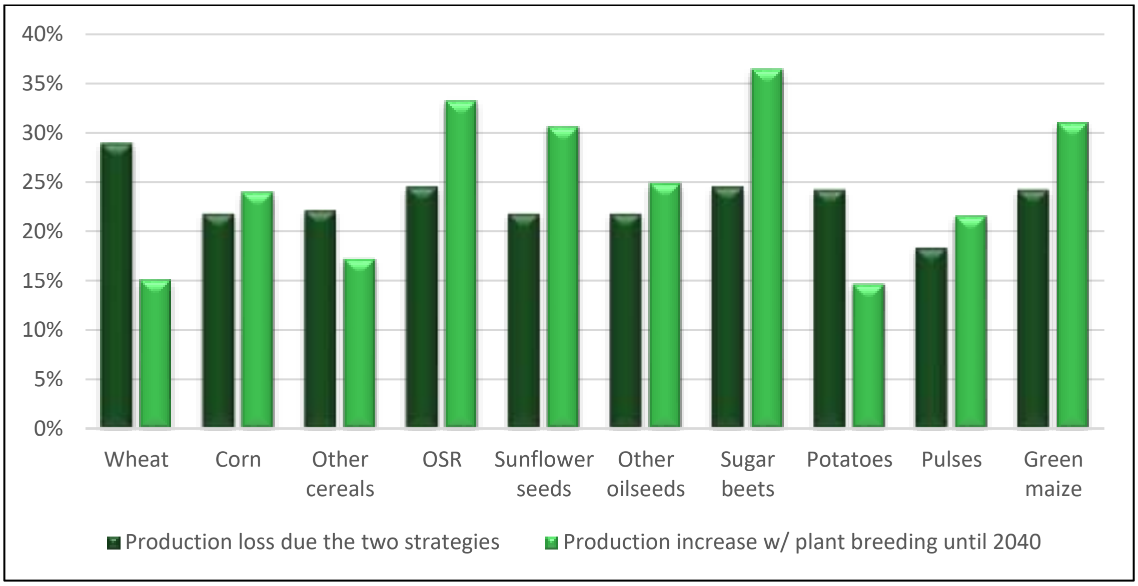
Source: Own calculations and figure.

Figure F.2: Production effects in 2040 of the "Farm to Fork" and "Biodiversity" strategies vs. with plant breeding progress between 2020 and 2039 in Germany



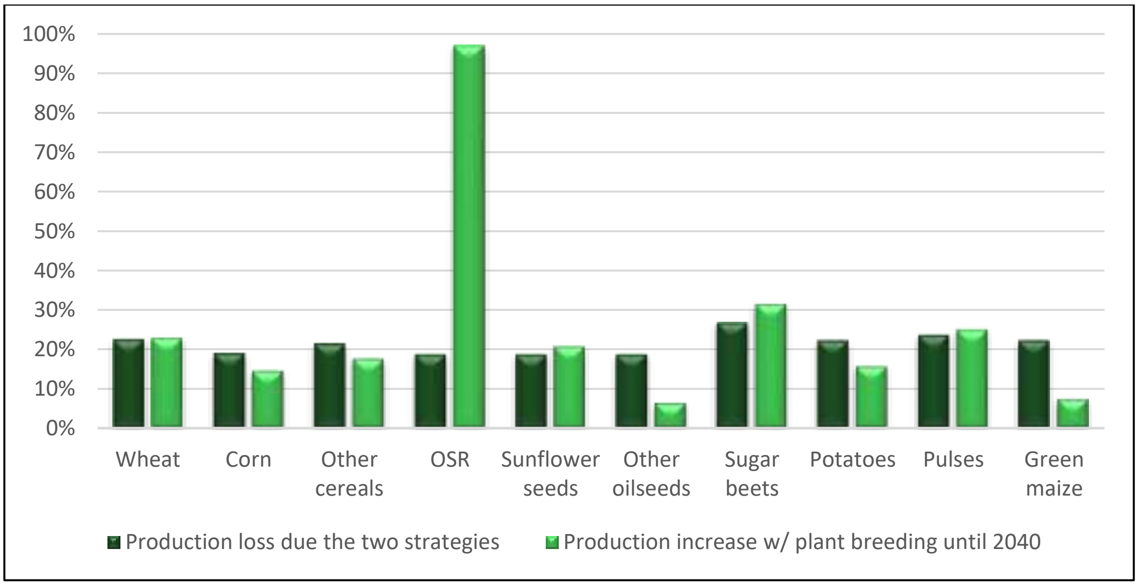
Source: Own calculations and figure.

Figure F.3: Production effects in 2040 of the "Farm to Fork" and "Biodiversity" strategies vs. with plant breeding progress between 2020 and 2039 in France



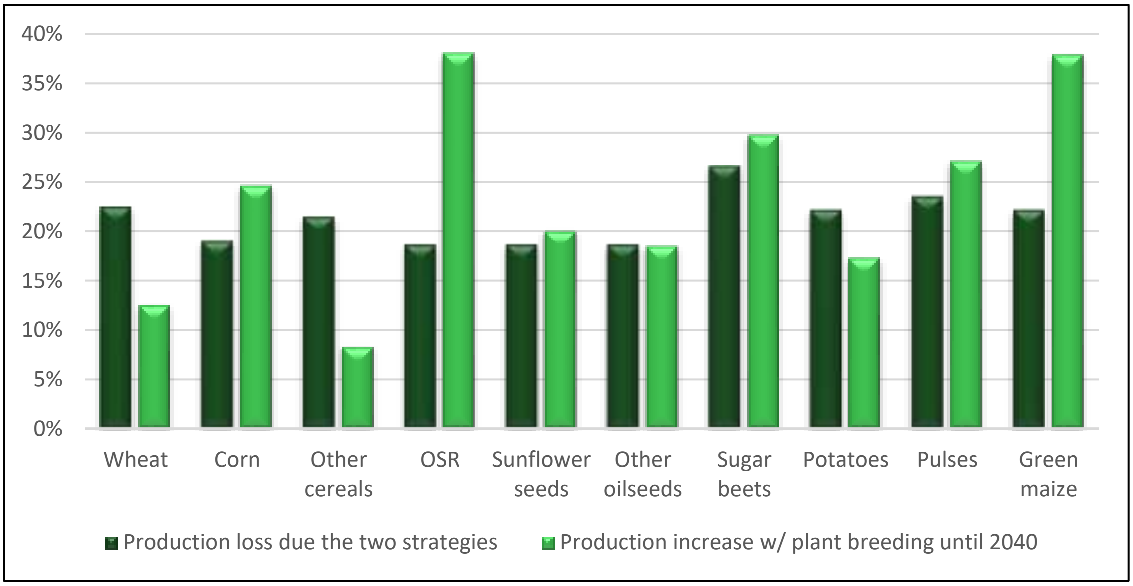
Source: Own calculations and figure.

Figure F.4: Production effects in 2040 of the "Farm to Fork" and "Biodiversity" strategies vs. with plant breeding progress between 2020 and 2039 in Italy



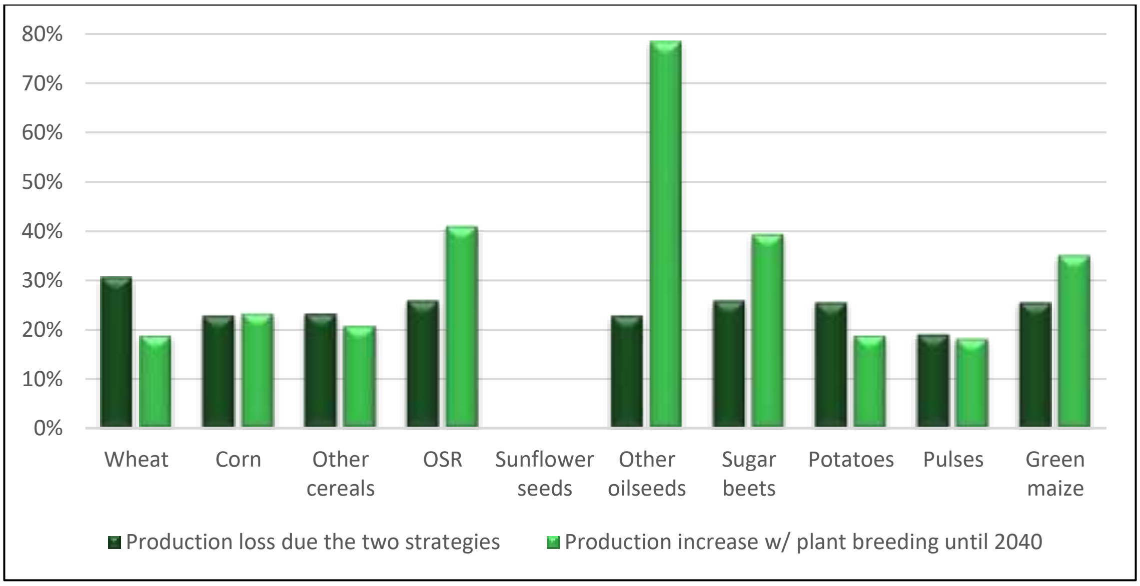
Source: Own calculations and figure.

Figure F.5: Production effects in 2040 of the "Farm to Fork" and "Biodiversity" strategies vs. with plant breeding progress between 2020 and 2039 in Spain



Source: Own calculations and figure.

Figure F.6: Production effects in 2040 of the "Farm to Fork" and "Biodiversity" strategies vs. with plant breeding progress between 2020 and 2039 in the UK



Source: Own calculations and figure.

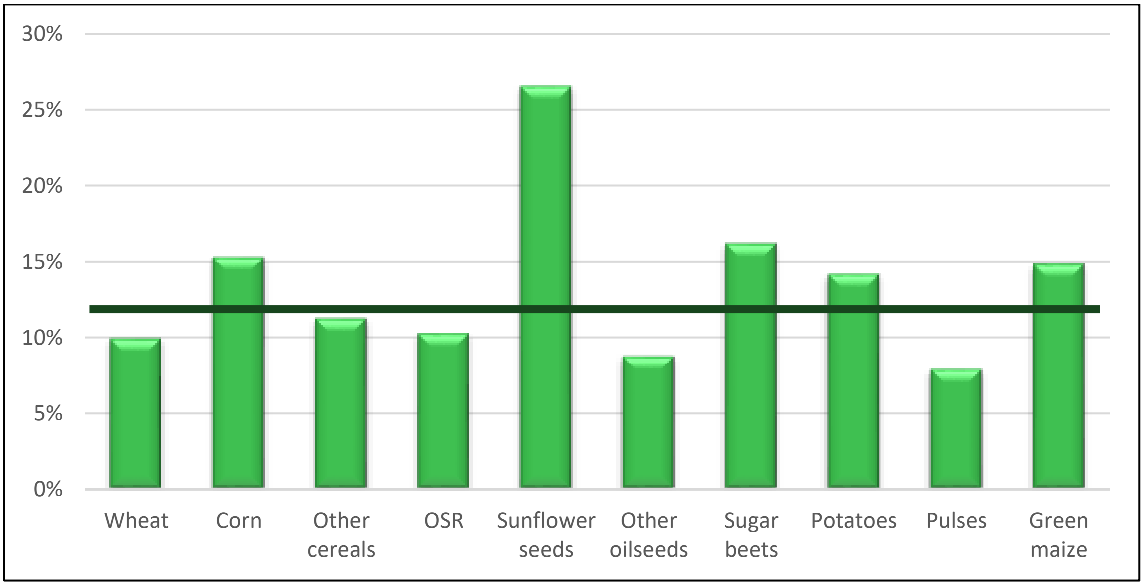
Annex G: Shift factors used for the 2030 scenario

Figure G.1: Simulated potential yield gain in arable farming of the EU and selected member states with plant breeding until 2030 (in percent)

Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	9.9	6.6	7.4	10.8	6.2	9.0
Corn	15.3	11.9	11.5	7.4	11.8	11.2
Other cereals	11.2	10.6	8.4	8.6	4.4	9.9
OSR	10.2	8.7	15.2	38.6	17.1	18.3
Sunflower seeds	26.5	13.0	14.9	10.7	10.4	N.A.
Other oilseeds	8.7	25.5	11.6	3.4	8.8	32.1
Sugar beets	16.2	14.9	16.8	14.7	14.0	17.9
Potatoes	14.1	7.5	7.4	7.9	8.6	9.3
Pulses	7.9	9.3	10.1	11.6	12.5	8.6
Green maize	14.8	8.2	14.5	4.2	17.3	16.1

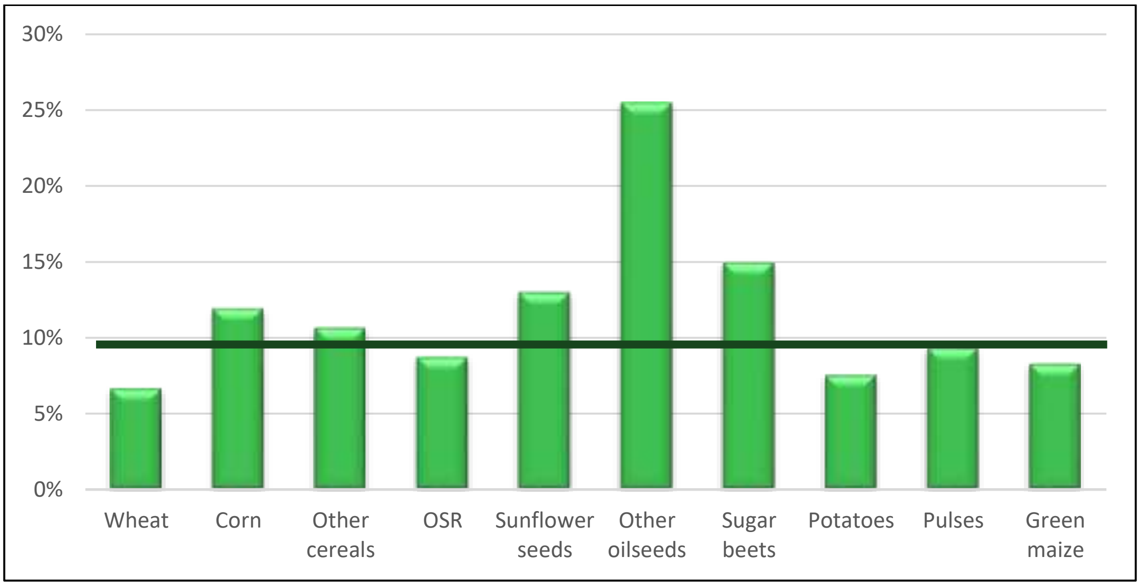
Source: Own calculations and figure.

Figure G.2: Simulated potential yield gain in arable farming of the EU with plant breeding until 2030



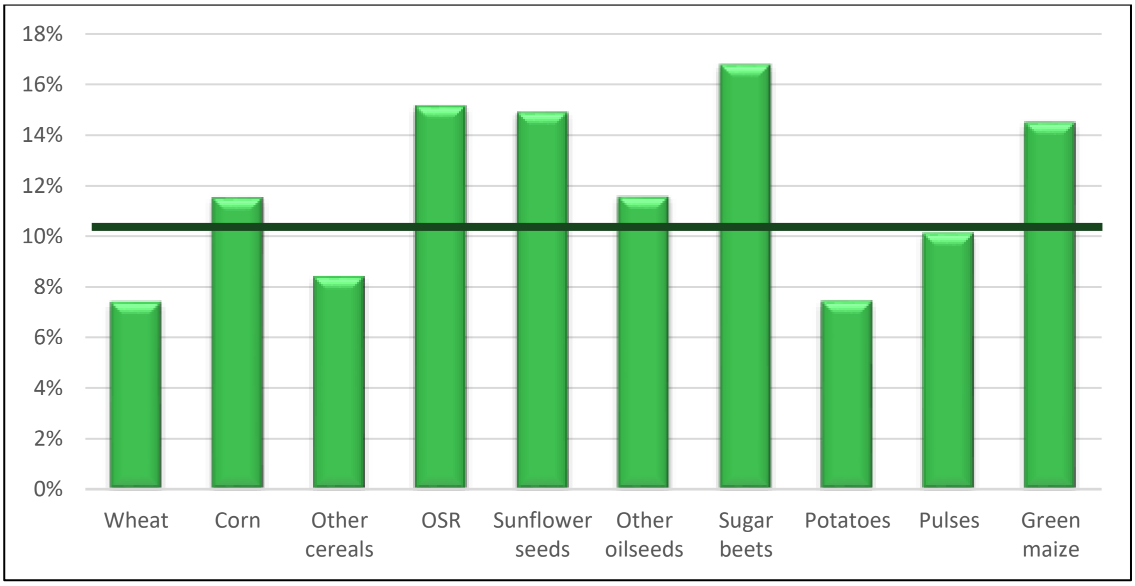
Source: Own calculations and figure.

Figure G.3: Simulated potential yield gain in arable farming of Germany with plant breeding until 2030



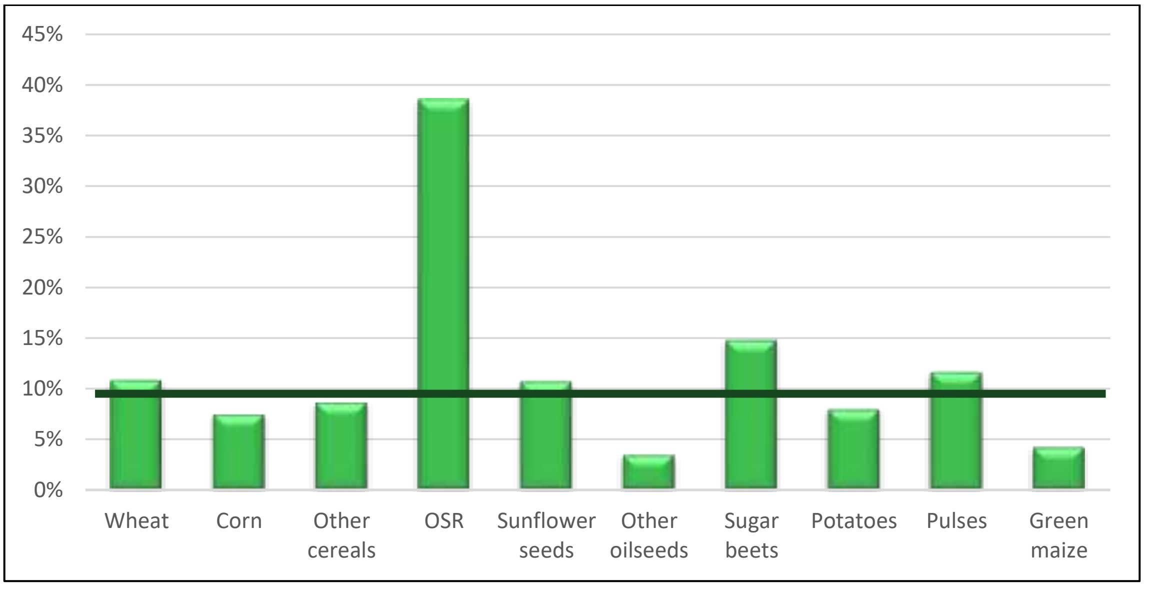
Source: Own calculations and figure.

Figure G.4: Simulated potential yield gain in arable farming of France with plant breeding until 2030



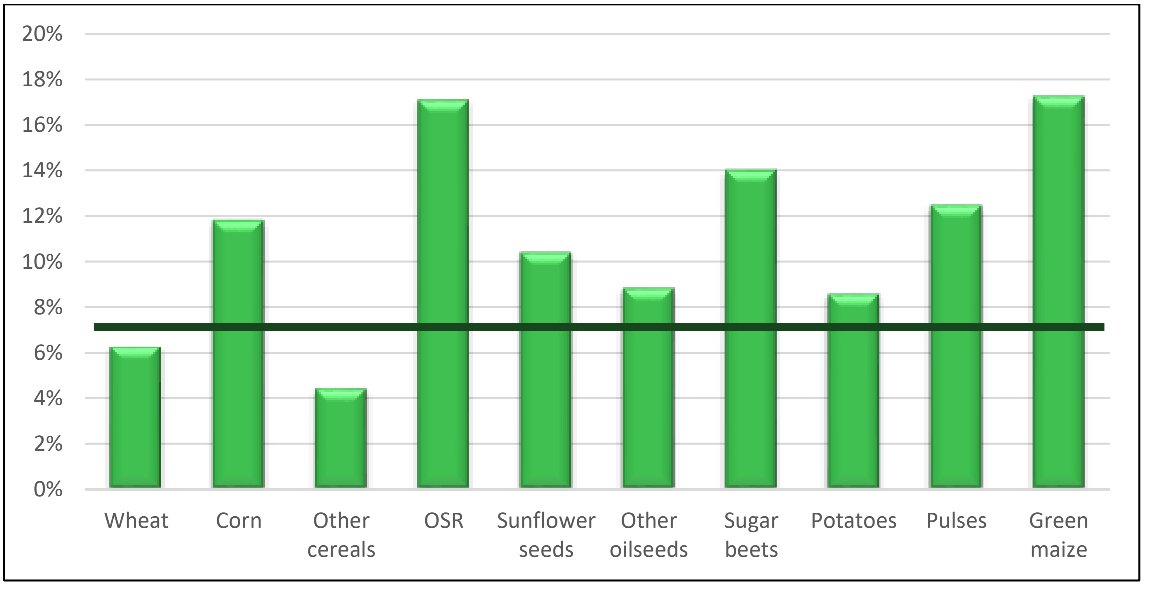
Source: Own calculations and figure.

Figure G.5: Simulated potential yield gain in arable farming of Italy with plant breeding until 2030



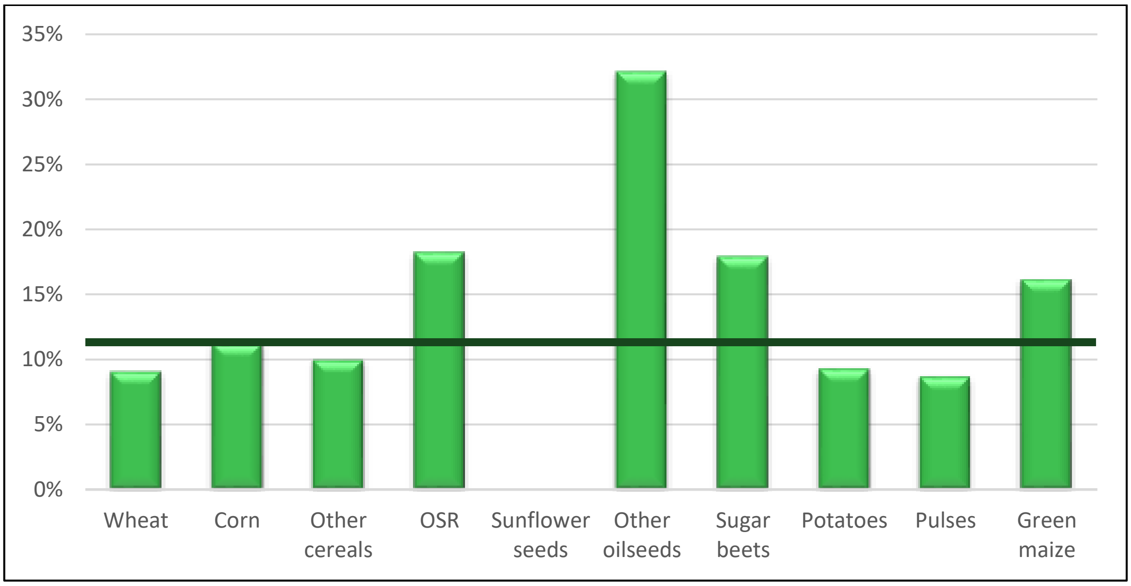
Source: Own calculations and figure.

Figure G.6: Simulated potential yield gain in arable farming of Spain with plant breeding until 2030



Source: Own calculations and figure.

Figure G.7: Simulated potential yield gain in arable farming of the UK with plant breeding until 2030



Source: Own calculations and figure.

