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

An addendum to prior research for tomato and alfalfa

Steffen Noleppa, Matti Cartsburg

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Content

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List of figures

List of abbreviations

AWU - Annual Working Unit

EC - European Commission

EEA - European Environment Agency

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)

IT - Italy

KTBL - Kuratorium für Technik und Bauwesen in der Landwirtschaft

NBI - National Biodiversity Index

NPBT - New Plant Breeding Technologies

PPP - Plant Protection Products

R&D - Research and Development

TFP - Total Factor Productivity

UK - United Kingdom

1 Introduction: objectives and structure of the report

While analysing various impacts of plant breeding in the European Union (EU) since the turn of the millennium, Noleppa and Cartsburg (2021) have most recently concluded that genetic crop improvements of the past 20 years have contributed various socio-economic and environmental benefits. It particularly turned 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 two thirds 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 year 2000.

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, harvestable volumes would have been more than 20 percent lower in 2020 without genetic crop improvements since the turn of the millennium. Thus, higher yields per hectare also increase the supply of primary agricultural products on European and international markets, what subsequently contributes to reducing price volatility. 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. In addition, plant breeding in the EU is also indispensable for combating hunger and malnutrition as it improves the world food security situation. Furthermore, plant breeding in the EU generates additional economic prosperity by increasing the gross domestic Product (GDP), secures employment in rural areas and increases the income of farmers and agricultural employees.

Noleppa and Cartsburg (2021) also conclude that plant breeding progress in the EU since the year 2000 does not only bring about positive economic and social effects, but also generates substantial environmental impacts. It particularly helps save scarce land resources around the globe by generating higher yields per unit of area. 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. Hence, plant breeding also contributes to preserving natural habitats and to reducing greenhouse gas (GHG) emissions resulting from an expansion of the global acreage. In addition, plant breeding in the EU generates a large positive biodiversity effect and it also contributes to saving scarce water resources around the globe.

Looking ahead, this perspective does not change a lot, what 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 societal challenges and dynamic policy settings. This surely includes a fulfilling of the various objectives of the “Farm to Fork” and “Biodiversity” strategies of the EU as plant breeders are certainly able to help compensate negative effects that may arise from a production decline triggered by the strategies. In this respect, Noleppa and Cartsburg (2021) have illustrated via case studies on potential impacts of resistant varieties developed through new plant breeding technologies (NPBT) that very specific potential genetic crop improvements may lead to remarkable benefits at farm and societal level if successfully implemented. However, to become effective, a proportionate and result-focussed regulatory framework is needed to establish clear and sustainable rules for the European plant breeding sector.

Although being already rather holistic, the analysis of Noleppa and Cartsburg (2021) was limited in the sense that it focussed on ten (groups of) arable crops cultivated in the EU only. Specialty crops were not subject of the research, and the feeding crop sector was also covered to a partial extent only. In this respect, it is the objective of this research to provide additional sophisticated quantitative information and additional qualitative arguments highlighting various socio-economic values and environmental benefits of plant breeding as it is performed in the EU and selected member states for such neglected crops. More particularly, the study aims at providing an enlargement of what has already been discussed by Noleppa and Cartsburg (2021) for two crops: tomato and alfalfa.

Again, an *ex-post* evaluation will be carried out looking backwards and aiming at a discussion of the various impacts of plant breeding in the EU for these two crops in the past two decades. But an *ex-ante* assessment will also be made looking forward and seeking 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. Finally, the two analyses will be accentuated by a case study analysis highlighting specific potential values of plant breeding for specialty crops through NPBT.

As in Noleppa and Cartsburg (2021), this research will be conducted for the EU-28 in total, i.e., still including the United Kingdom (UK). In addition, it will focus on three selected EU member states, namely France (FR), Italy (IT), and Spain (ES) as these countries are particularly important in European tomato and alfalfa production.

The structure of this report mirrors the crop coverage as well as the above-described workload of research. First, the focus of chapter 2 will be on tomato. Then, alfalfa will be emphasised in chapter 3. In both cases, the discussion will start with the *ex-post* evaluation particularly looking at primary productivity impacts first to properly derive secondary socio-economic consequences and tertiary environmental effects then. The following *ex-ante* assessment based on a sound scenario definition including a consideration of the "Farm to Fork" and "Biodiversity" strategies of the EU will then analyse the value of plant breeding with respect to specific potential socio-economic consequences and environmental effects. Then, chapter 4 will deal with the case study analyses. Based on conclusions, recommendations for private as well as public decision making will finally be given in chapter 5. Annexes will provide additional information.

In general, the study is based on the same or at least similar data sources used and methodologies applied in Noleppa and Cartsburg (2021). Respective background information will not be repeated hereafter in full. Details can be obtained from the previous study. However, important particularities with respect to the data and methods of the following research which are different in comparison with Noleppa and Cartsburg (2021) will be highlighted. This also concerns missing reliable data and, thus, partly missing analyses.

2 The importance of tomato plant breeding in the EU

2.1 Ex-post evaluation