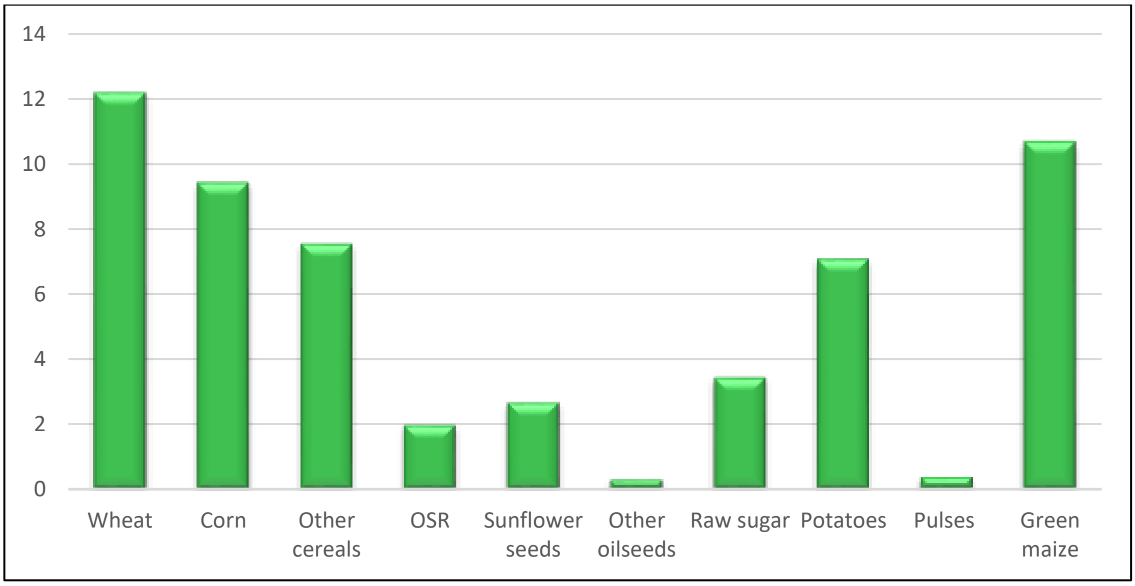
Annex H: Market supply impacts for the 2030 scenario

Figure H.1: Potential extra market supply for major arable crops in 2030 with plant breeding progress between 2020 and 2029 in the EU and selected member states (in million tons)

Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	12.195	1.329	2.393	0.484	0.303	1.157
Corn	9.432	0.457	1.528	0.484	0.494	0.004
Other cereals	7.523	1.155	0.879	0.264	0.284	0.517
OSR	1.958	0.344	0.694	0.012	0.025	0.380
Sunflower seeds	2.654	0.005	0.212	0.031	0.094	N.A.
Other oilseeds	0.257	0.010	0.033	0.040	0.004	0.008
Raw sugar	3.420	0.721	1.159	0.058	0.087	0.234
Potatoes	7.059	0.713	0.521	0.097	0.174	0.469
Pulses	0.349	0.055	0.080	0.017	0.048	0.069
Green maize	10.684	2.242	1.266	0.216	0.241	0.337

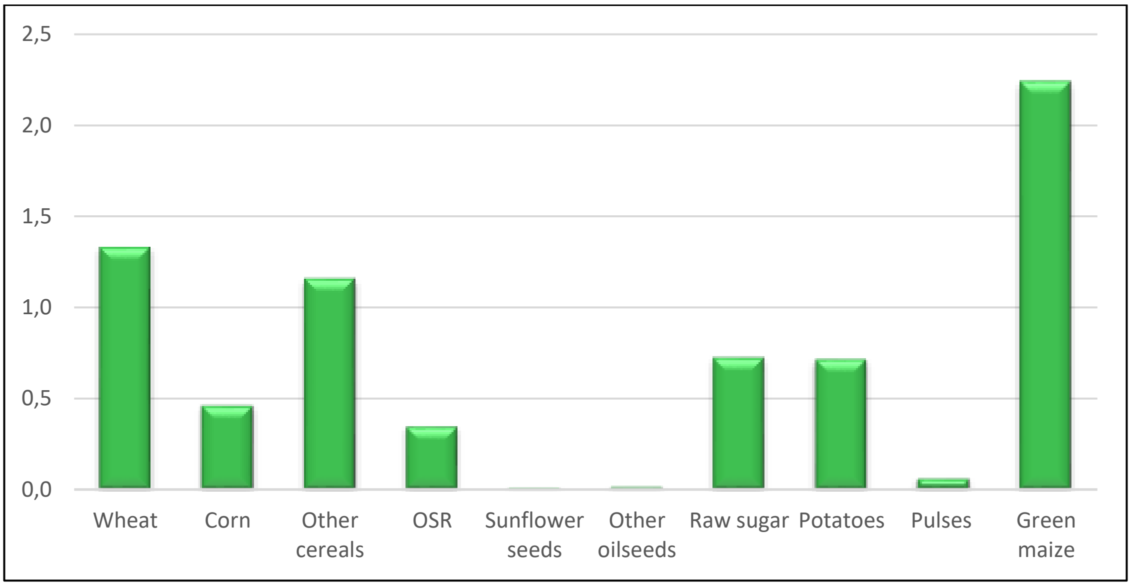
Source: Own calculations and figure.

Figure H.2: Potential extra market supply for major arable crops in 2030 with plant breeding progress between 2020 and 2029 in the EU (in million tons)



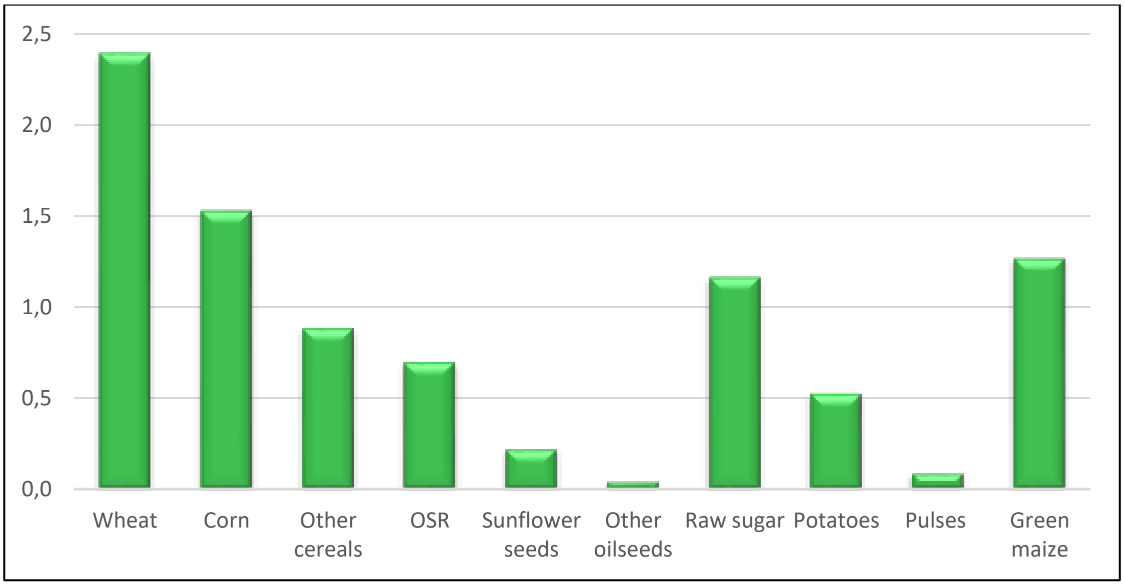
Source: Own calculations and figure.

Figure H.3: Potential extra market supply for major arable crops in 2030 with plant breeding progress between 2020 and 2029 in Germany (in million tons)



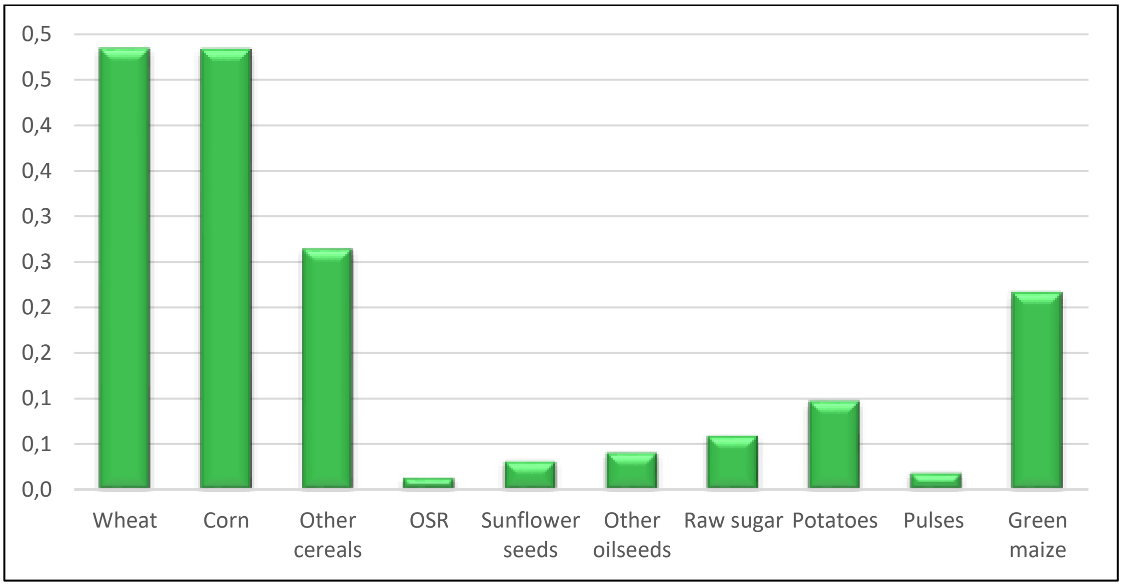
Source: Own calculations and figure.

Figure H.4: Potential extra market supply for major arable crops in 2030 with plant breeding progress between 2020 and 2029 in France (in million tons)



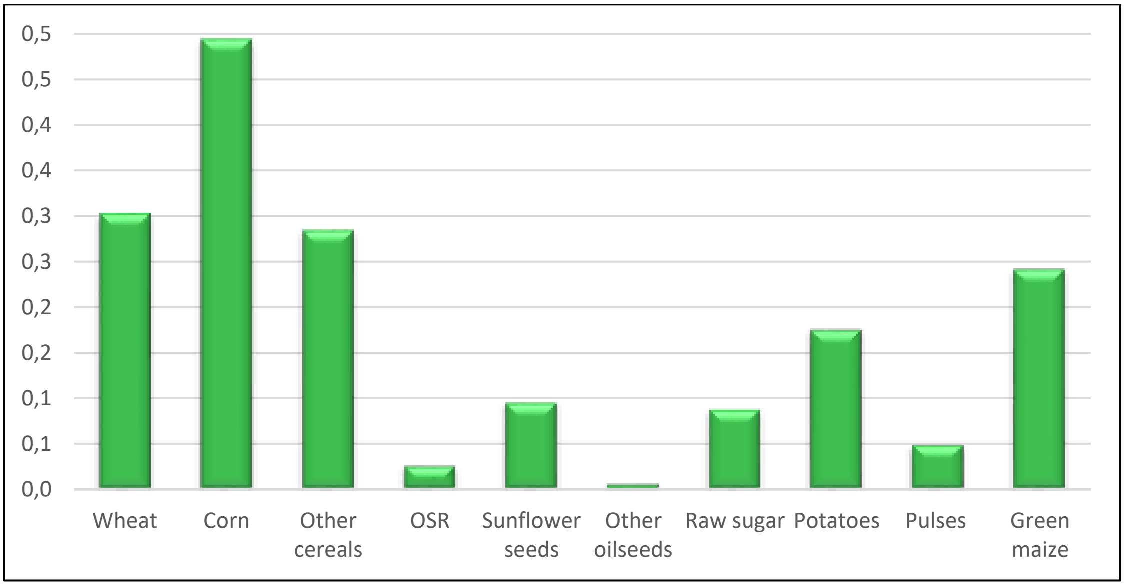
Source: Own calculations and figure.

Figure H.5: Potential extra market supply for major arable crops in 2030 with plant breeding progress between 2020 and 2029 in Italy (in million tons)



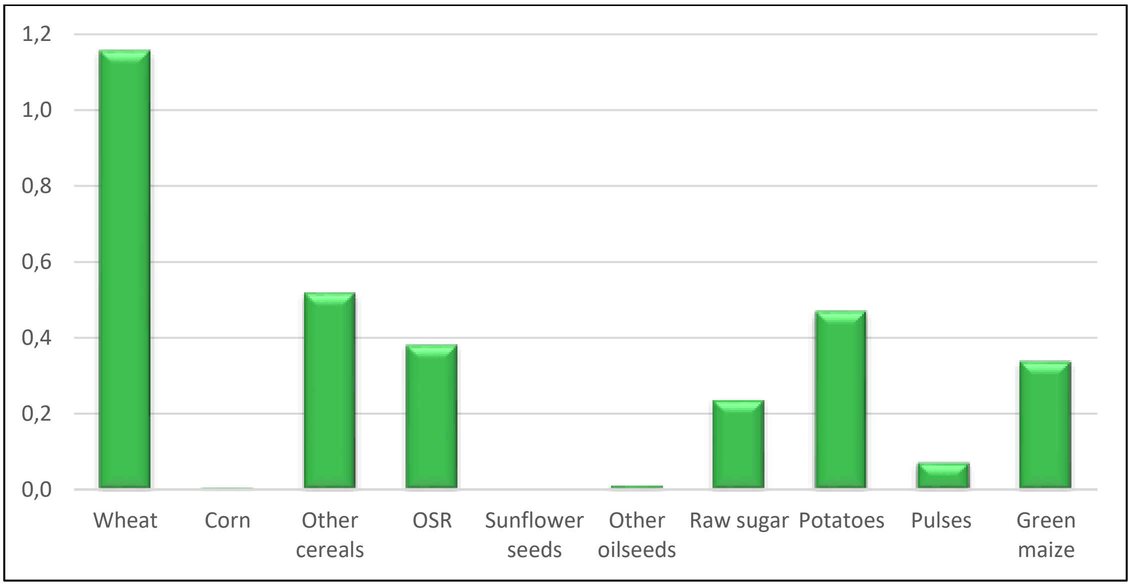
Source: Own calculations and figure.

Figure H.6: Potential extra market supply for major arable crops in 2030 with plant breeding progress between 2020 and 2029 in Spain (in million tons)



Source: Own calculations and figure.

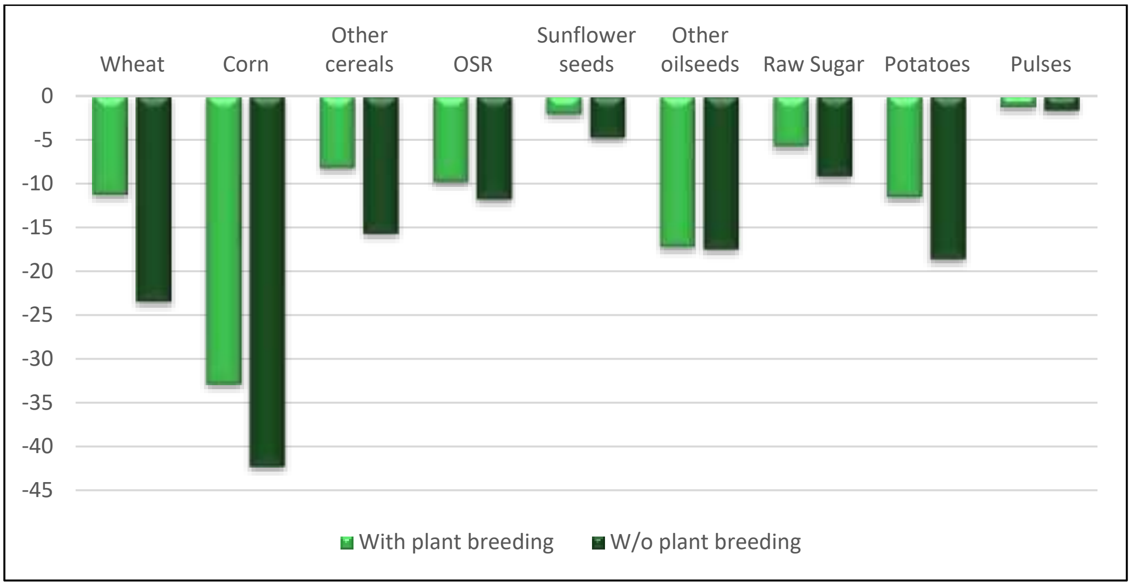
Figure H.7: Potential extra market supply for major arable crops in 2030 with plant breeding progress between 2020 and 2029 in the UK (in million tons)



Source: Own calculations and figure.

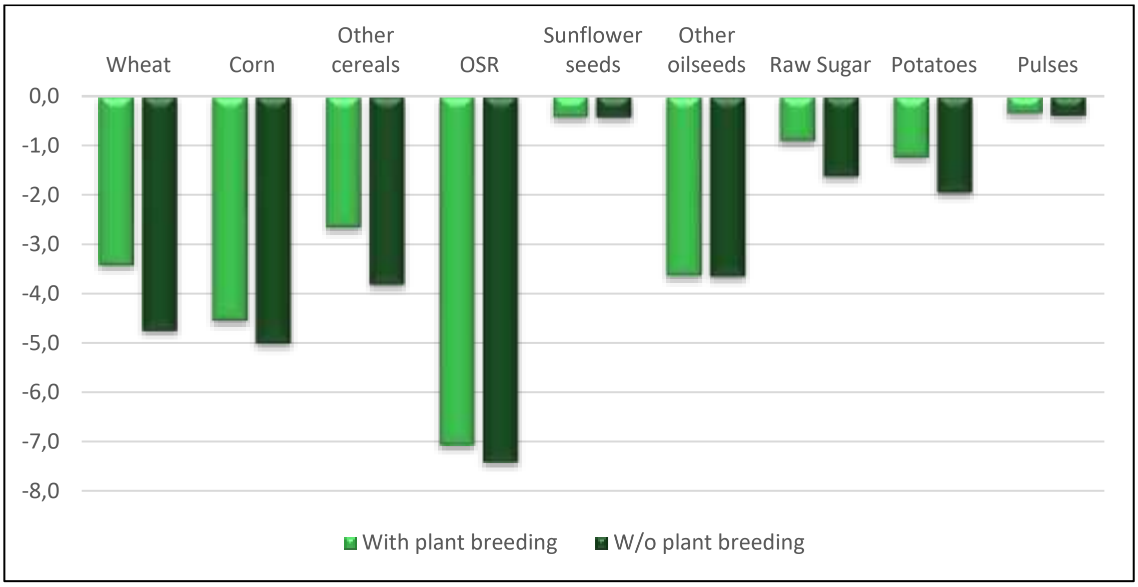
Annex I: Net trade impacts for the 2030 scenario

Figure I.1: Potential net trade volumes of the EU for major arable crops in 2030 with and without plant breeding progress between 2020 and 2029 (in million tons)



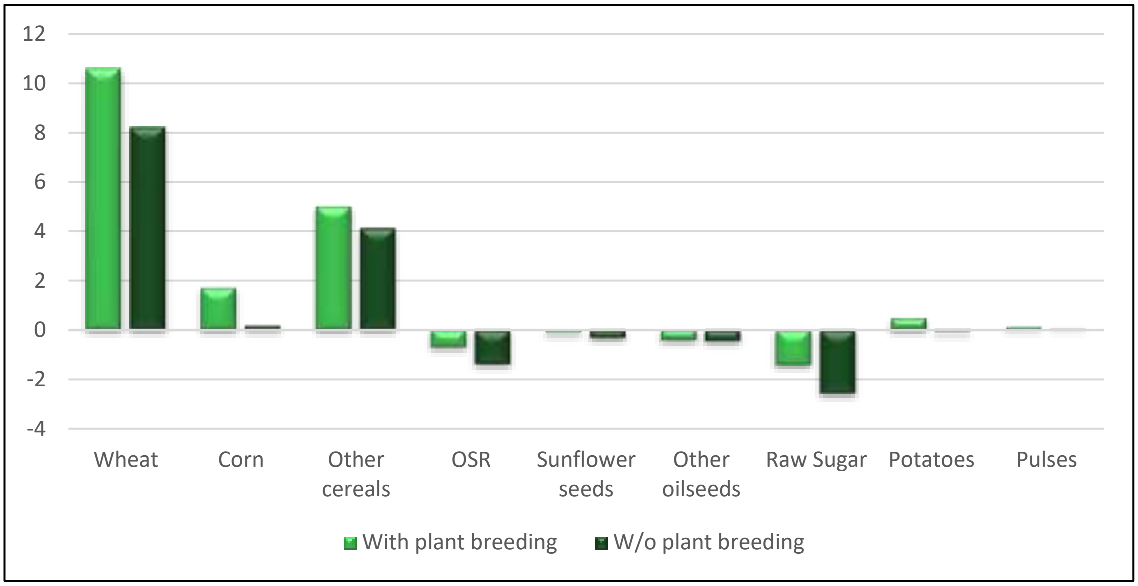
Source: Own calculations and figure.

Figure I.2: Potential net trade volumes of Germany for major arable crops in 2030 with and without plant breeding progress between 2020 and 2029 (in million tons)



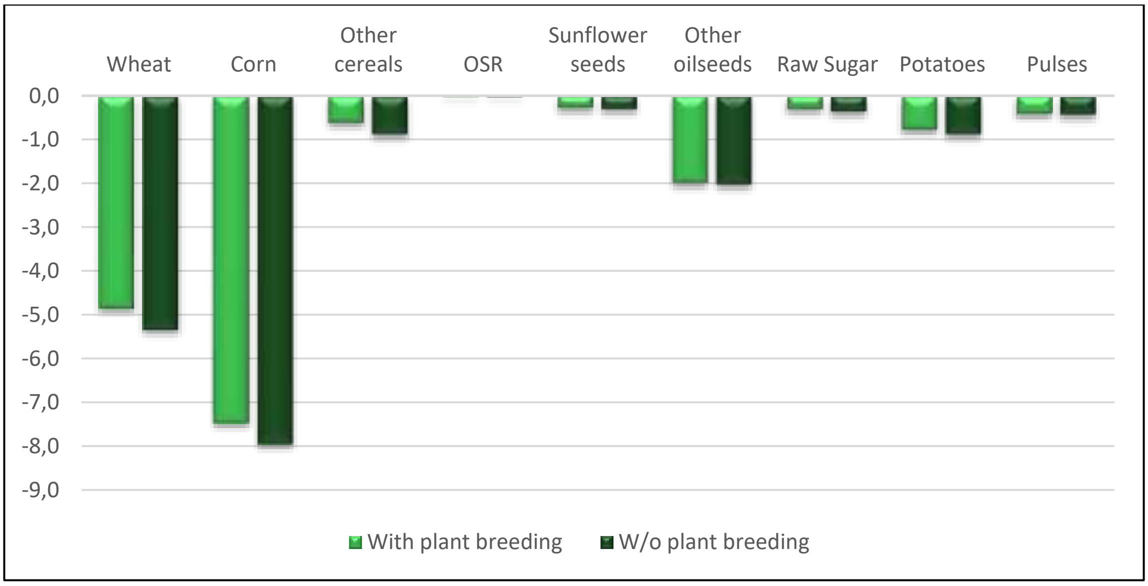
Source: Own calculations and figure.

Figure I.3: Potential net trade volumes of France for major arable crops in 2030 with and without plant breeding progress between 2020 and 2029 (in million tons)



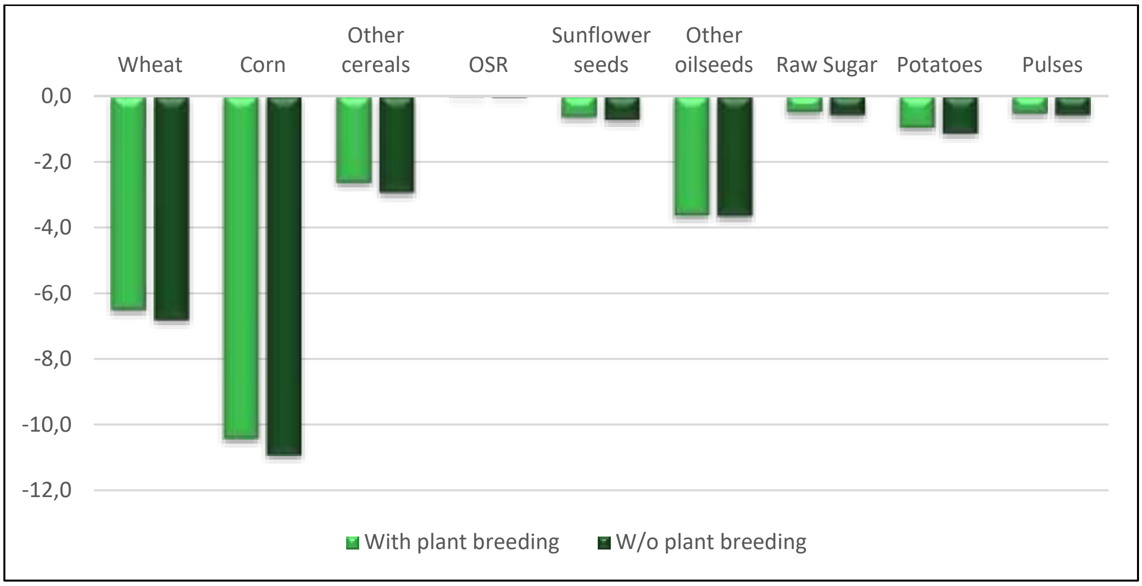
Source: Own calculations and figure.

Figure I.4: Potential net trade volumes of Italy in for major arable crops 2030 with and without plant breeding progress between 2020 and 2029 (in million tons)



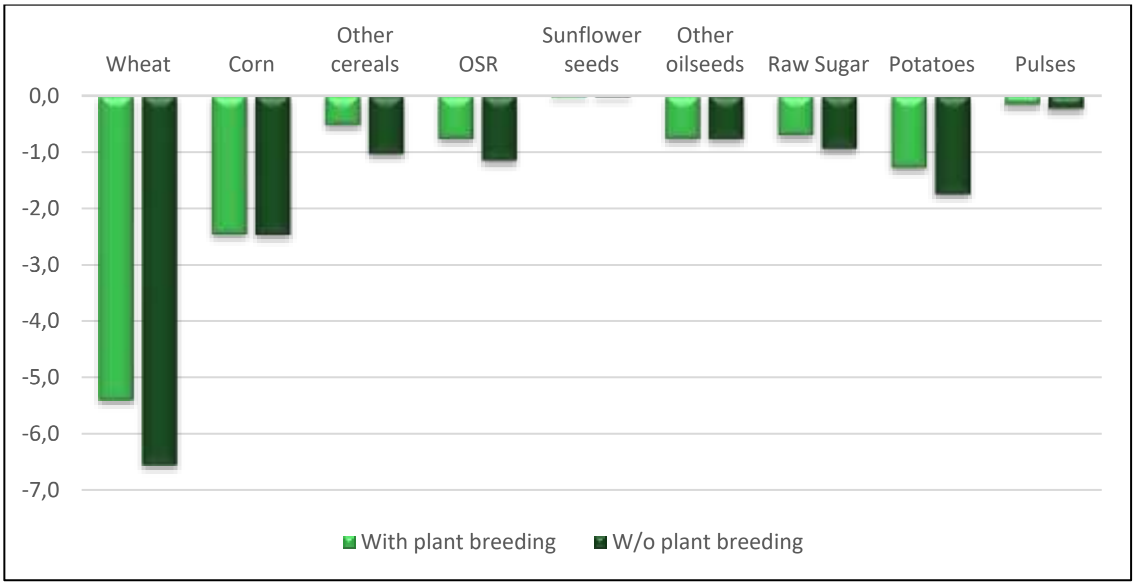
Source: Own calculations and figure.

Figure I.5: Potential net trade volumes of Spain for major arable crops in 2030 with and without plant breeding progress between 2020 and 2029 (in million tons)



Source: Own calculations and figure.

Figure I.6: Potential net trade volumes of the UK for major arable crops in 2030 with and without plant breeding progress between 2020 and 2029 (in million tons)



Source: Own calculations and figure.

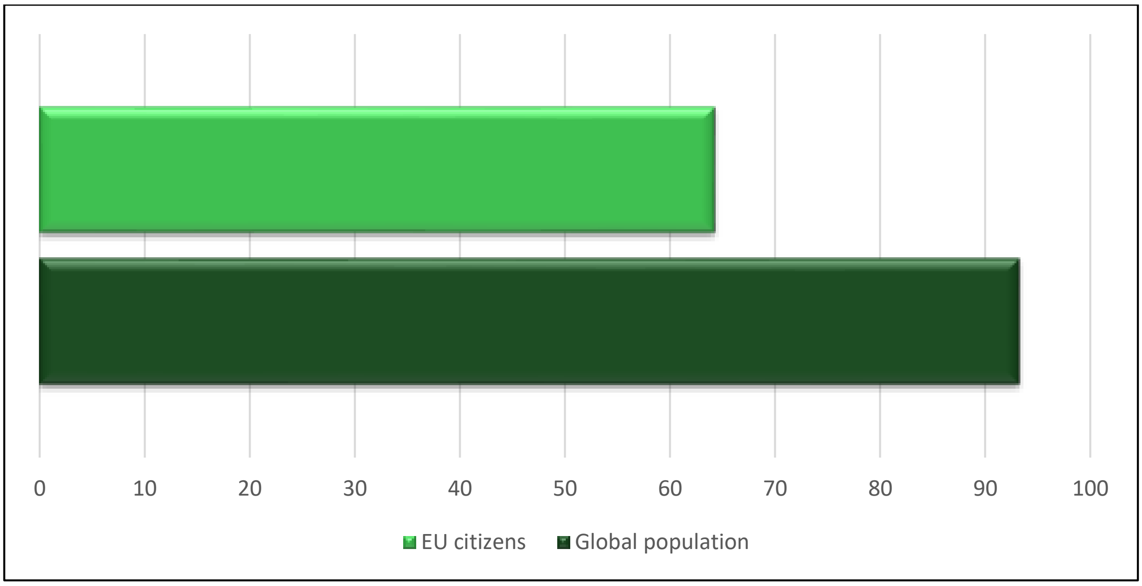
Annex J: Food availability impacts for the 2030 scenario

Figure J. 1: Potential additionally available food in 2030 with plant breeding progress between 2020 and 2029 in the EU and selected member states (in food for million people)

Food basket of ...	EU	DE	FR	IT	ES	UK
EU citizens	64.4	8.4	12.0	1.7	1.7	4.9
Global population	93.3	11.9	16.0	2.9	2.8	7.1

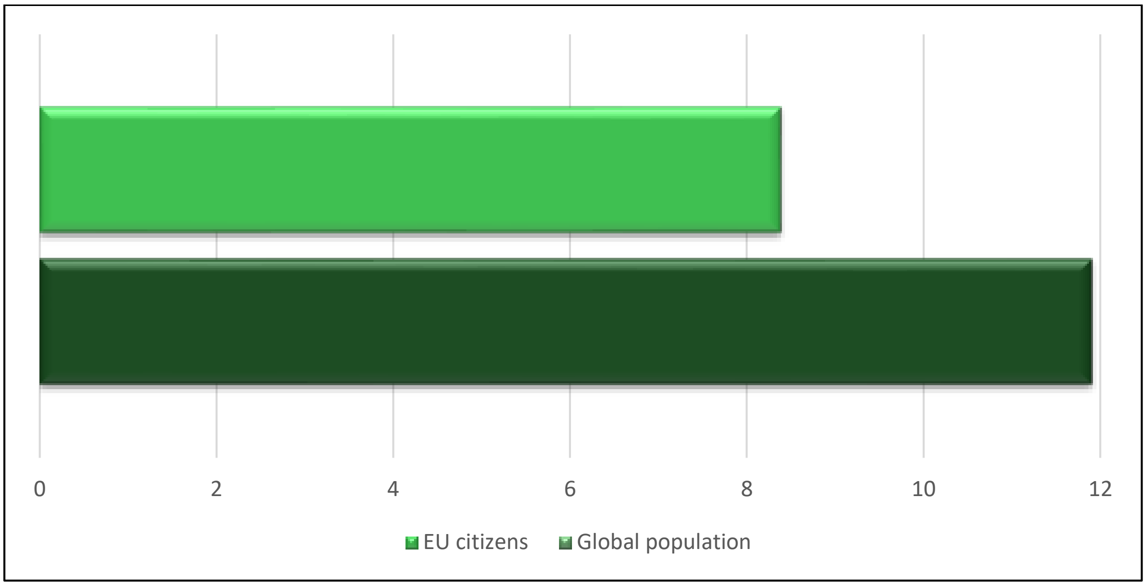
Source: Own calculations and figure.

Figure J.2: Potential additionally available food in 2030 with plant breeding progress between 2020 and 2029 in the EU in total (in food for million people)



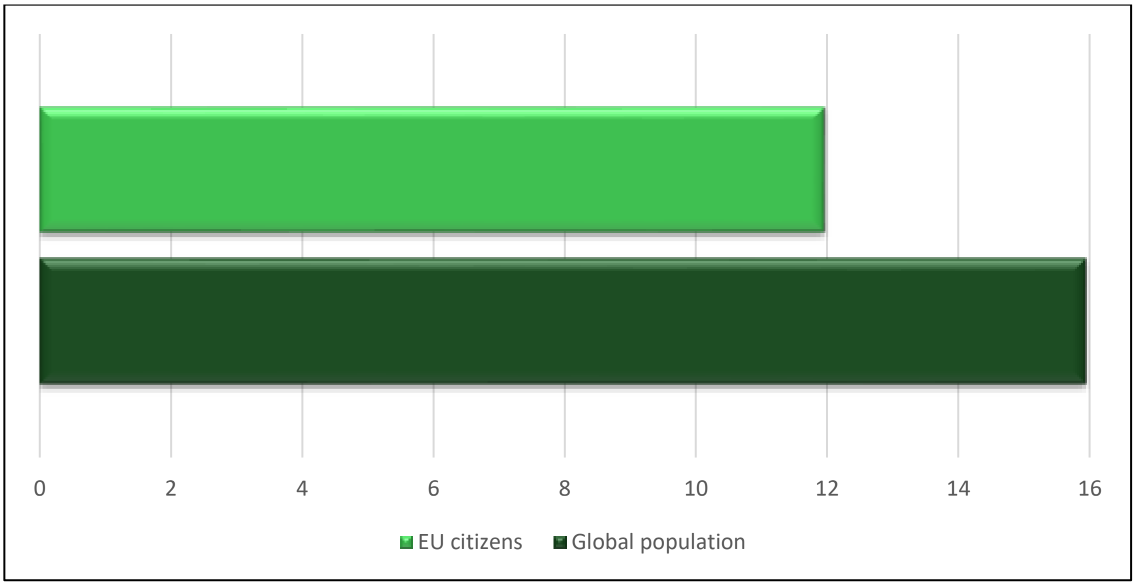
Source: Own calculations and figure.

Figure J.3: Potential additionally available food in 2030 with plant breeding progress between 2020 and 2029 in Germany (in food for million people)



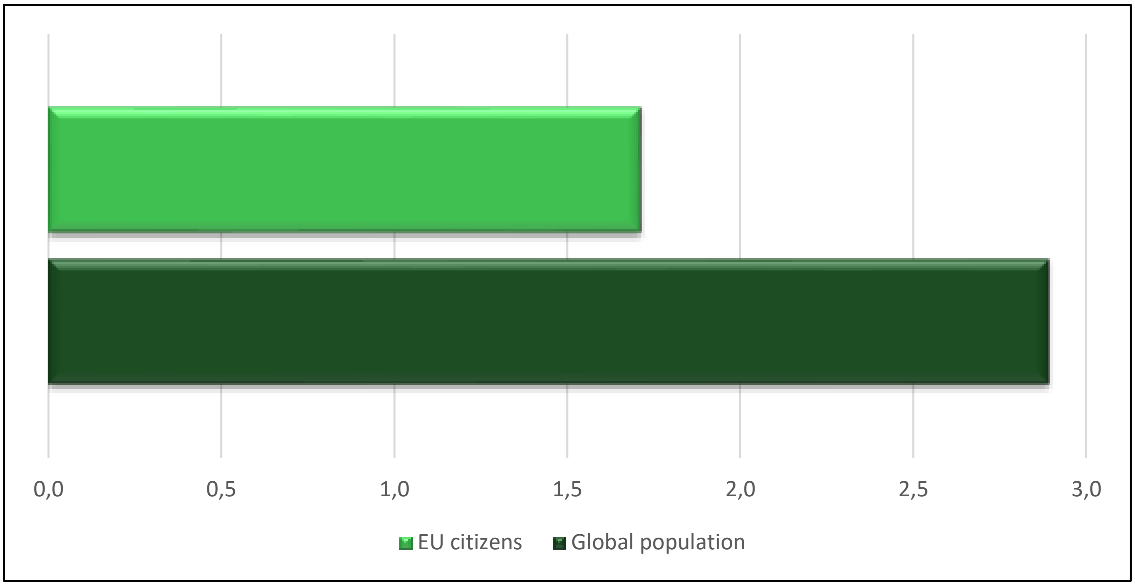
Source: Own calculations and figure.

Figure J.4: Potential additionally available food in 2030 with plant breeding progress between 2020 and 2029 in France (in food for million people)



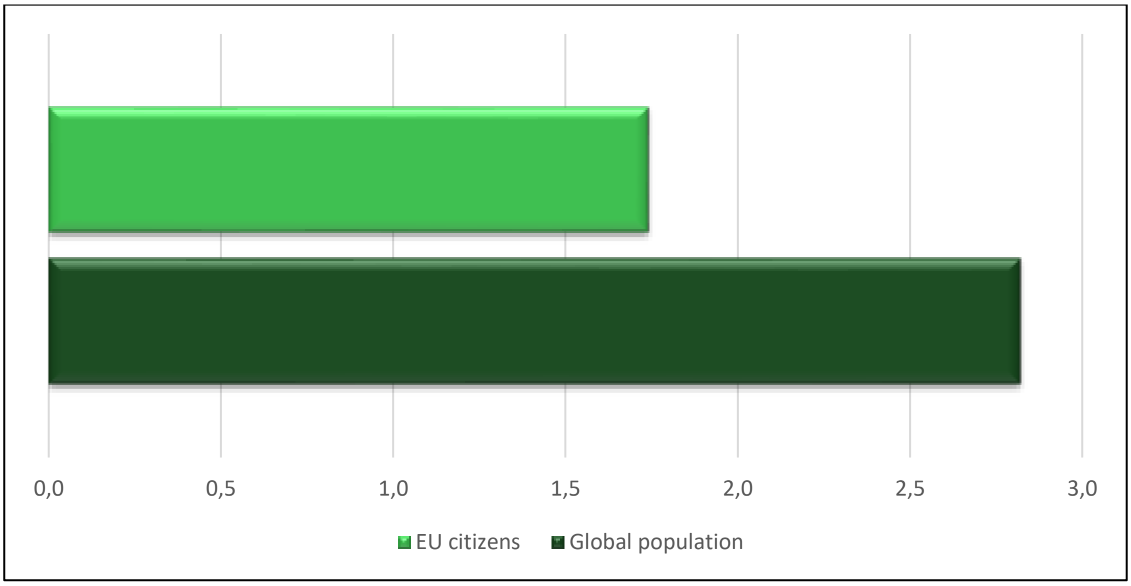
Source: Own calculations and figure.

Figure J.5: Potential additionally available food in 2030 with plant breeding progress between 2000 and 2029 in Italy (in food for million people)



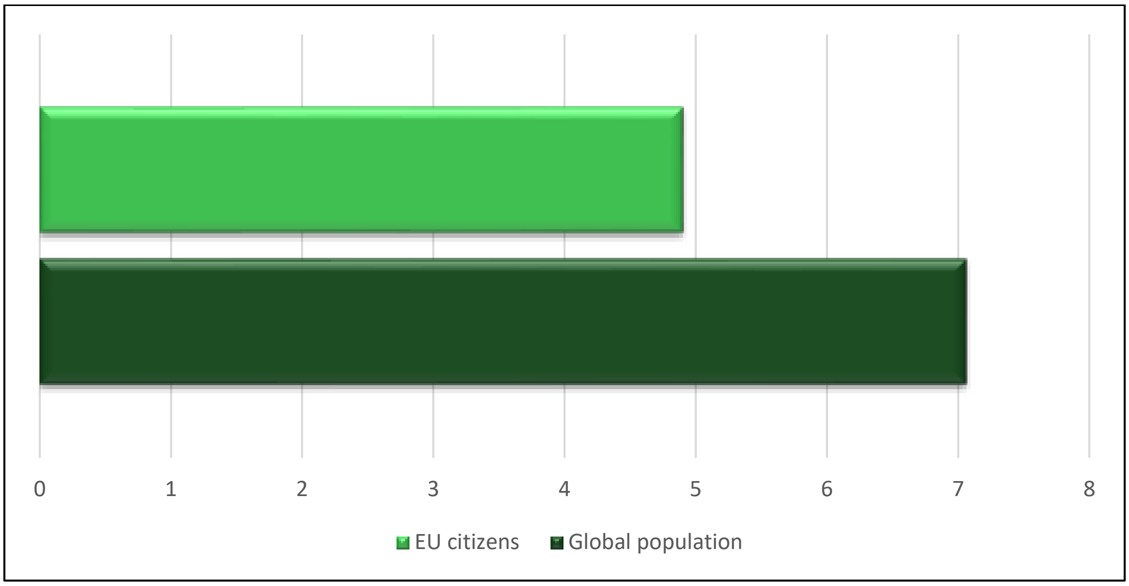
Source: Own calculations and figure.

Figure J.6: Potential additionally available food in 2030 with plant breeding progress between 2000 and 2029 in Spain (in food for million people)



Source: Own calculations and figure.

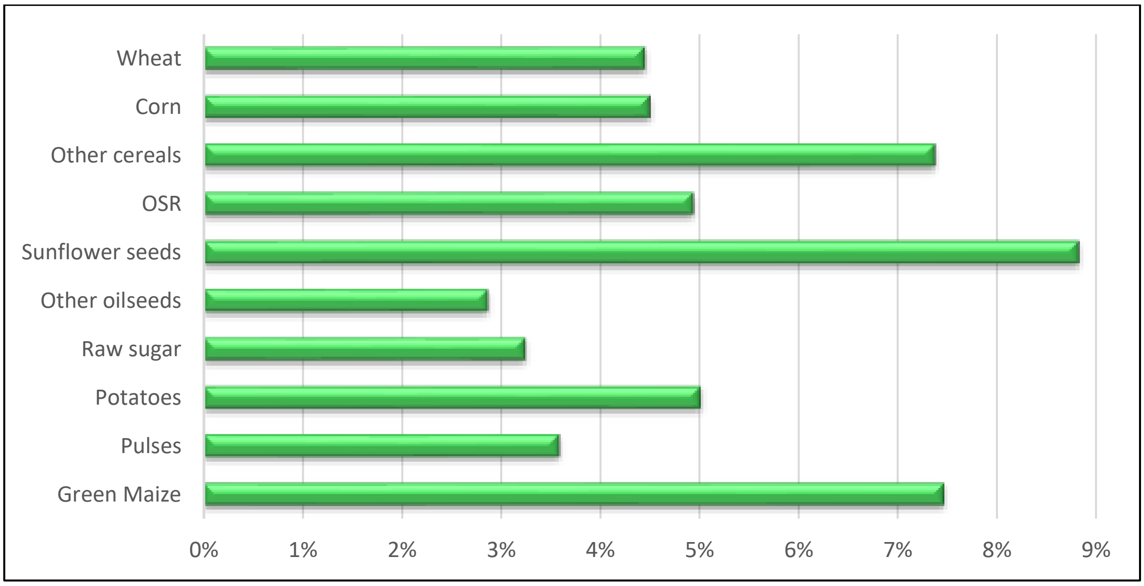
Figure J.7: Potential additionally available food in 2030 with plant breeding progress between 2000 and 2029 in the UK (in food for million people)



Source: Own calculations and figure.

Annex K: Market price impacts for the 2030 scenario

Figure K.1: Potentially avoided price increases for major agricultural commodity markets in 2030 with EU plant breeding between 2020 and 2020 in the EU



Source: Own calculations and figure.

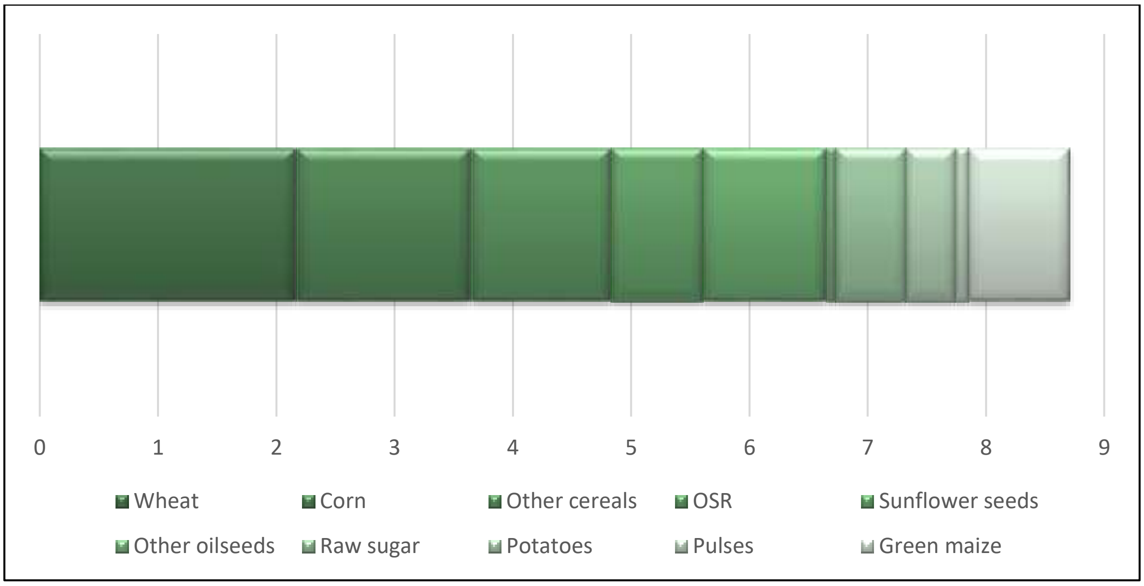
Annex L: Sectoral income impacts for the 2030 scenario

Figure L.1: Potential additional sectoral income for major arable crops in 2030 with plant breeding progress between 2020 and 2029 in the EU and selected member states (in billion EUR)

Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	2.174	0.237	0.427	0.086	0.054	0.206
Corn	1.477	0.072	0.239	0.076	0.077	0.001
Other cereals	1.184	0.182	0.138	0.041	0.045	0.081
OSR	0.774	0.136	0.274	0.005	0.010	0.150
Sunflower seeds	1.046	0.002	0.084	0.012	0.037	N.A.
Other oilseeds	0.076	0.003	0.010	0.012	0.001	0.002
Raw sugar	0.593	0.125	0.201	0.010	0.015	0.041
Potatoes	0.417	0.042	0.031	0.006	0.010	0.028
Pulses	0.112	0.018	0.026	0.006	0.015	0.022
Green maize	0.860	0.180	0.102	0.017	0.019	0.027

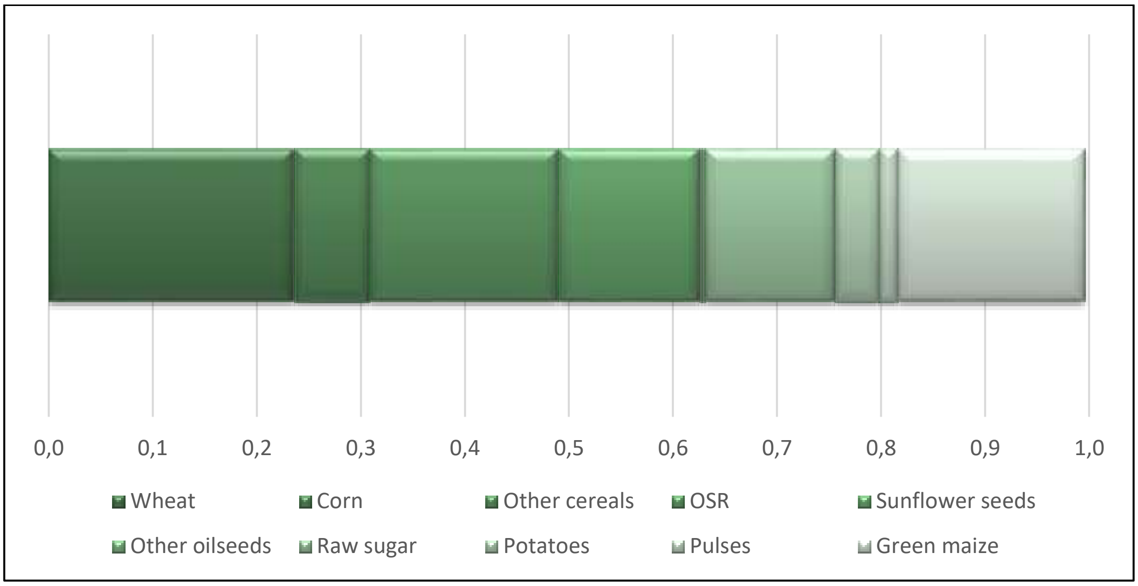
Source: Own calculations and figure.

Figure L.2: Potential additional sectoral income for major arable crops in 2030 with plant breeding progress between 2020 and 2029 in the EU (in billion EUR)



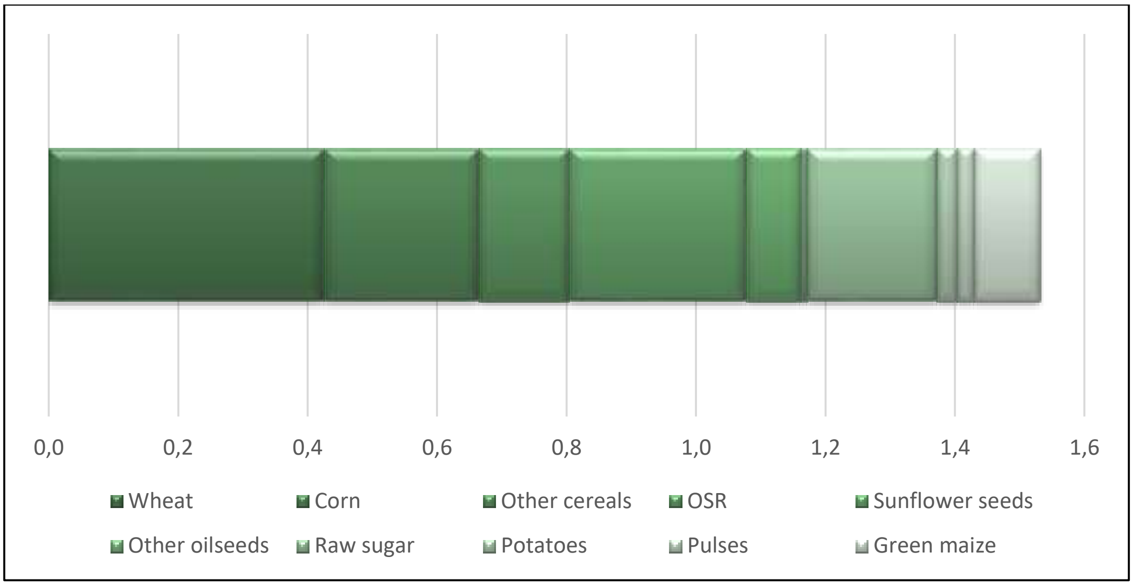
Source: Own calculations and figure.

Figure L.3: Potential additional sectoral income for major arable crops in 2030 with plant breeding progress between 2020 and 2029 in Germany (in billion EUR)



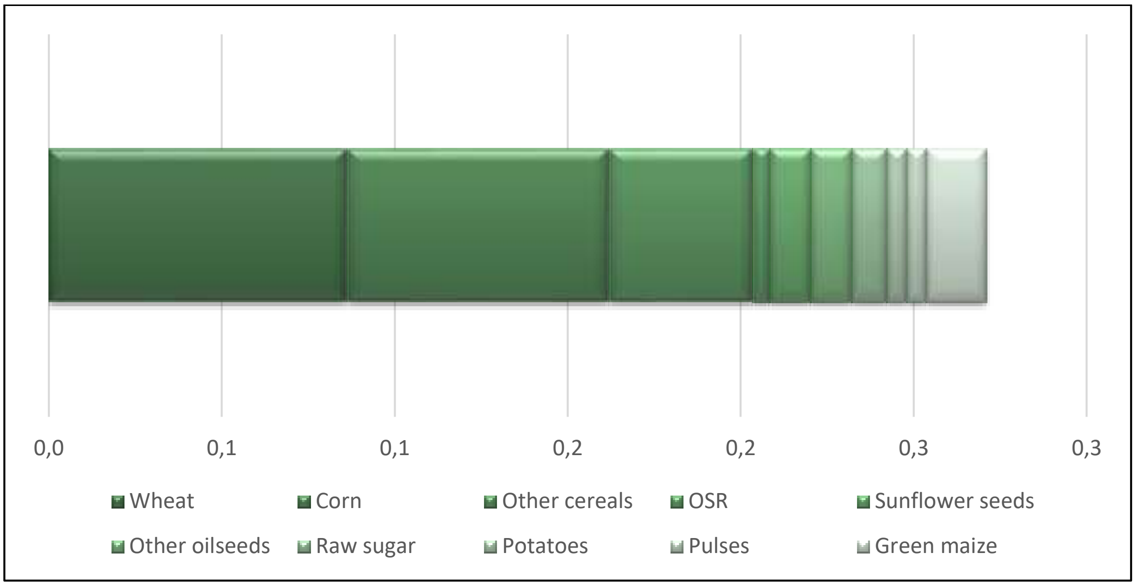
Source: Own calculations and figure.

Figure L.4: Potential additional sectoral income for major arable crops in 2030 with plant breeding progress between 2020 and 2029 in France (in billion EUR)



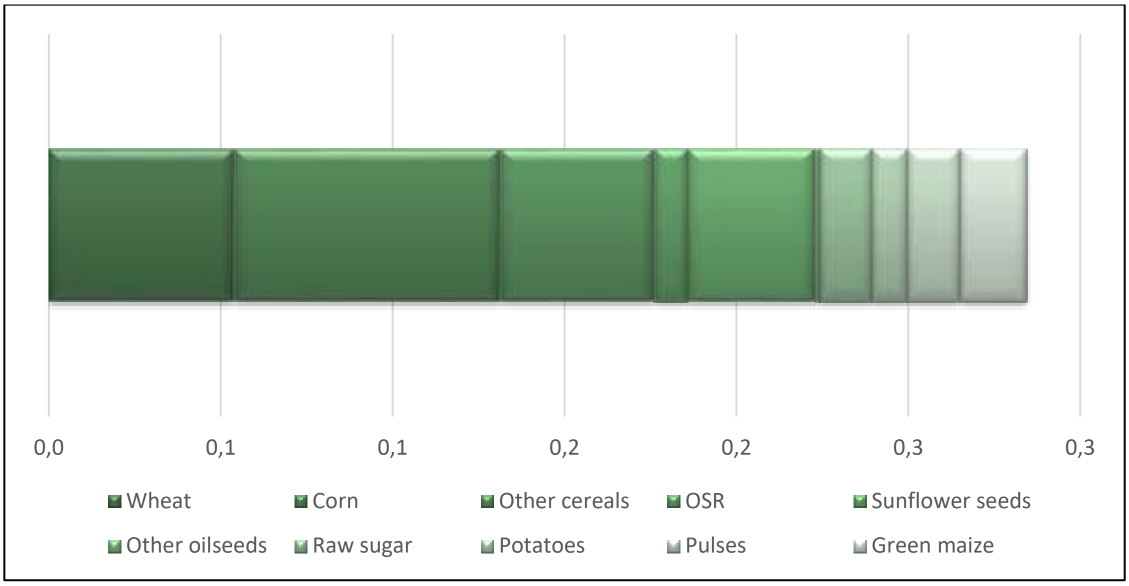
Source: Own calculations and figure.

Figure L.5: Potential additional sectoral income for major arable crops in 2030 with plant breeding progress between 2020 and 2029 in Italy (in billion EUR)



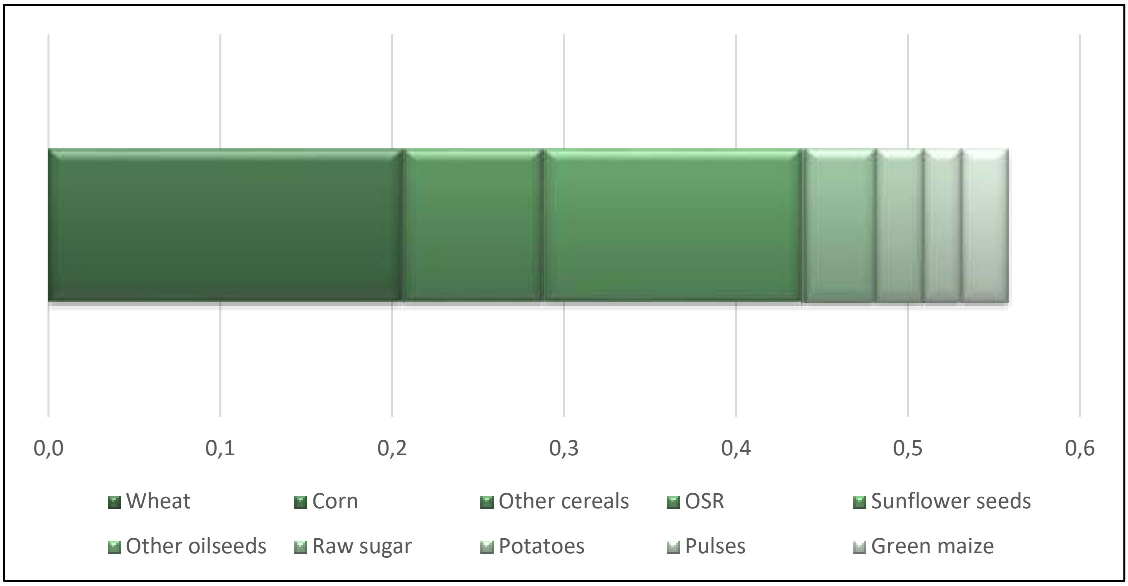
Source: Own calculations and figure.

Figure L.6: Potential additional sectoral income for major arable crops in 2030 with plant breeding progress between 2020 and 2029 in Spain (in billion EUR)



Source: Own calculations and figure.

Figure L.7: Potential additional sectoral income for major arable crops in 2030 with plant breeding progress between 2020 and 2029 in the UK (in billion EUR)



Source: Own calculations and figure.

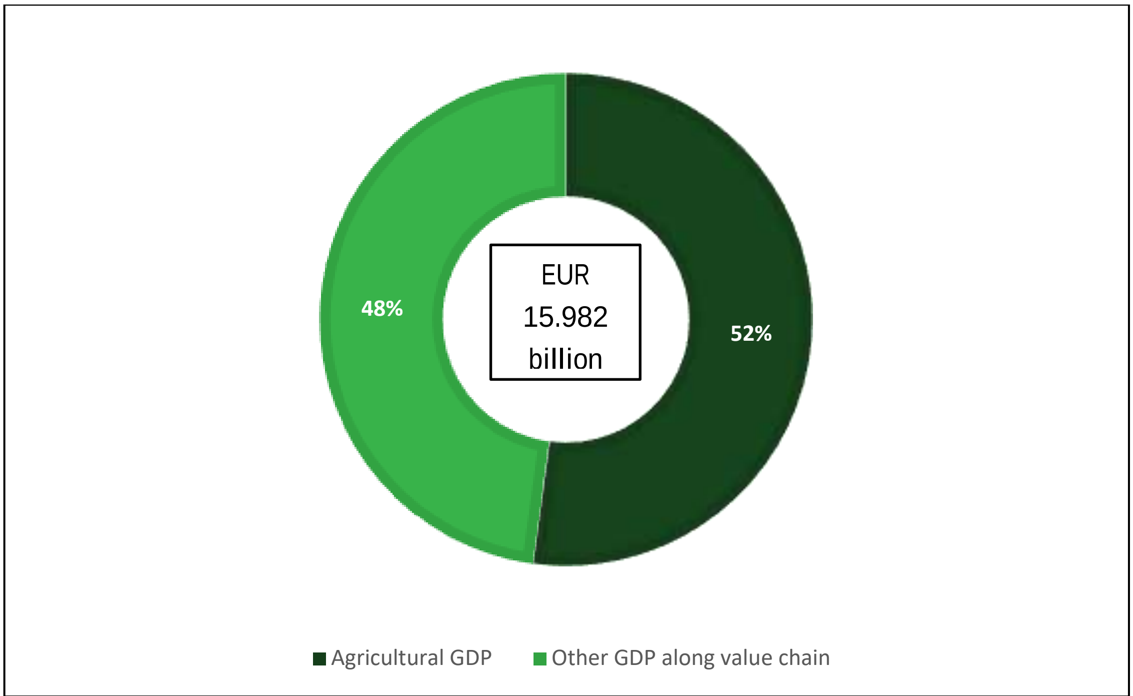
Annex M: GDP impacts for the 2030 scenario

Figure M.1: Potential additional GDP attributable to major arable crops in 2030 with plant breeding progress between 2020 and 2029 in the EU and selected member states (in billion EUR)

Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	3.966	0.419	0.872	0.190	0.120	0.378
Corn	2.694	0.126	0.489	0.166	0.172	0.001
Other cereals	2.159	0.321	0.283	0.091	0.100	0.149
OSR	1.257	0.214	0.499	0.009	0.019	0.245
Sunflower seeds	1.698	0.003	0.152	0.024	0.074	N.A.
Other oilseeds	0.124	0.005	0.018	0.023	0.003	0.004
Raw sugar	1.337	0.273	0.508	0.028	0.041	0.092
Potatoes	0.941	0.092	0.078	0.016	0.028	0.063
Pulses	0.253	0.039	0.065	0.015	0.042	0.050
Green maize	1.552	0.315	0.206	0.038	0.043	0.049

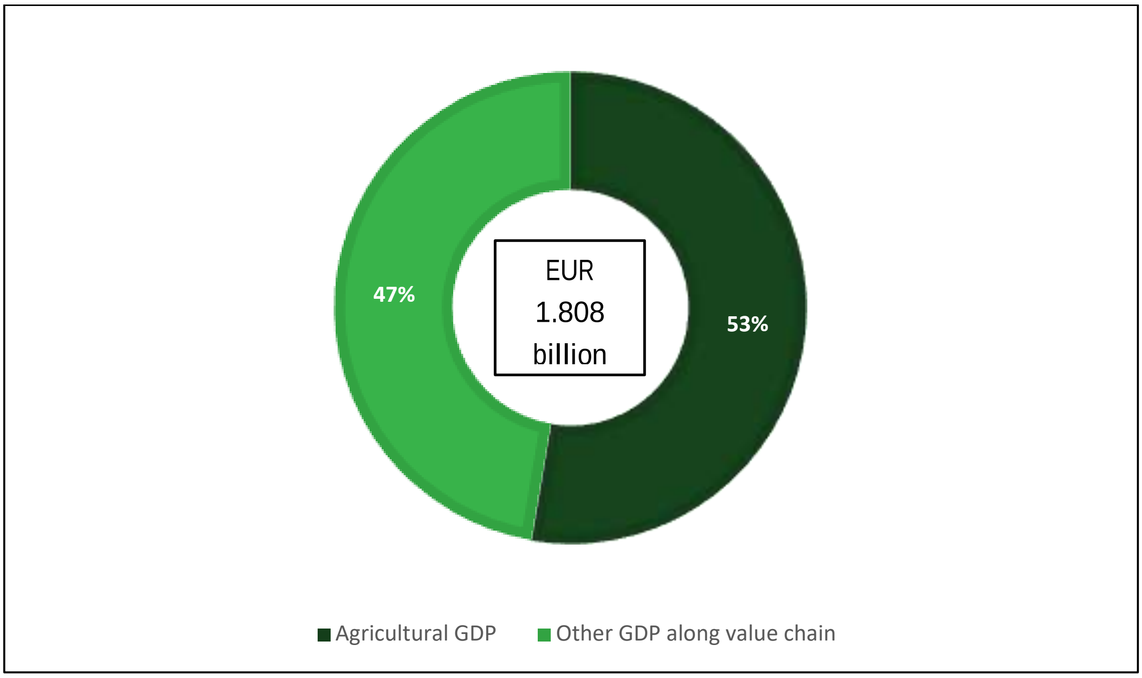
Source: Own calculations and figure.

Figure M.2: Level and composition of the additional GDP attributable to major arable crops in 2030 with plant breeding progress between 2020 and 2029 in the EU



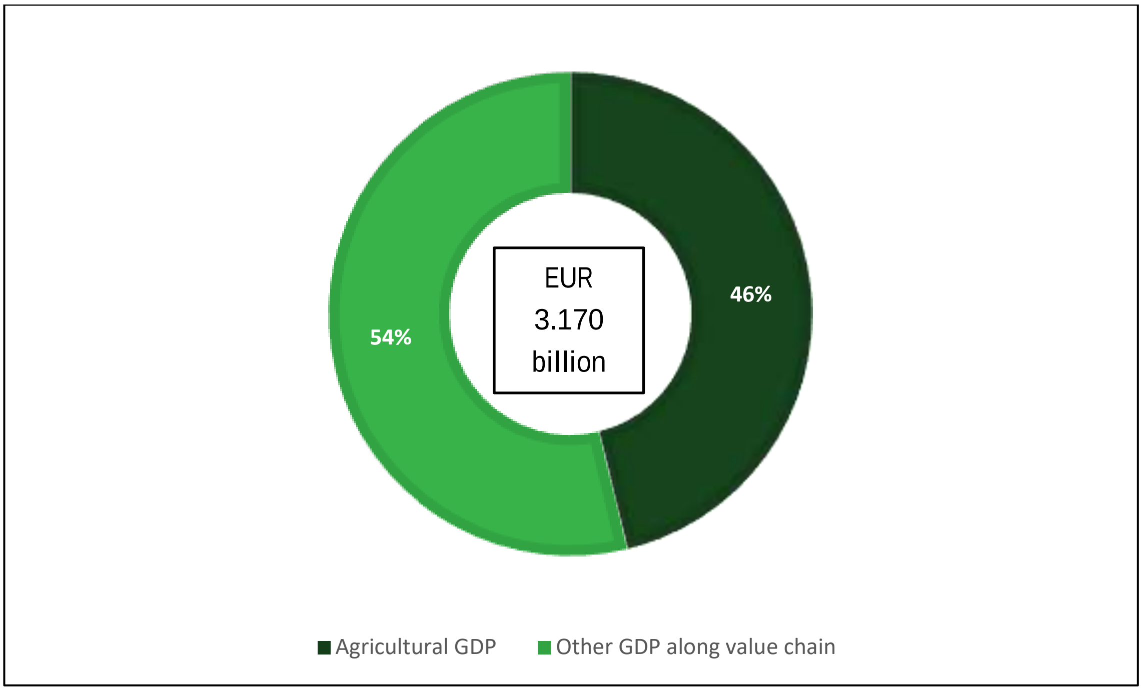
Source: Own calculations and figure.

Figure M.3: Level and composition of the additional GDP attributable to major arable crops in 2030 with plant breeding progress between 2020 and 2029 in Germany



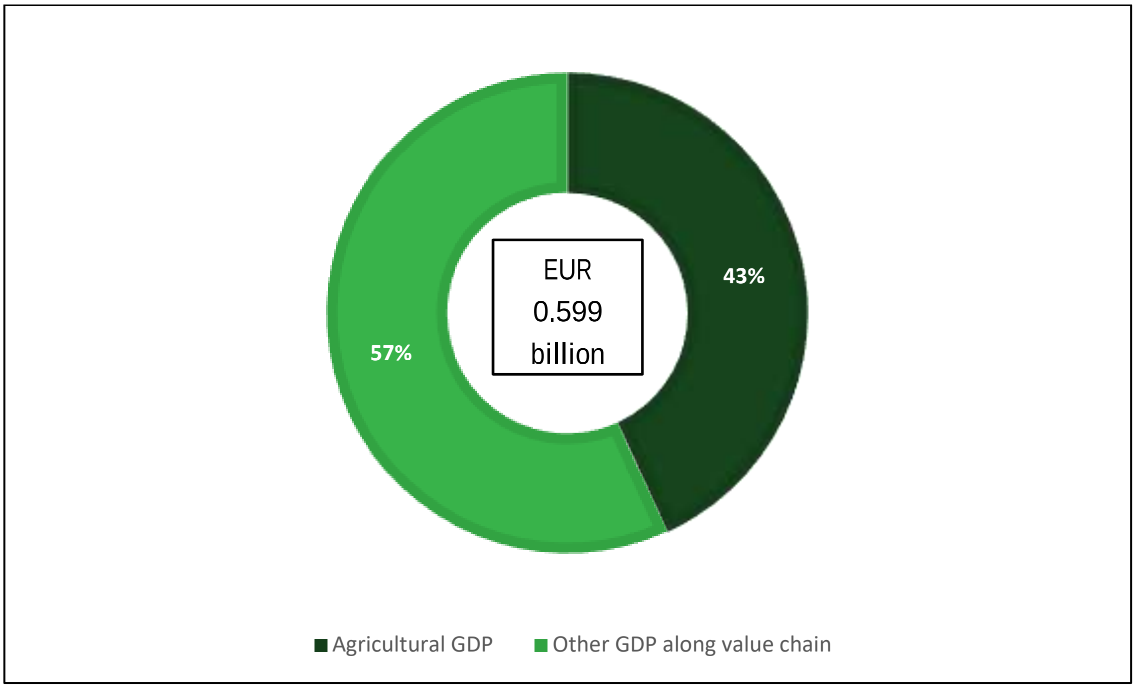
Source: Own calculations and figure.

Figure M.4: Level and composition of the additional GDP attributable to major arable crops in 2030 with plant breeding progress between 2020 and 2029 in France



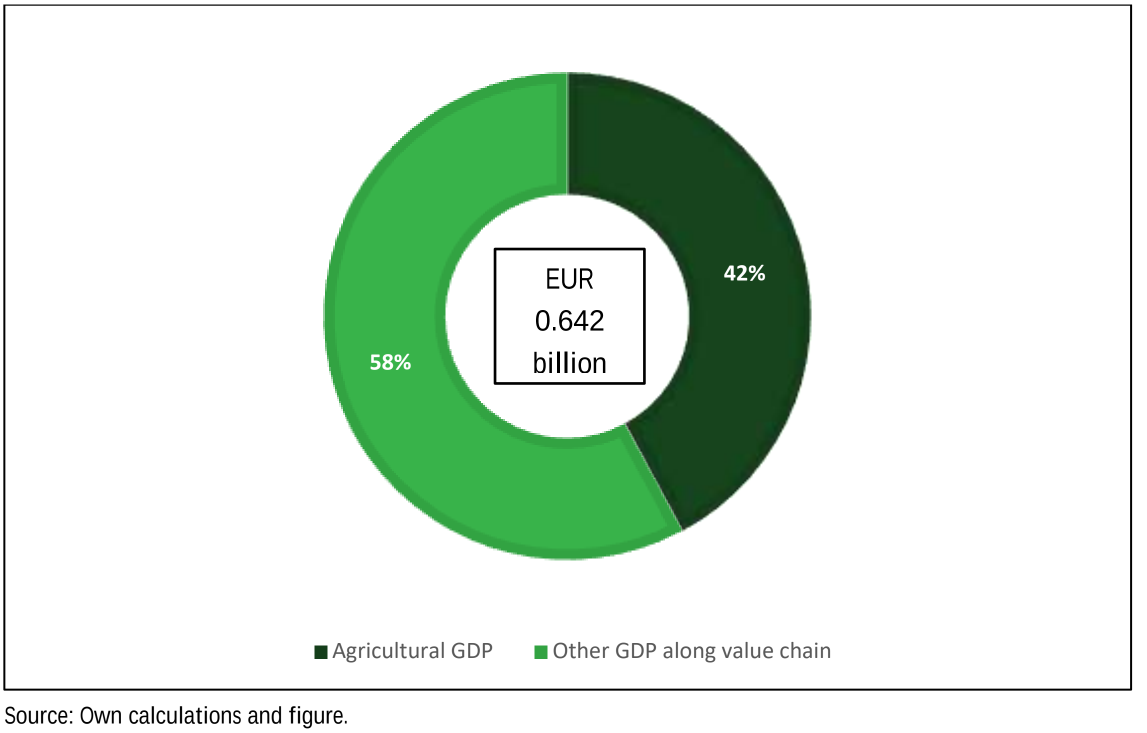
Source: Own calculations and figure.

Figure M.5: Level and composition of the additional GDP attributable to major arable crops in 2030 with plant breeding progress between 2020 and 2029 in Italy



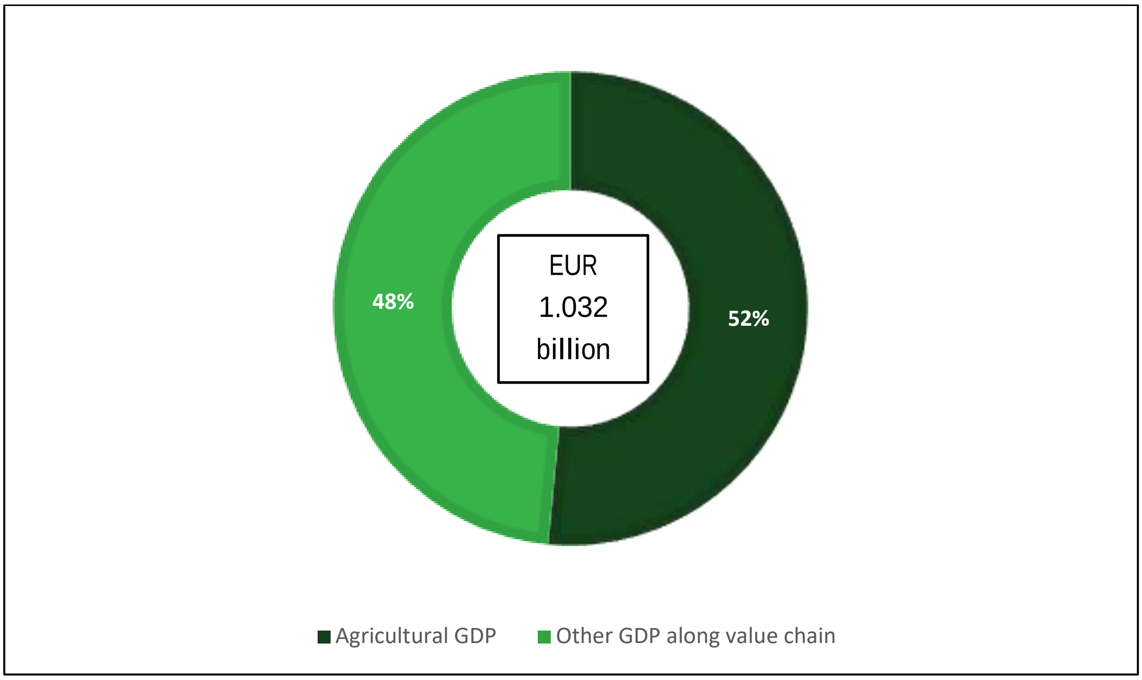
Source: Own calculations and figure.

Figure M.6: Level and composition of the additional GDP attributable to major arable crops in 2030 with plant breeding progress between 2020 and 2029 in Spain



Source: Own calculations and figure.

Figure M.7: Level and composition of the additional GDP attributable to major arable crops in 2030 with plant breeding progress between 2020 and 2029 in the UK



Source: Own calculations and figure.

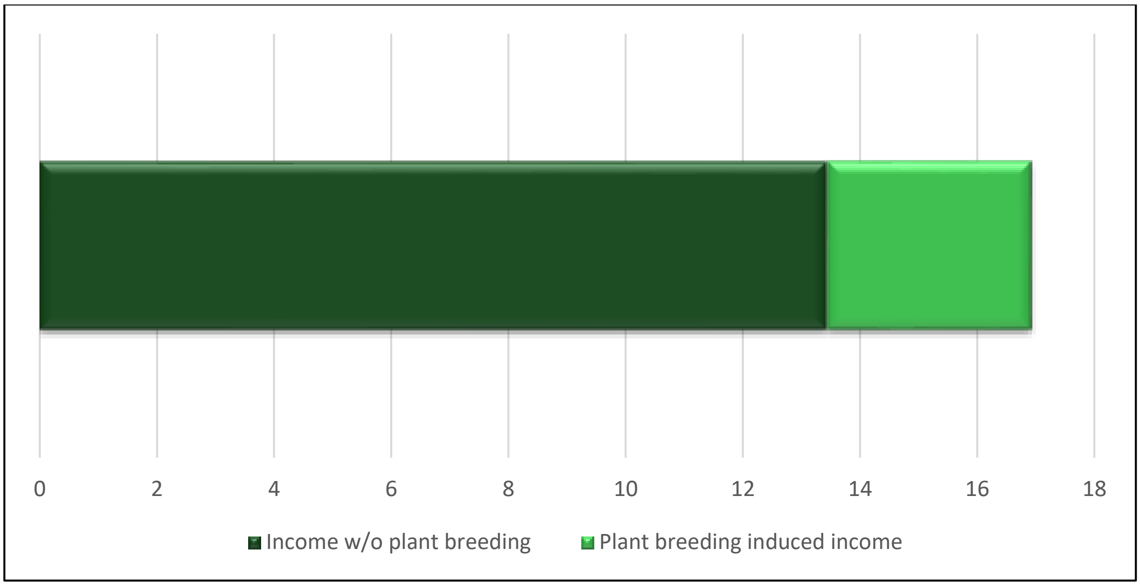
Annex N: Farm income impacts for the 2030 scenario

Figure N.1: Potential farm income of arable farms in 2030 and income induced by plant breeding progress between 2020 and 2029 in the EU and selected member states (in EUR/AWU)

Indicator/Region	EU	DE	FR	IT	ES	UK
Farm income	16 946	37 135	24 751	20 489	20 396	35 361
Income induced by plant breeding	3 502	4 577	6 447	1 452	867	9 960
Other farm income	13 444	32 557	18 304	19 037	19 528	25 401

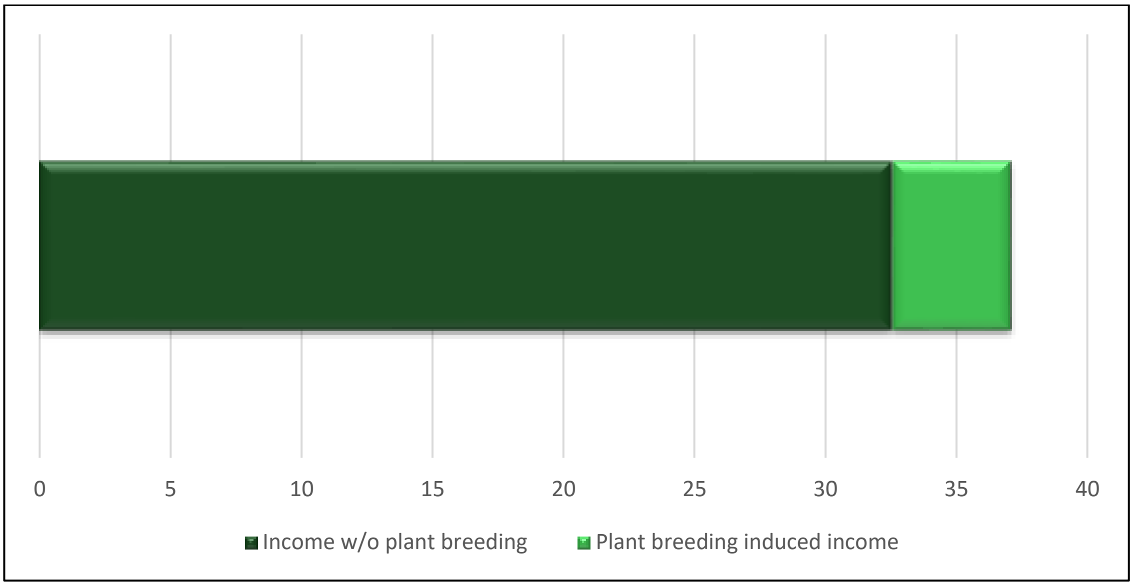
Source: Own calculations and figure.

Figure N.2: Potential farm income of arable farms in 2030 and income induced by plant breeding progress between 2020 and 2029 in the EU (in thousand EUR/AWU)



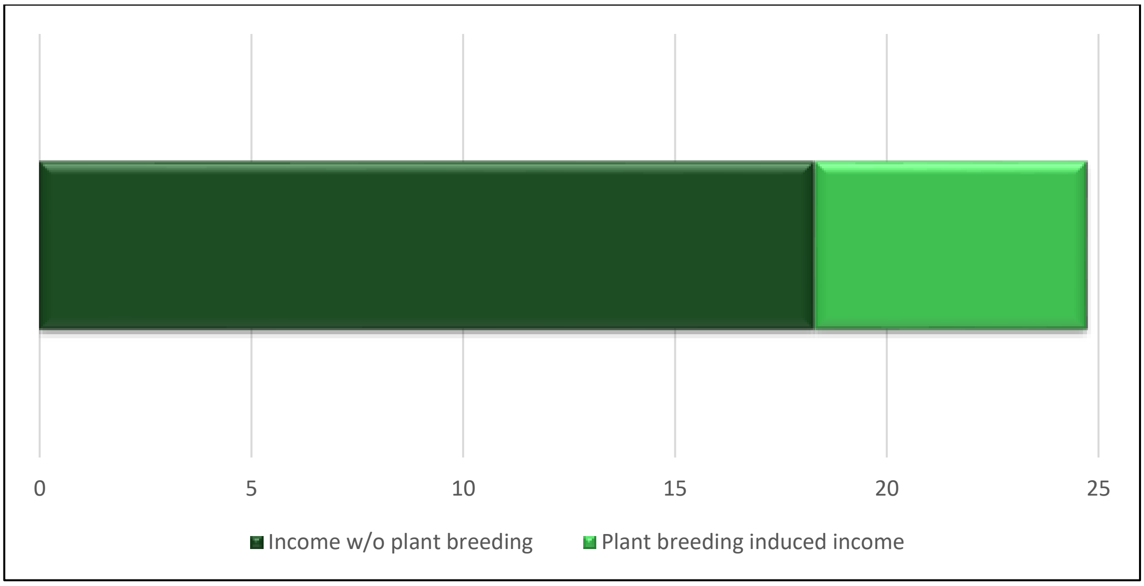
Source: Own calculations and figure.

Figure N.3: Potential farm income of arable farms in 2030 and income induced by plant breeding progress between 2020 and 2029 in Germany (in thousand EUR/AWU)



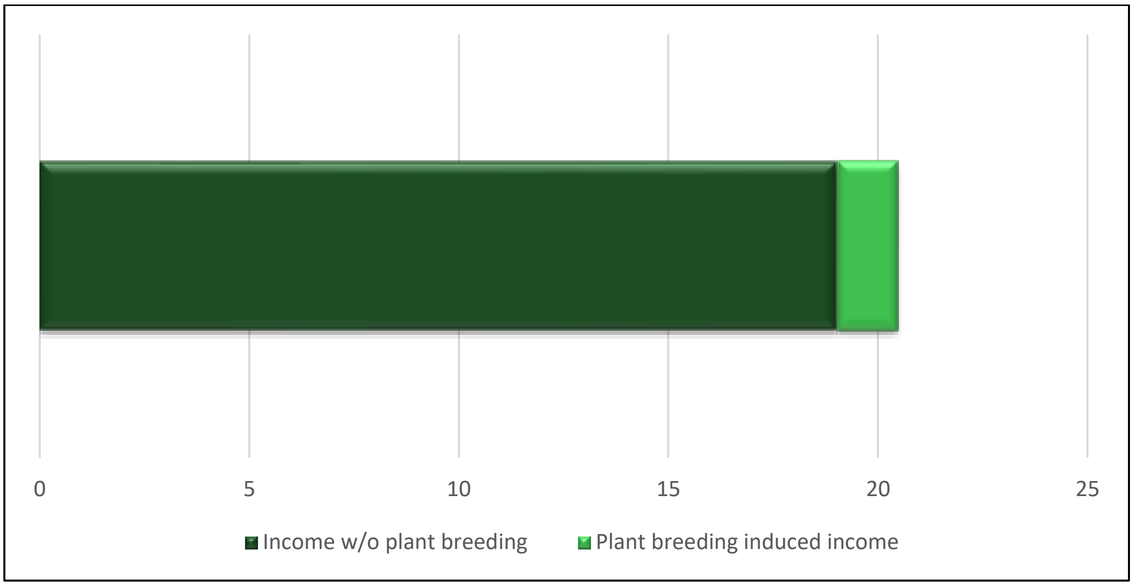
Source: Own calculations and figure.

Figure N.4: Potential farm income of arable farms in 2030 and income induced by plant breeding progress between 2020 and 2029 in France (in thousand EUR/AWU)



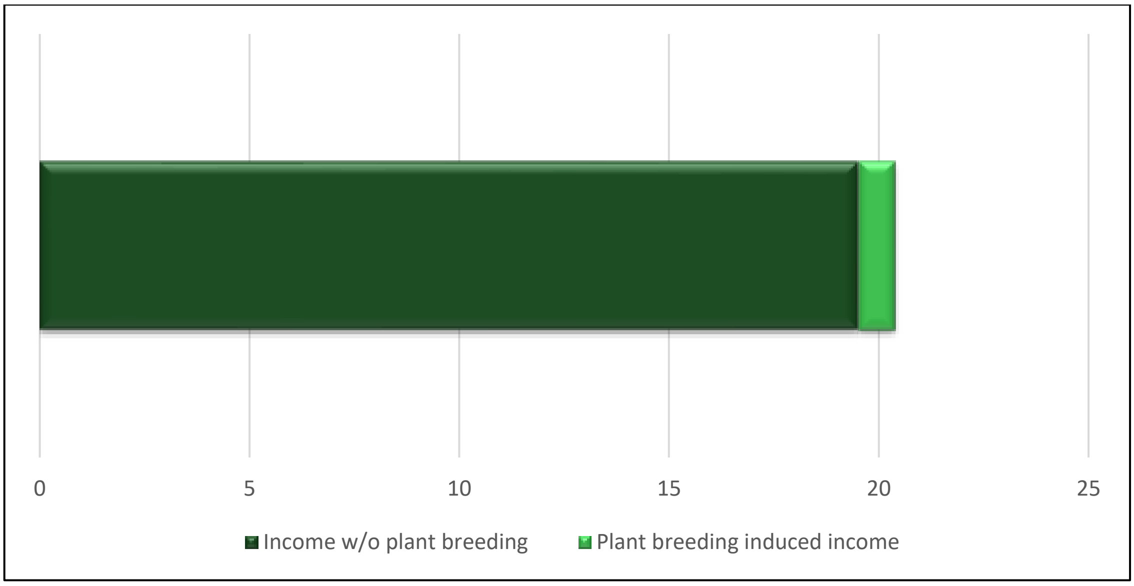
Source: Own calculations and figure.

Figure N.5: Potential farm income of arable farms in 2030 and income induced by plant breeding progress between 2020 and 2029 in Italy (in thousand EUR/AWU)



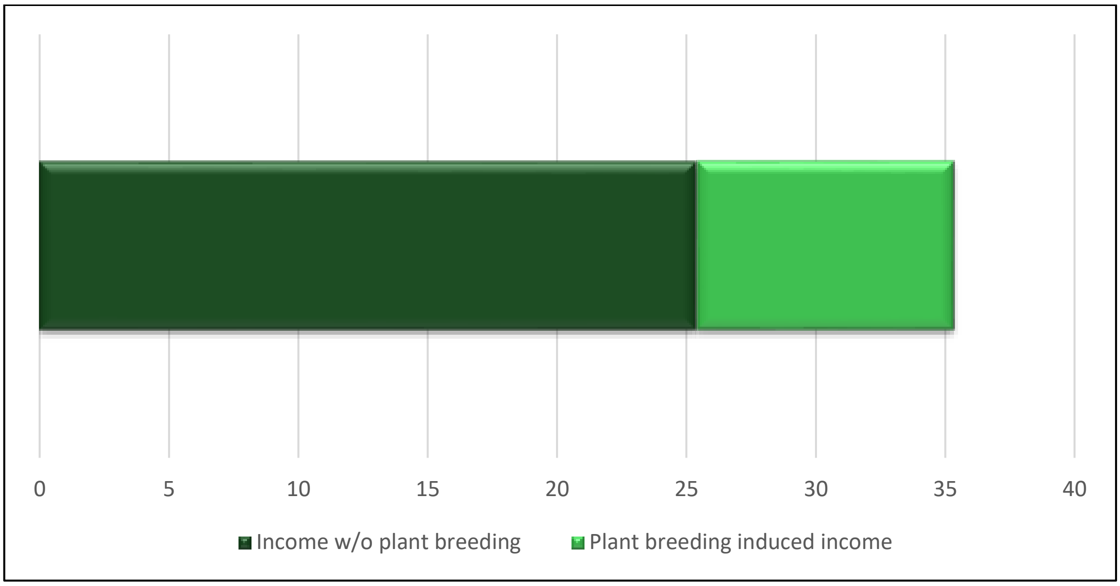
Source: Own calculations and figure.

Figure N.6: Potential farm income of arable farms in 2030 and income induced by plant breeding progress between 2020 and 2029 in Spain (in thousand EUR/AWU)



Source: Own calculations and figure.

Figure N.7: Potential farm income of arable farms in 2030 and income induced by plant breeding progress between 2020 and 2029 in the UK (in thousand EUR/AWU)



Source: Own calculations and figure.

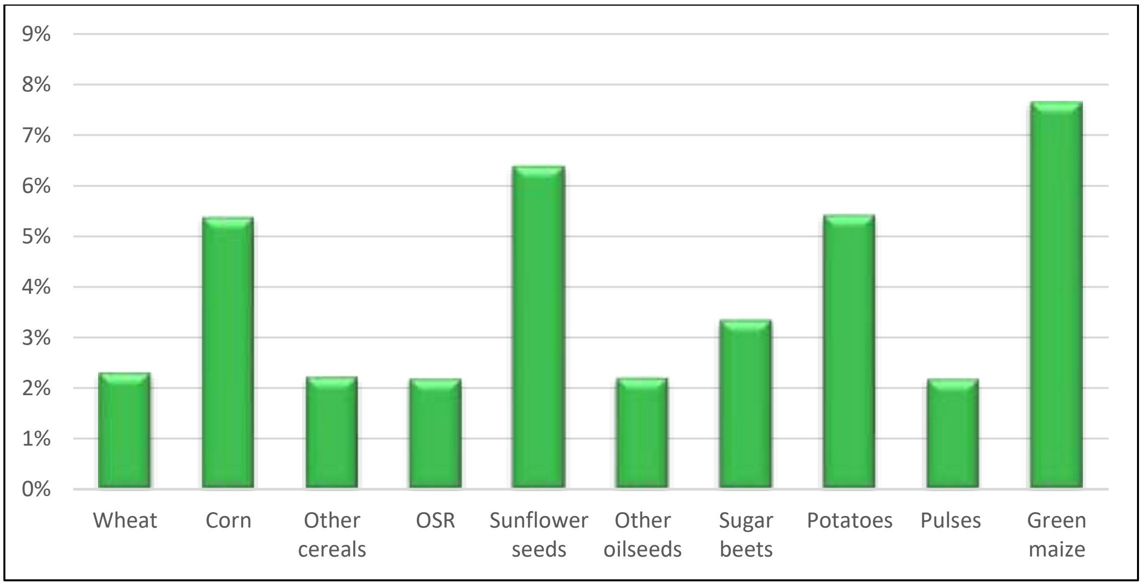
Annex O: Farm and other labour impacts for the 2030 scenario

Figure O.1: Potential farm labour losses attributable to major arable crops in 2030 without plant breeding progress between 2020 and 2029 in the EU and selected member states (in percent)

Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	2.3	1.5	1.7	2.5	1.4	2.1
Corn	5.4	4.2	4.1	2.6	4.2	4.0
Other cereals	2.2	2.1	1.6	1.7	0.9	2.0
OSR	2.2	1.8	3.2	8.2	3.6	3.9
Sunflower seeds	6.4	3.1	3.6	2.6	2.5	N.A.
Other oilseeds	2.2	6.	2.9	0.9	2.2	8.1
Raw sugar	3.3	3.1	3.	3.0	2.9	3.7
Potatoes	5.4	2.9	2.8	3.0	3.3	3.5
Pulses	2.2	2.6	2.8	3.2	3.4	2.4
Green maize	7.7	4.3	7.5	2.2	8.9	8.3

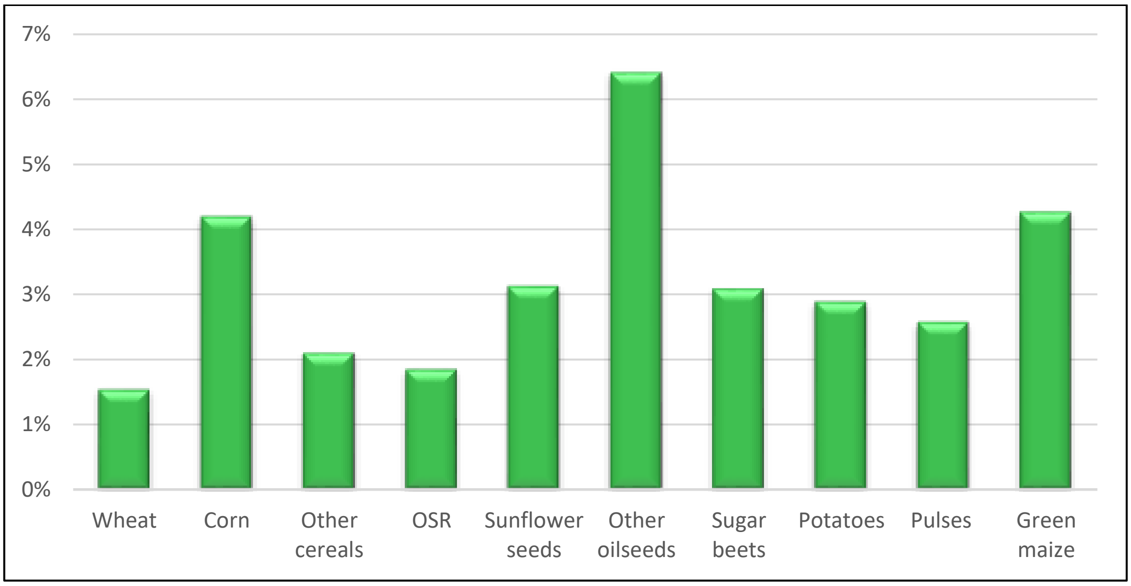
Source: Own calculations and figure.

Figure O.2: Potential farm labour losses attributable to major arable crops in 2030 without plant breeding progress between 2020 and 2029 in the EU



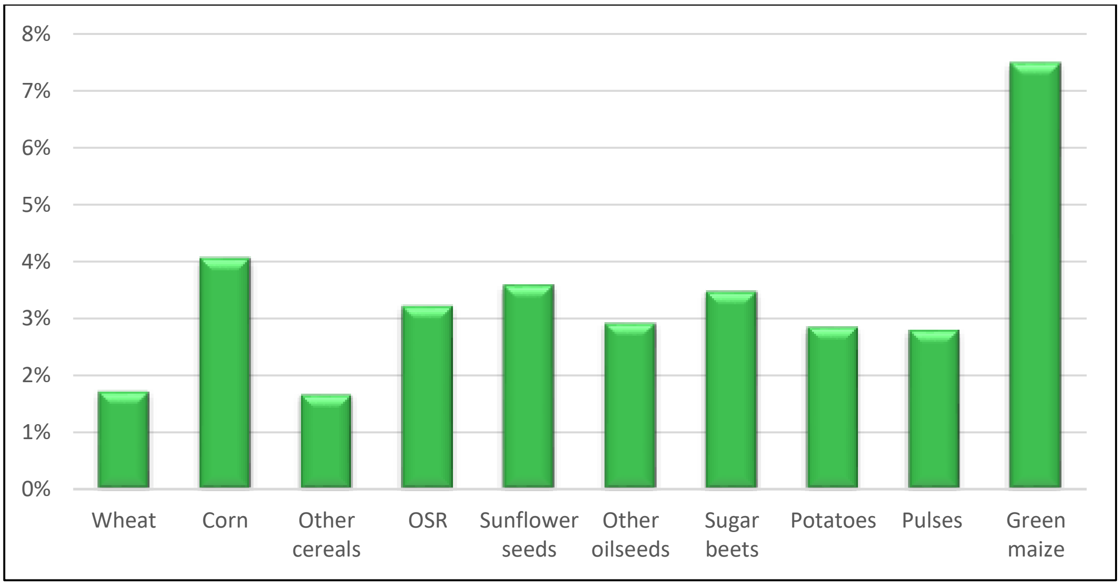
Source: Own calculations and figure (loss in arable farming: 42 000 AWU; loss along the value chains: 410 000 AWU).

Figure O.3: Potential farm labour losses attributable to major arable crops in 2030 without plant breeding progress between 2020 and 2029 in Germany



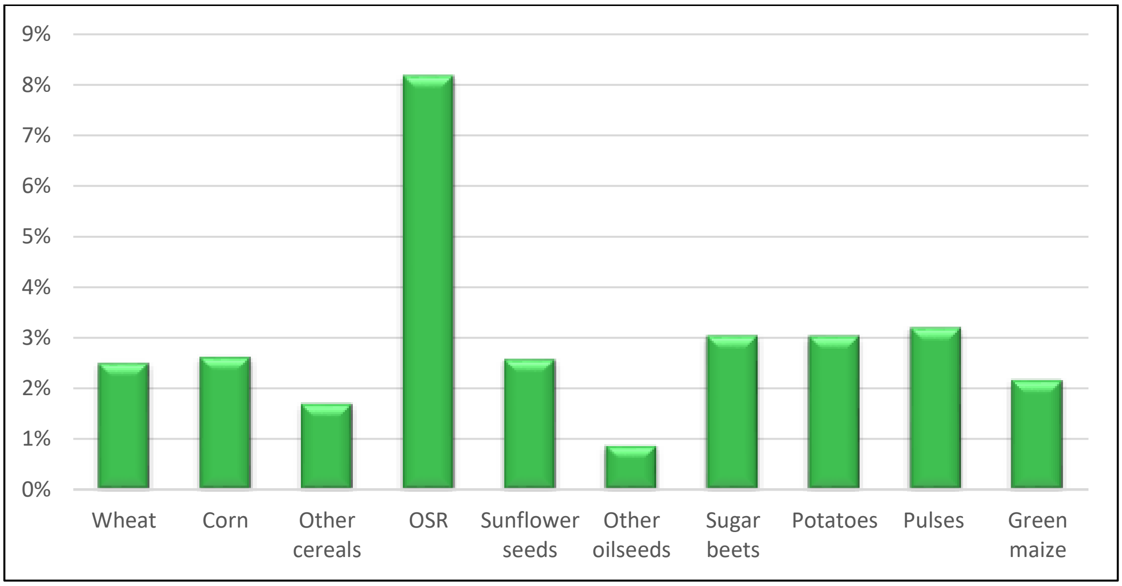
Source: Own calculations and figure (loss in arable farming: 3 000 AWU; loss along the value chains: 22 500 AWU).

Figure O.4: Potential farm labour losses attributable to major arable crops in 2030 without plant breeding progress between 2020 and 2029 in France



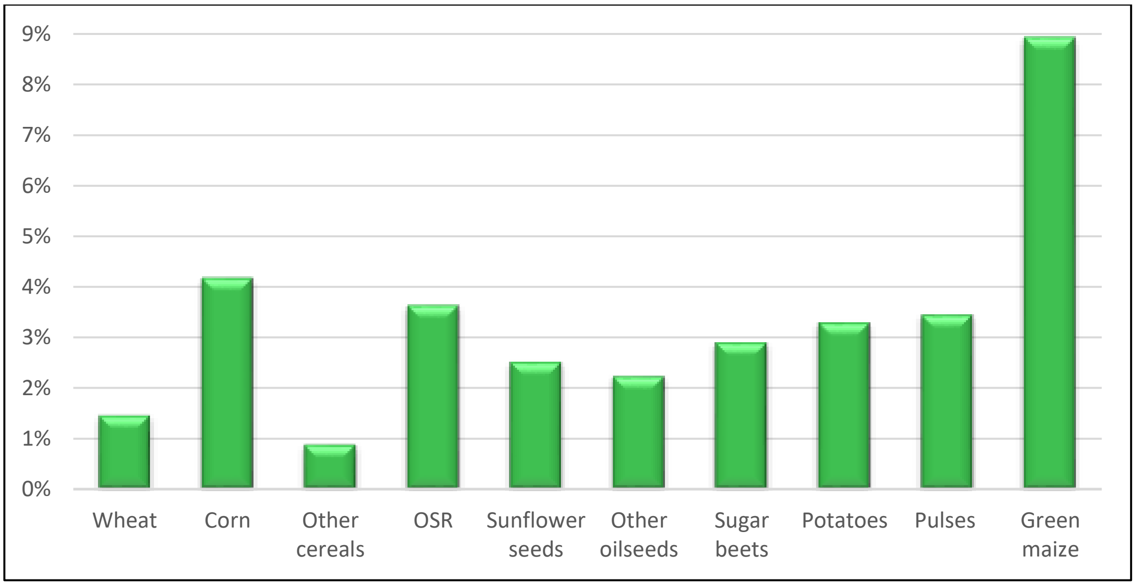
Source: Own calculations and figure (loss in arable farming: 4 100 AWU; loss along the value chains: 31 000 AWU).

Figure O.5: Potential farm labour losses attributable to major arable crops in 2030 without plant breeding progress between 2020 and 2029 in Italy



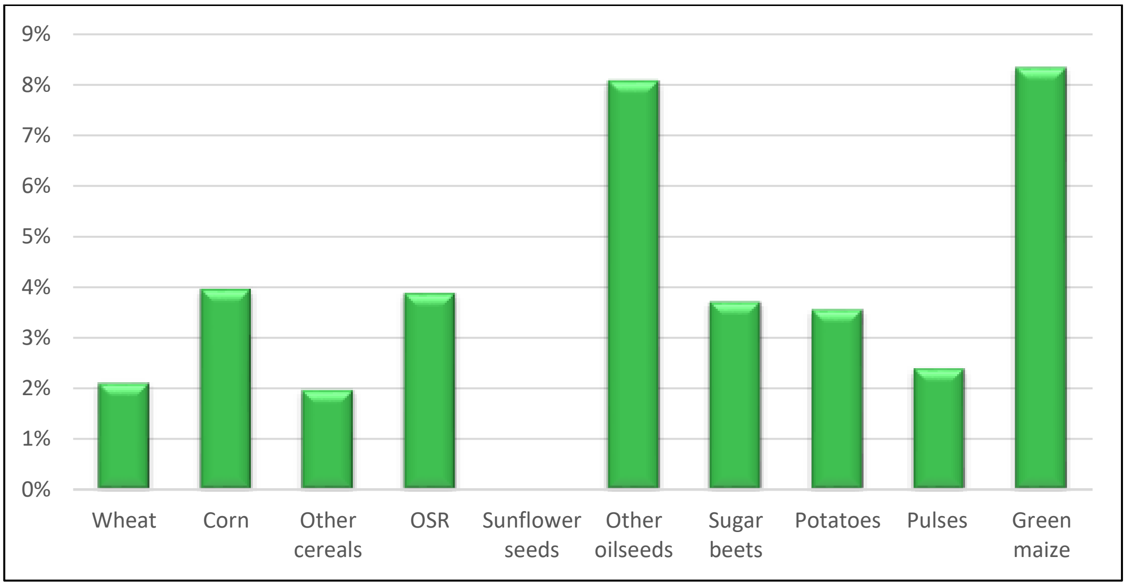
Source: Own calculations and figure (loss in arable farming: 2 700 AWU; loss along the value chains: 23 000 AWU).

Figure O.6: Potential farm labour losses attributable to major arable crops in 2030 without plant breeding progress between 2020 and 2029 in Spain



Source: Own calculations and figure (loss in arable farming: 1 300 AWU; loss along the value chains: 13 000 AWU).

Figure O.7: Potential farm labour losses attributable to major arable crops in 2030 without plant breeding progress between 2020 and 2029 in the UK



Source: Own calculations and figure (loss in arable farming: 1 000 AWU; loss along the value chains: 8 000 AWU).

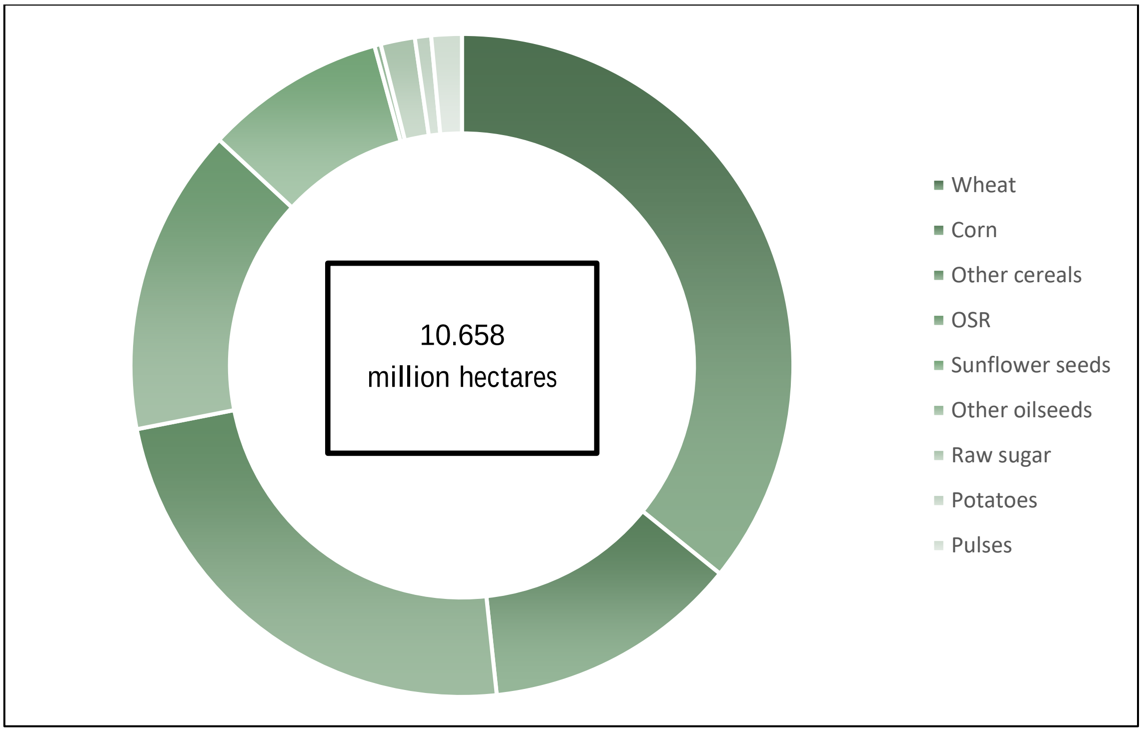
Annex P: Virtual land trade impacts for the 2030 scenario

Figure P.1: Potentially avoided net virtual land imports attributable to major arable crops in 2030 with plant breeding progress between 2020 and 2029 in the EU and selected member states (in million hectares)

Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	3.768	0.411	0.739	0.150	0.094	0.357
Corn	1.356	0.066	0.220	0.070	0.071	0.001
Other cereals	2.392	0.367	0.280	0.084	0.090	0.165
OSR	1.608	0.282	0.570	0.010	0.020	0.312
Sunflower seeds	1.083	0.002	0.087	0.012	0.039	0.000
Other oilseeds	0.033	0.001	0.004	0.005	0.001	0.001
Raw sugar	0.182	0.038	0.062	0.003	0.005	0.013
Potatoes	0.085	0.009	0.006	0.001	0.002	0.006
Pulses	0.150	0.024	0.035	0.007	0.020	0.030

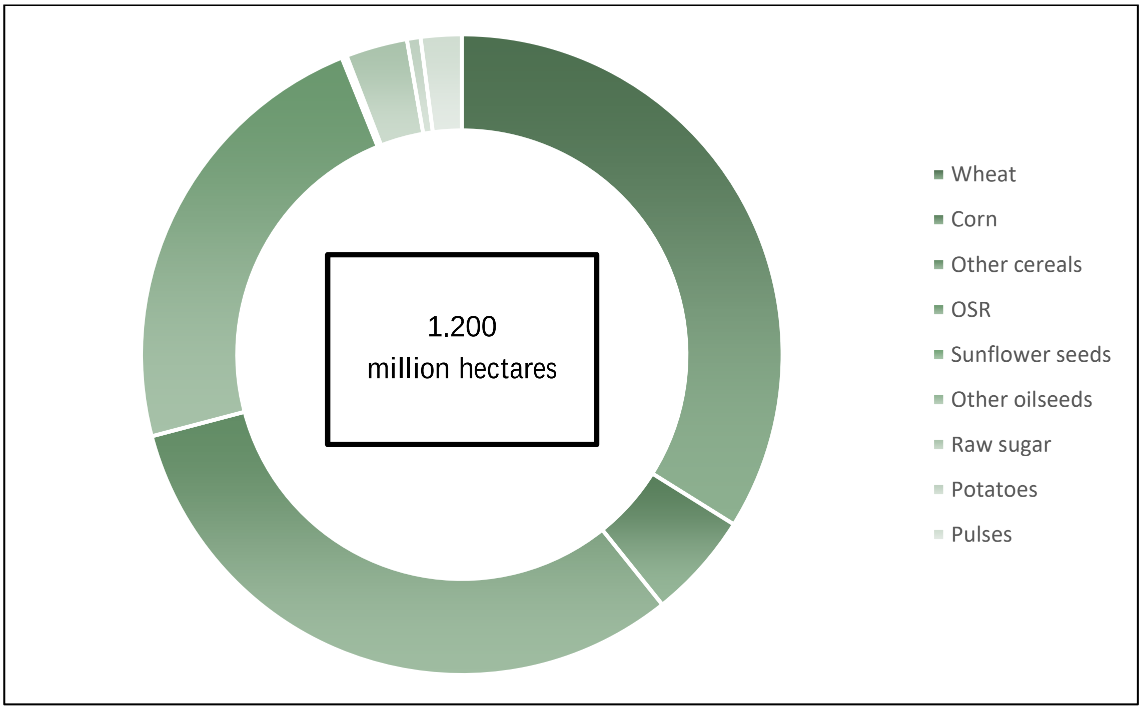
Source: Own calculations and figure.

Figure P.2: Potentially avoided net virtual land imports in 2030 with plant breeding progress between 2020 and 2029 in the EU, by crop



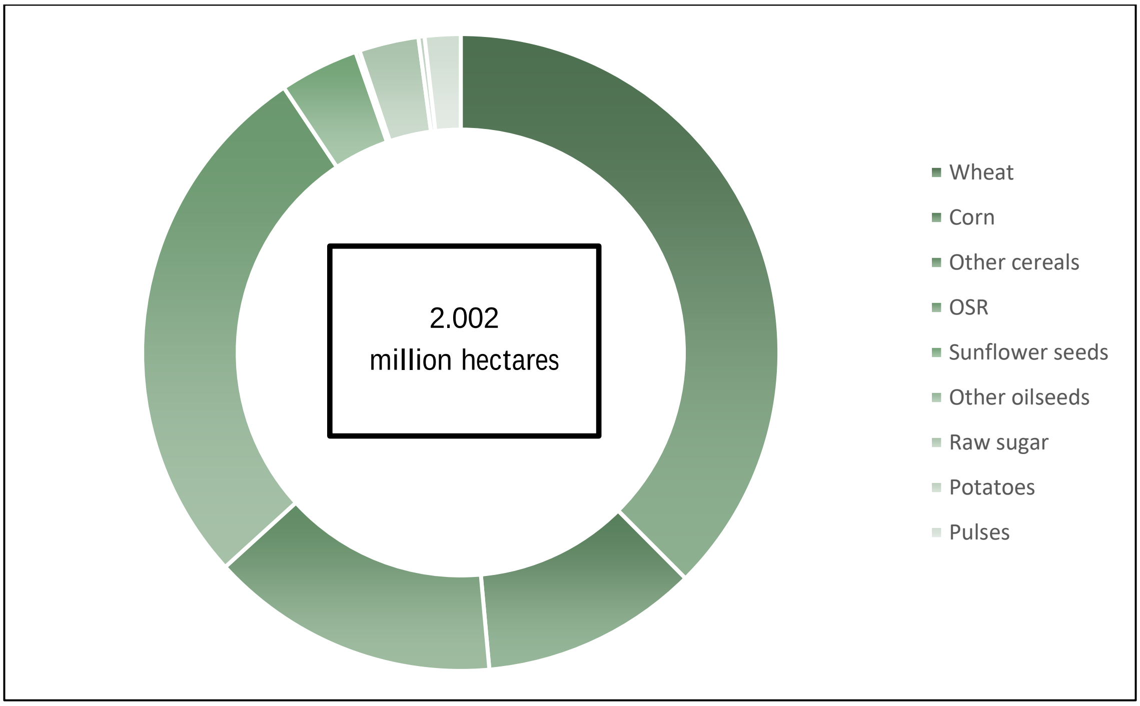
Source: Own calculations and figure.

Figure P.3: Potentially avoided net virtual land imports in 2030 with plant breeding progress between 2020 and 2029 in Germany, by crop



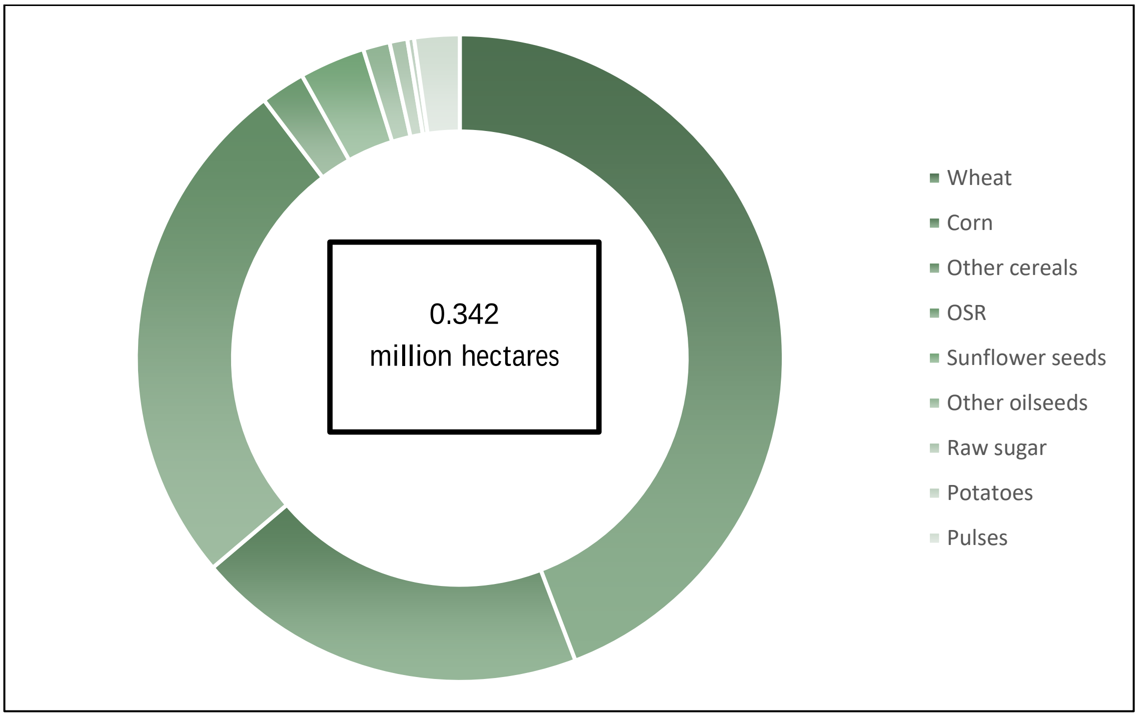
Source: Own calculations and figure.

Figure P.4: Potentially avoided net virtual land imports in 2030 with plant breeding progress between 2020 and 2029 in France, by crop



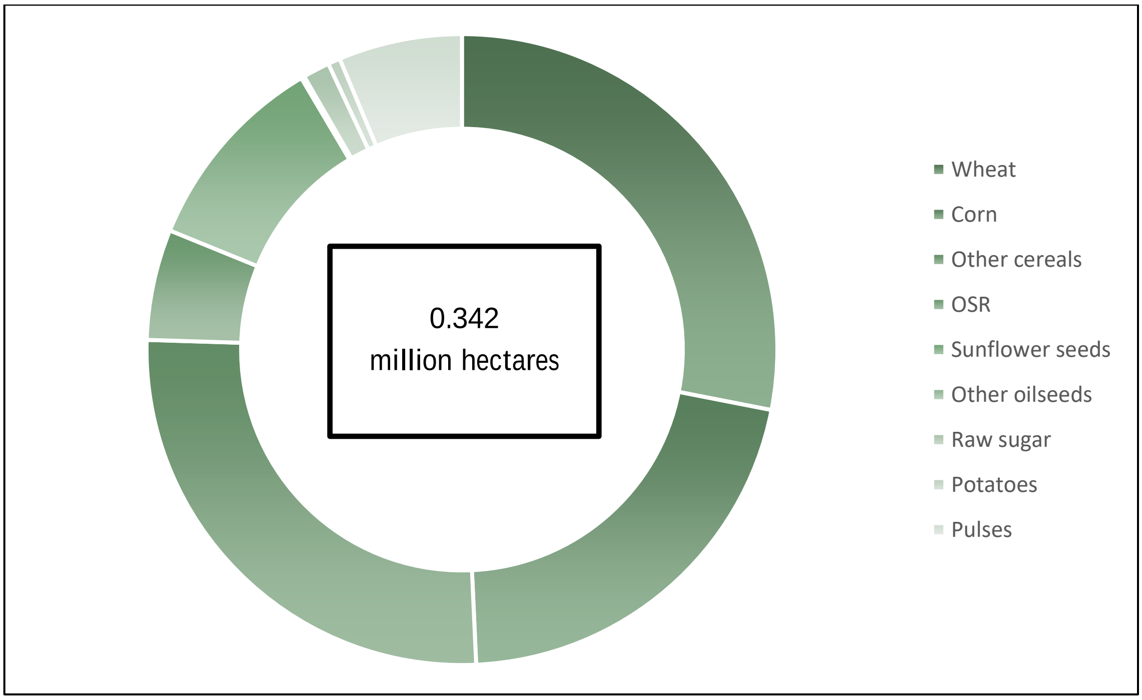
Source: Own calculations and figure.

Figure P.5: Potentially avoided net virtual land imports in 2030 with plant breeding progress between 2020 and 2029 in Italy, by crop



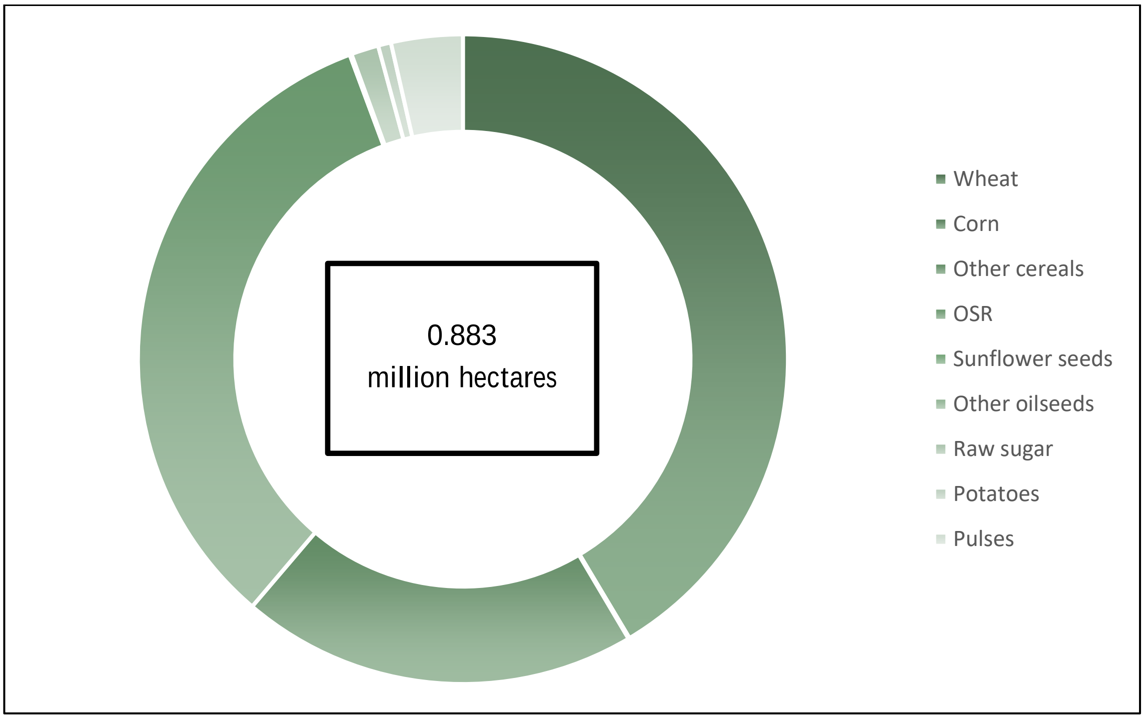
Source: Own calculations and figure.

Figure P.6: Potentially avoided net virtual land imports in 2030 with plant breeding progress between 2020 and 2029 in Spain, by crop



Source: Own calculations and figure.

Figure P.7: Potentially avoided net virtual land imports in 2030 with plant breeding progress between 2020 and 2029 in the UK, by crop



Source: Own calculations and figure.

Figure P.8: Potentially avoided net virtual land imports in 2030 with plant breeding progress between 2020 and 2029 in the EU, by region (in million hectares)

Region	Value	Region	Value
North America	1.196	Sub-Sahara Africa	1.137
South America	0.903	Oceania	1.304
Asia	1.456	CIS	2.691
MENA	1.739	RoW	0.233

Source: Own calculations and figure.

Figure P.9: Potentially avoided net virtual land imports in 2030 with plant breeding progress between 2020 and 2029 in Germany, by region (in million hectares)

Region	Value	Region	Value
North America	0.167	Sub-Sahara Africa	0.131
South America	0.095	Oceania	0.185
Asia	0.137	CIS	0.250
MENA	0.209	RoW	0.026

Source: Own calculations and figure.

Figure P.10: Potentially avoided net virtual land imports in 2030 with plant breeding progress between 2020 and 2029 in France, by region (in million hectares)

Region	Value	Region	Value
North America	0.275	Sub-Sahara Africa	0.201
South America	0.144	Oceania	0.295
Asia	0.227	CIS	0.526
MENA	0.293	RoW	0.042

Source: Own calculations and figure.

Figure P.11: Potentially avoided net virtual land imports in 2030 with plant breeding progress between 2020 and 2029 in Italy, by region (in million hectares)

Region	Value	Region	Value
North America	0.032	Sub-Sahara Africa	0.044
South America	0.038	Oceania	0.036
Asia	0.043	CIS	0.077
MENA	0.065	RoW	0.006

Source: Own calculations and figure.

Figure P.12: Potentially avoided net virtual land imports in 2030 with plant breeding progress between 2020 and 2029 in Spain, by region (in million hectares)

Region	Value	Region	Value
North America	0.040	Sub-Sahara Africa	0.036
South America	0.036	Oceania	0.032
Asia	0.047	CIS	0.089
MENA	0.055	RoW	0.007

Source: Own calculations and figure.

Figure P.13: Potentially avoided net virtual land imports in 2030 with plant breeding progress between 2020 and 2029 in the UK, by region (in million hectares)

Region	Value	Region	Value
North America	0.140	Sub-Sahara Africa	0.088
South America	0.050	Oceania	0.155
Asia	0.091	CIS	0.197
MENA	0.143	RoW	0.018

Source: Own calculations and figure

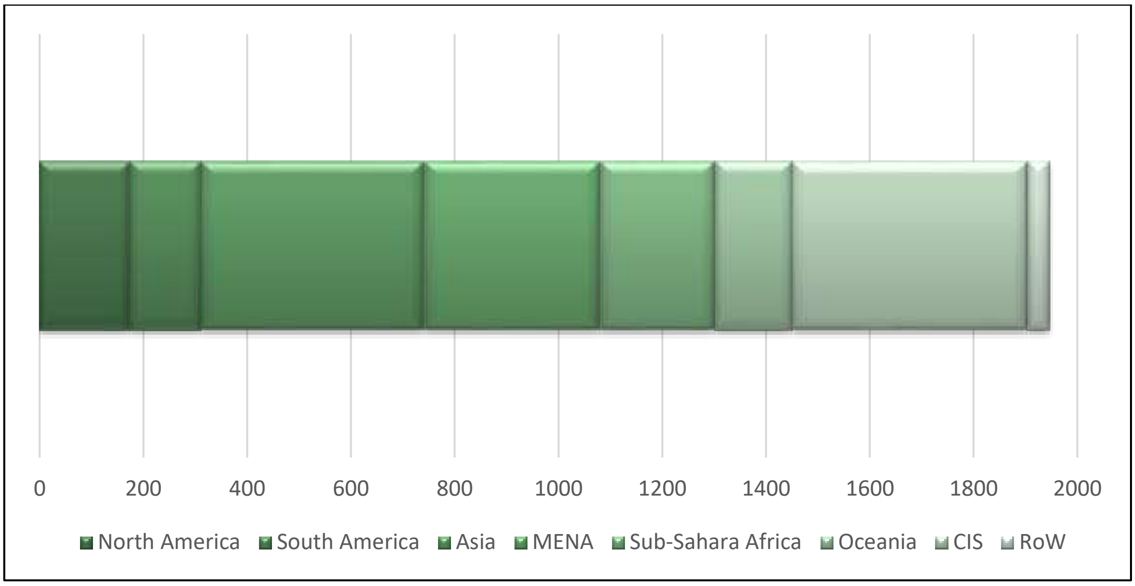
Annex Q: GHG emission impacts for the 2030 scenario

Figure Q.1: Potentially avoided regional CO_2 emissions attributable to major arable crops until 2030 with plant breeding progress between 2020 and 2029 in the EU and selected member states (in million tons)

Region	EU	DE	FR	IT	ES	UK
North America	175	24	40	5	6	20
South America	136	14	22	6	5	8
Asia	431	40	67	13	14	27
MENA	339	41	57	13	11	28
Sub-Sahara Africa	222	26	39	9	7	17
Oceania	147	21	33	4	4	17
CIS	455	42	89	13	15	33
RoW	42	5	8	1	1	3

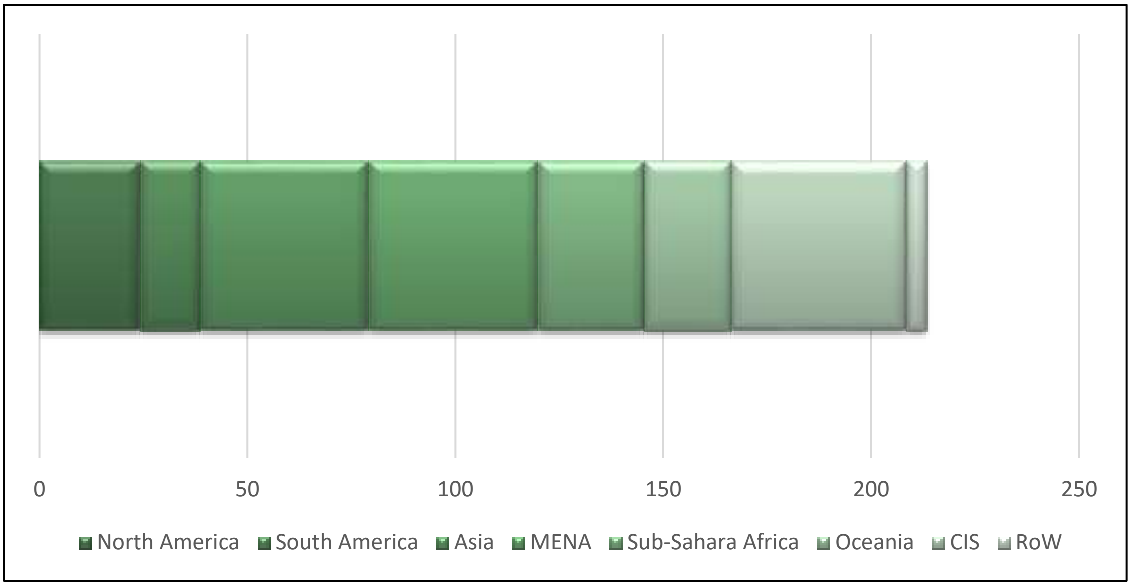
Source: Own calculations and figure.

Figure Q.2: Potentially avoided regional CO_2 emissions until 2030 with plant breeding progress between 2020 and 2029 in the EU (in million tons)



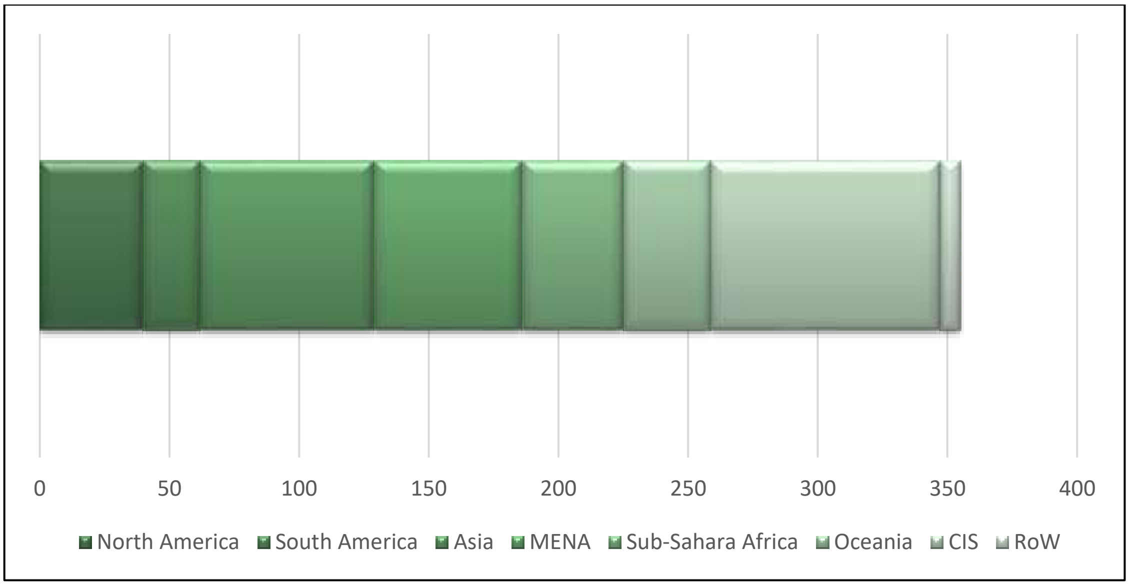
Source: Own calculations and figure.

Figure Q.3: Potentially avoided regional CO_2 emissions until 2030 with plant breeding progress between 2020 and 2029 in Germany (in million tons)



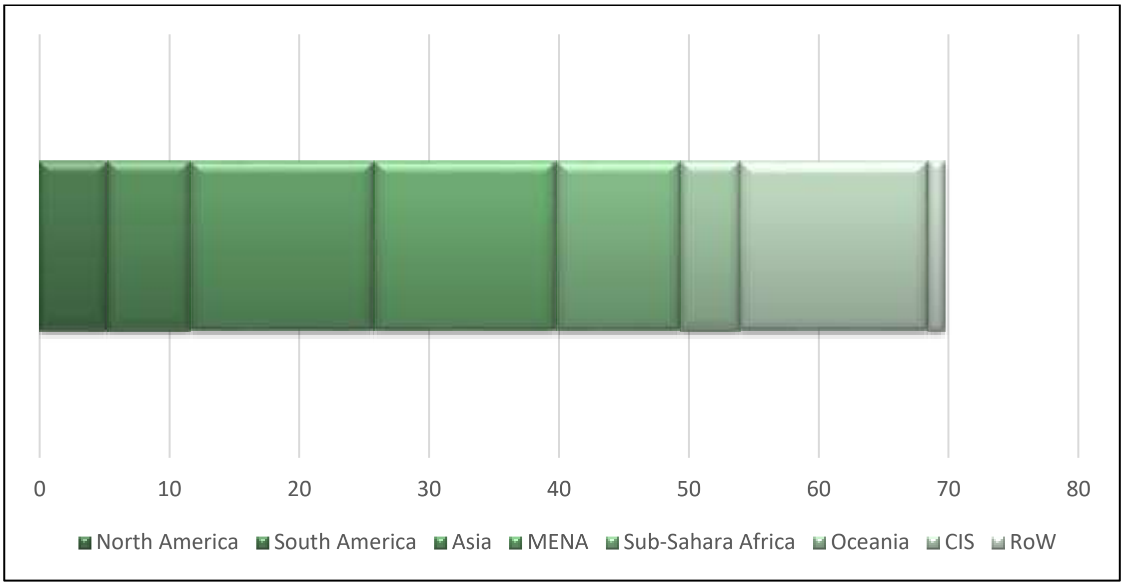
Source: Own calculations and figure.

Figure Q.4: Potentially avoided regional CO_2 emissions until 2030 with plant breeding progress between 2020 and 2029 in France (in million tons)



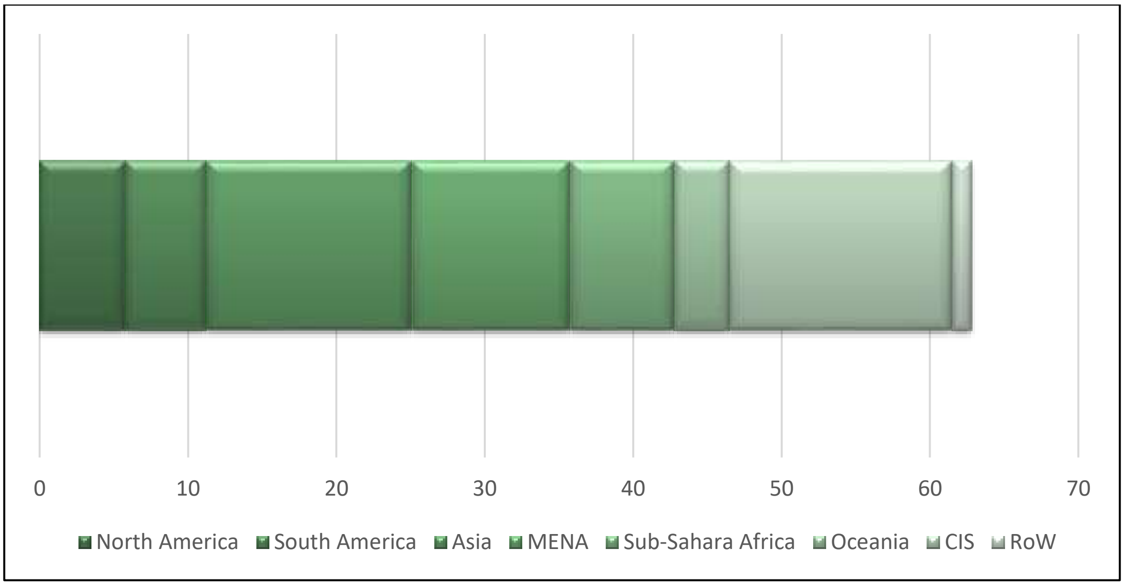
Source: Own calculations and figure.

Figure Q.5: Potentially avoided regional CO_2 emissions until 2030 with plant breeding progress between 2020 and 2029 in Italy (in million tons)



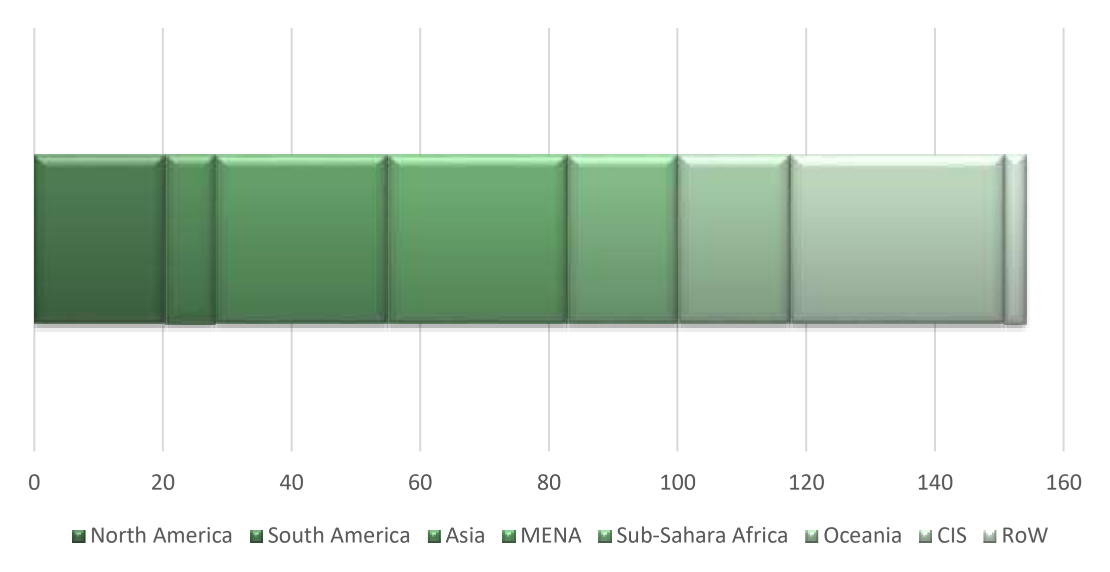
Source: Own calculations and figure.

Figure Q.6: Potentially avoided regional CO_2 emissions until 2030 with plant breeding progress between 2020 and 2029 in Spain (in million tons)



Source: Own calculations and figure.

Figure Q.7: Potentially avoided regional CO_2 emissions until 2030 with plant breeding progress between 2020 and 2029 in the UK (in million tons)



Source: Own calculations and figure.

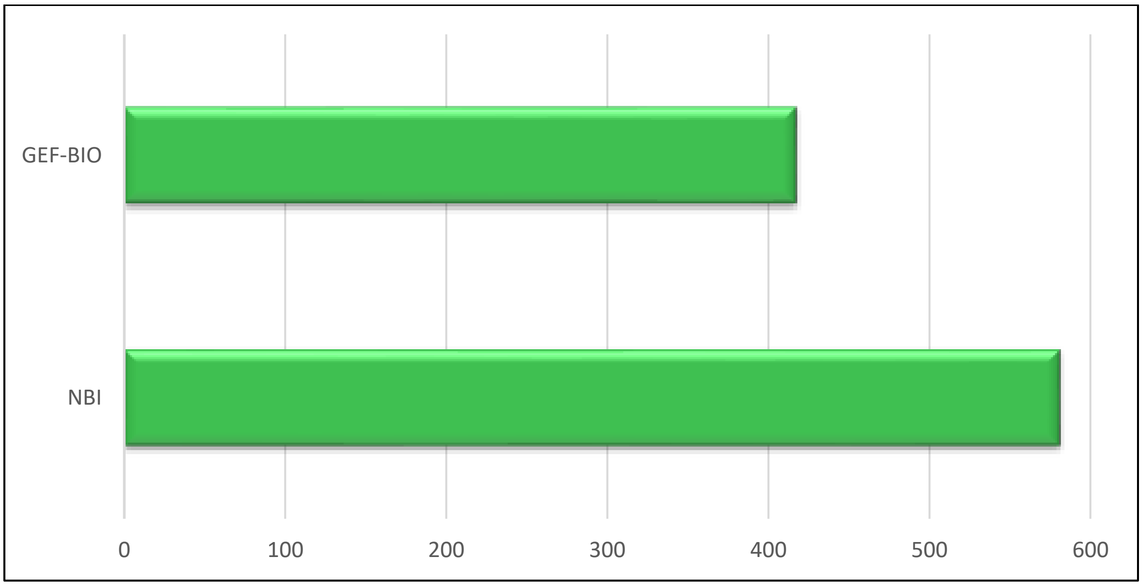
Annex R: Global biodiversity impacts of the 2030 scenario

Figure R.1: Potentially avoided biodiversity loss until 2030 with plant breeding progress between 2020 and 2029 in the EU and selected member states (in million points)

Region	EU	DE	FR	IT	ES	UK
GEF-BIO						
North America	49	7	11	1	2	6
South America	55	6	9	2	2	3
Asia	26	2	4	1	1	2
MENA	3	0	1	0	0	0
Sub-Sahara Africa	7	1	1	0	0	1
Oceania	40	6	9	1	1	5
CIS	229	21	45	7	8	17
RoW	8	1	1	0	0	1
NBI						
North America	48	7	11	1	2	6
South America	79	8	13	3	3	4
Asia	57	5	9	2	2	4
MENA	54	6	9	2	2	4
Sub-Sahara Africa	48	6	8	2	2	4
Oceania	59	8	13	2	1	7
CIS	226	21	44	7	7	17
RoW	12	1	2	0	0	1

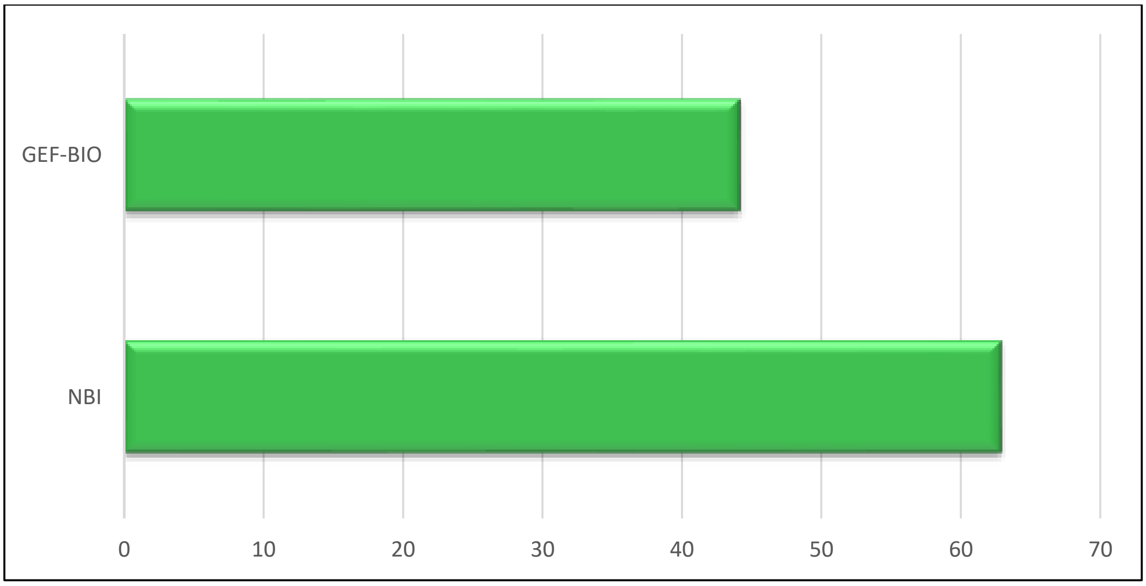
Source: Own calculations and figure.

Figure R.2: Potentially avoided global biodiversity loss until 2030 with plant breeding progress between 2020 and 2029 in the EU (in million points)



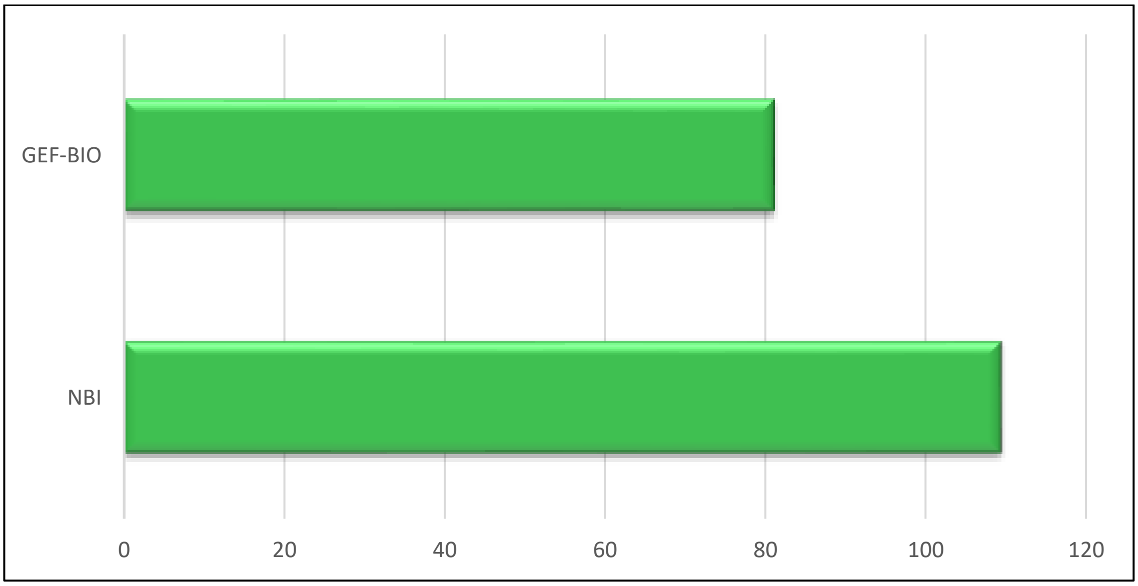
Source: Own calculations and figure.

Figure R.3: Potentially avoided global biodiversity loss until 2030 with plant breeding progress between 2020 and 2029 in Germany (in million points)



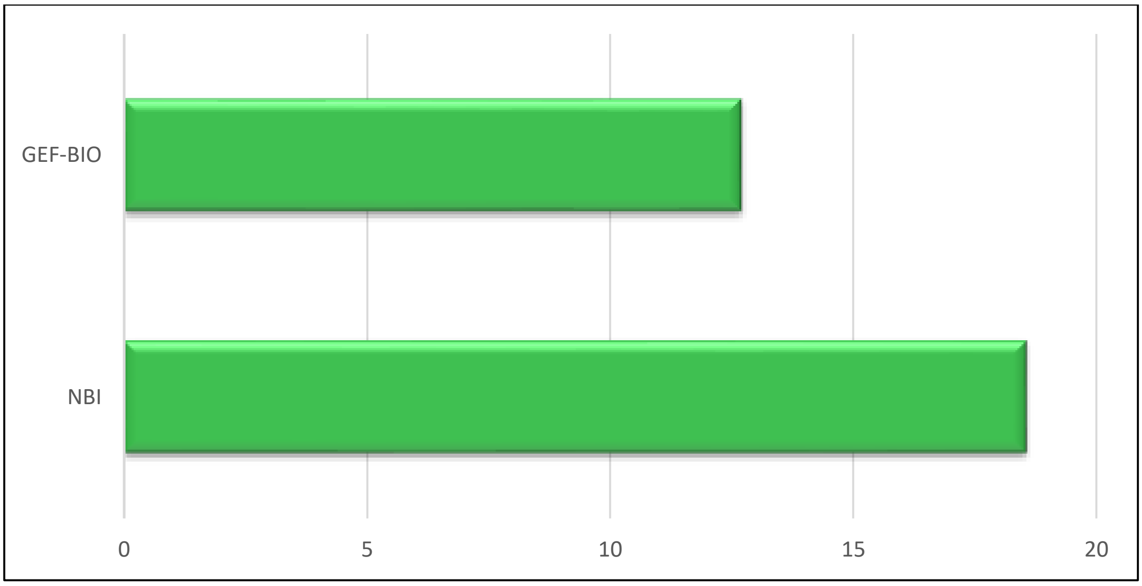
Source: Own calculations and figure.

Figure R.4: Potentially avoided global biodiversity loss until 2030 with plant breeding progress between 2020 and 2029 in France (in million points)



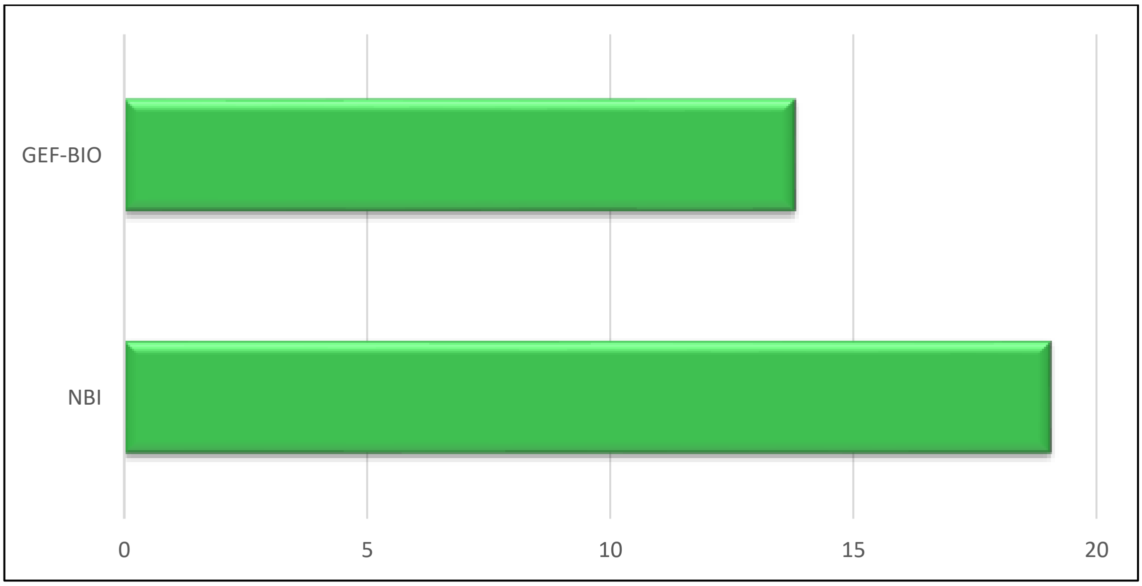
Source: Own calculations and figure.

Figure R.5: Potentially avoided global biodiversity loss until 2030 with plant breeding progress between 2020 and 2029 in Italy (in million points)



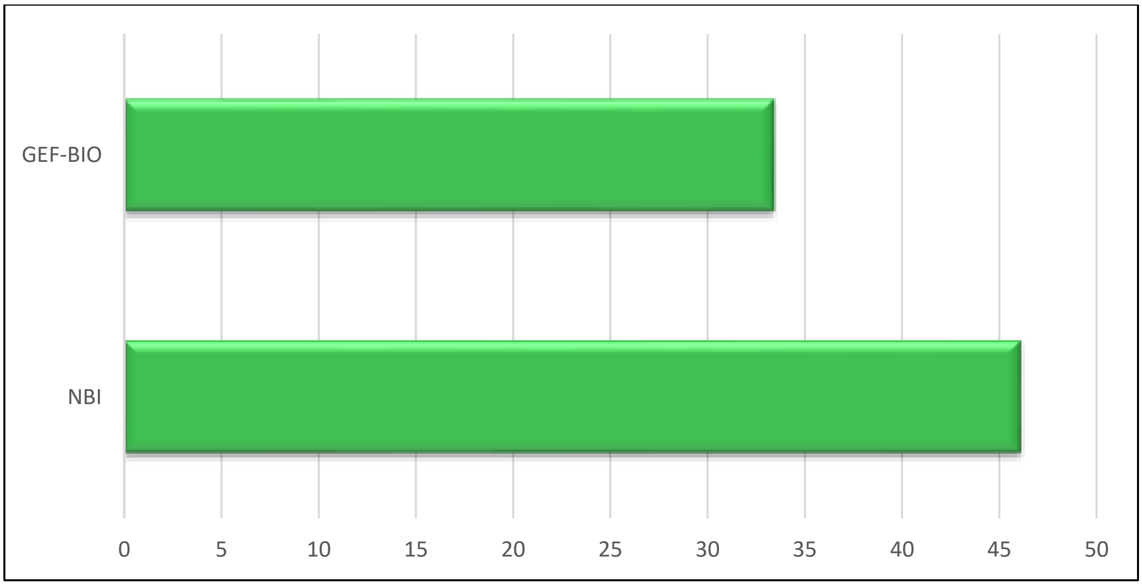
Source: Own calculations and figure.

Figure R.6: Potentially avoided global biodiversity loss until 2030 with plant breeding progress between 2020 and 2029 in Spain (in million points)



Source: Own calculations and figure.

Figure R.7: Potentially avoided global biodiversity loss until 2030 with plant breeding progress between 2020 and 2029 in the UK (in million points)



Source: Own calculations and figure.

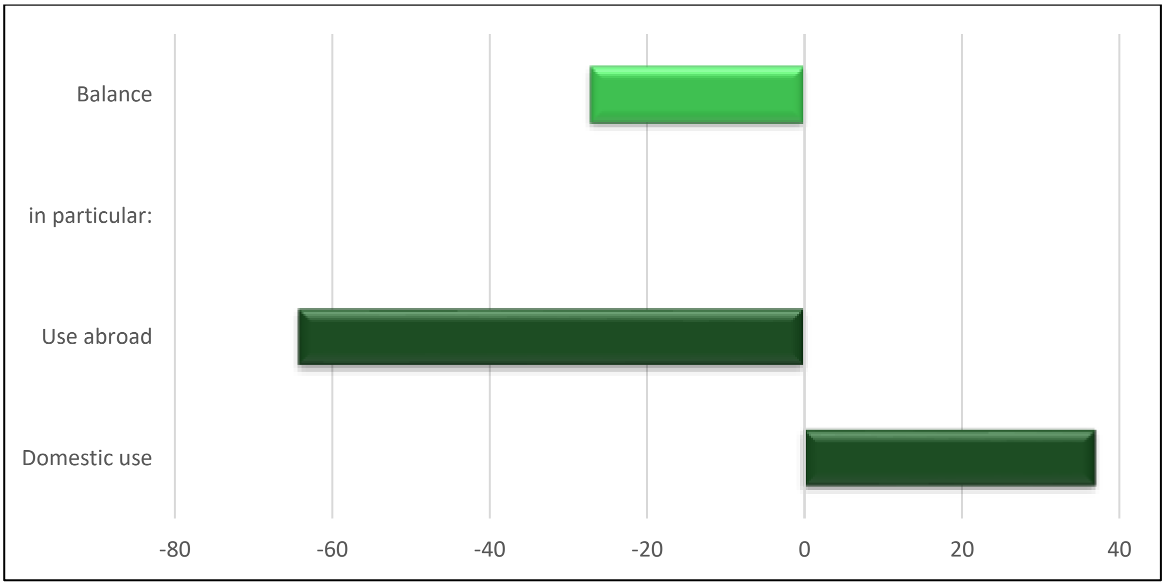
Annex S: Global water impacts of the 2030 scenario

Figure S.1: Potential global water use balance in 2030 with plant breeding progress between 2020 and 2029 in the EU and selected member states (in billion m³)

Crop/Region	EU	DE	FR	IT	ES	UK
Wheat	-7.500	-1.144	-2.529	-0.123	0.023	-1.248
Corn	-9.205	-0.493	-1.482	-0.467	-0.360	-0.003
Other cereals	-6.951	-1.088	-0.850	-0.203	-0.091	-0.617
OSR	-1.610	-0.382	-0.693	0.012	-0.007	-0.399
Sunflower seeds	-1.342	0.003	-0.127	-0.005	0.108	N.A.
Other oilseeds	-0.130	0.000	-0.006	-0.043	0.004	-0.004
Raw sugar	-0.304	-0.082	-0.169	-0.005	-0.007	-0.028
Potatoes	-1.755	-0.191	-0.128	-0.016	-0.030	-0.133
Pulses	-1.093	-0.184	-0.269	-0.052	-0.076	-0.239
Green maize	2.703	0.567	0.320	0.055	0.061	0.085

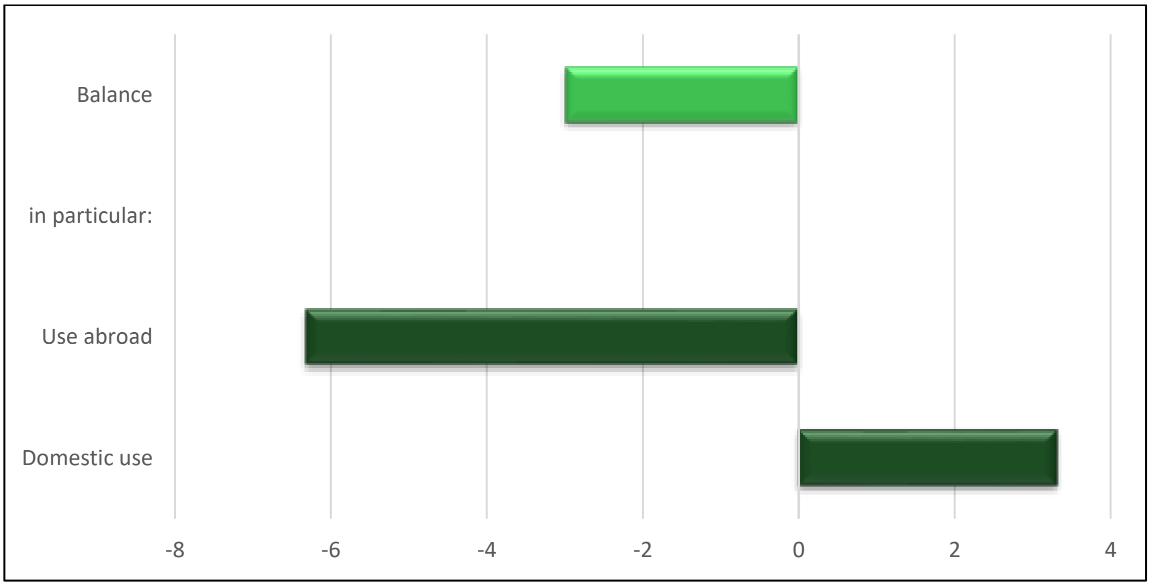
Source: Own calculations and figure.

Figure S.2: Potential global and regional water use balances in 2030 with plant breeding progress between 2020 and 2029 in the EU (in billion m³)



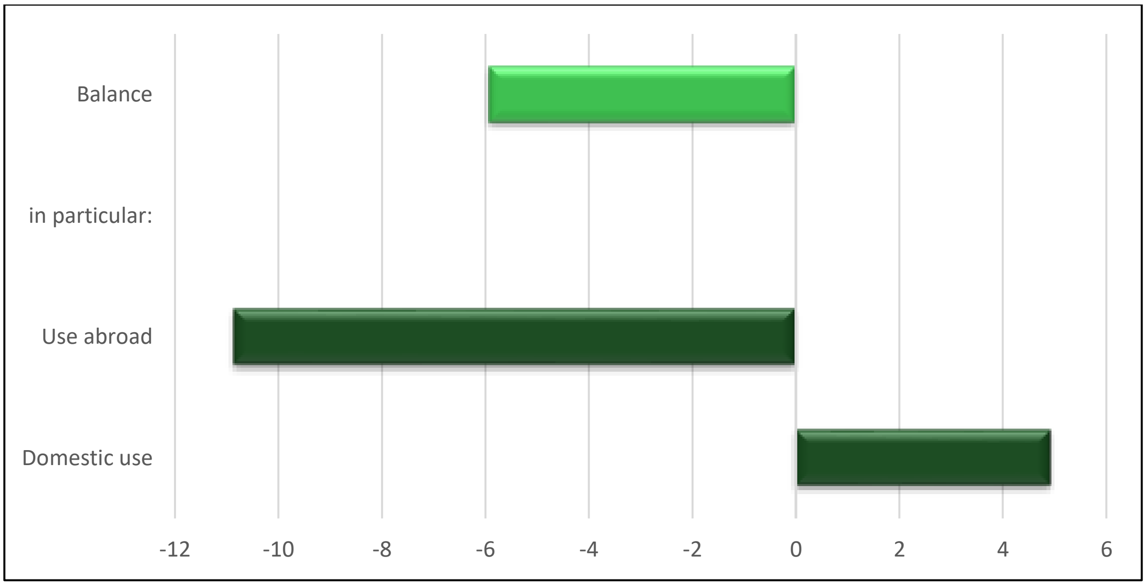
Source: Own calculations and figure.

Figure S.3: Potential global and regional water use balances in 2030 with plant breeding progress between 2020 and 2029 in Germany (in billion m³)



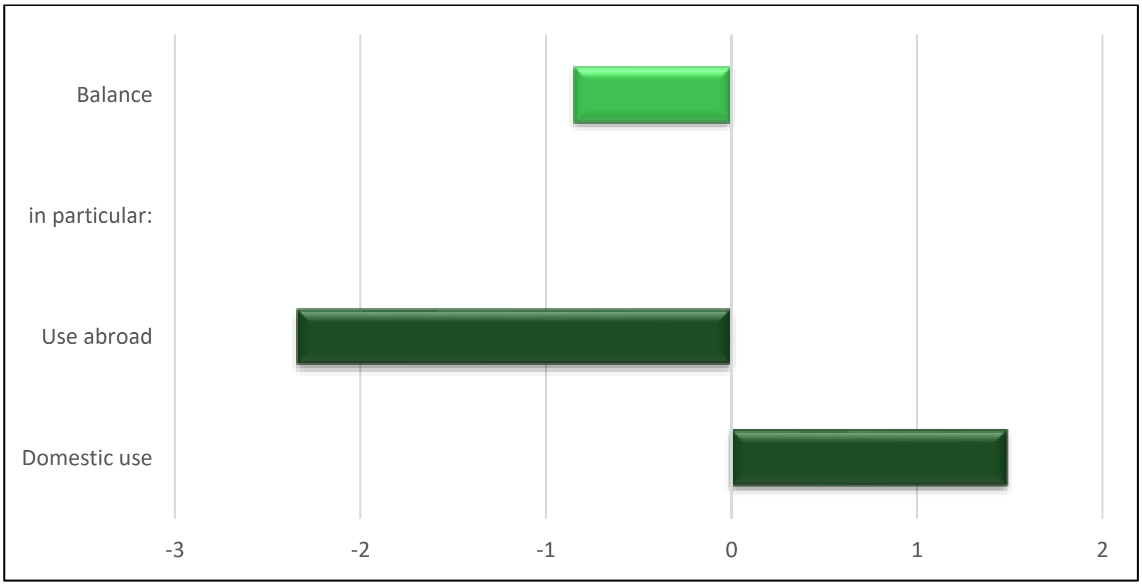
Source: Own calculations and figure.

Figure S.4: Potential global and regional water use balances in 2030 with plant breeding progress between 2020 and 2029 in France (in billion m³)



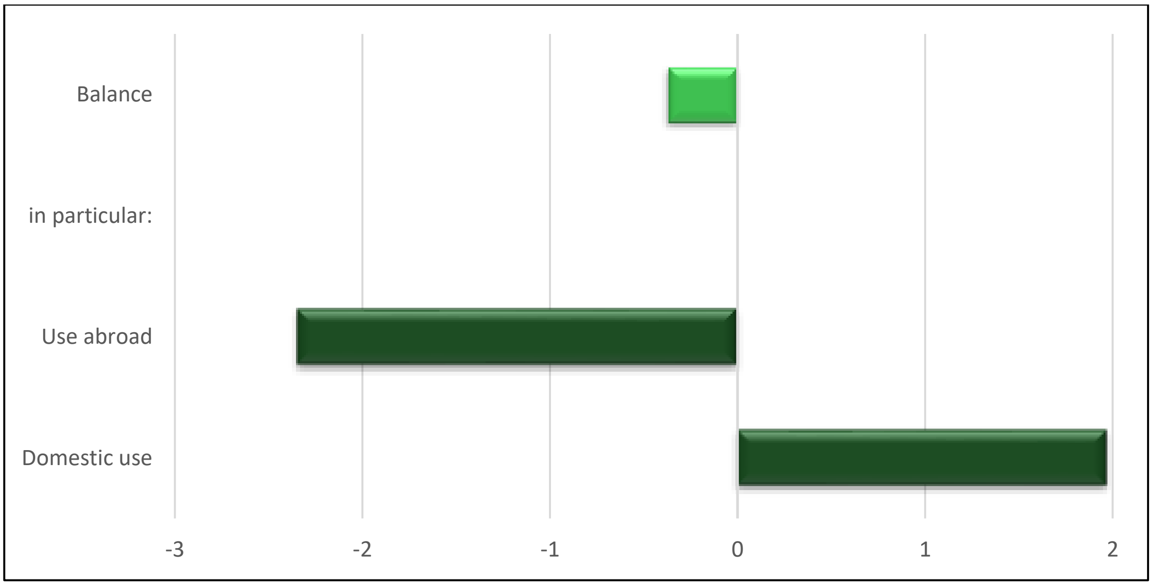
Source: Own calculations and figure.

Figure S.5: Potential global and regional water use balances in 2030 with plant breeding progress between 2020 and 2029 in Italy (in billion m³)



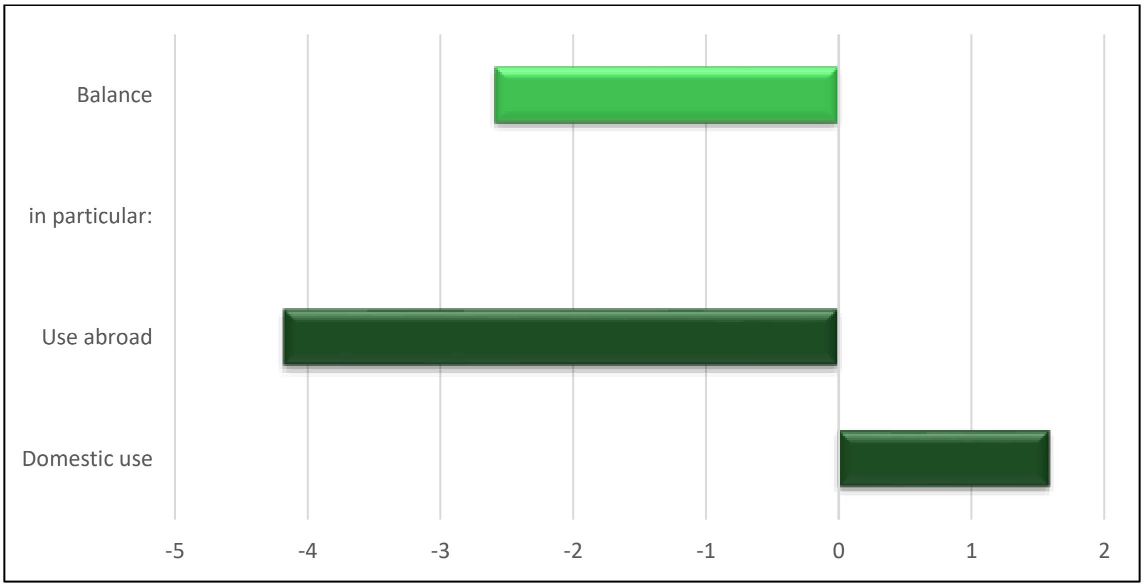
Source: Own calculations and figure.

Figure S.6: Potential global and regional water use balances in 2030 with plant breeding progress between 2020 and 2029 in Spain (in billion m³)



Source: Own calculations and figure.

Figure S.7: Potential global and regional water use balances in 2030 with plant breeding progress between 2020 and 2029 in the UK (in billion m³)



Source: Own calculations and figure.

HFFA Research Paper 2021

Imprint

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An ex-post evaluation and ex-ante assessment considering the "Farm to Fork" and "Biodiversity" strategies

Steffen Noleppa, Matti Cartsburg

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Berlin, May 2021

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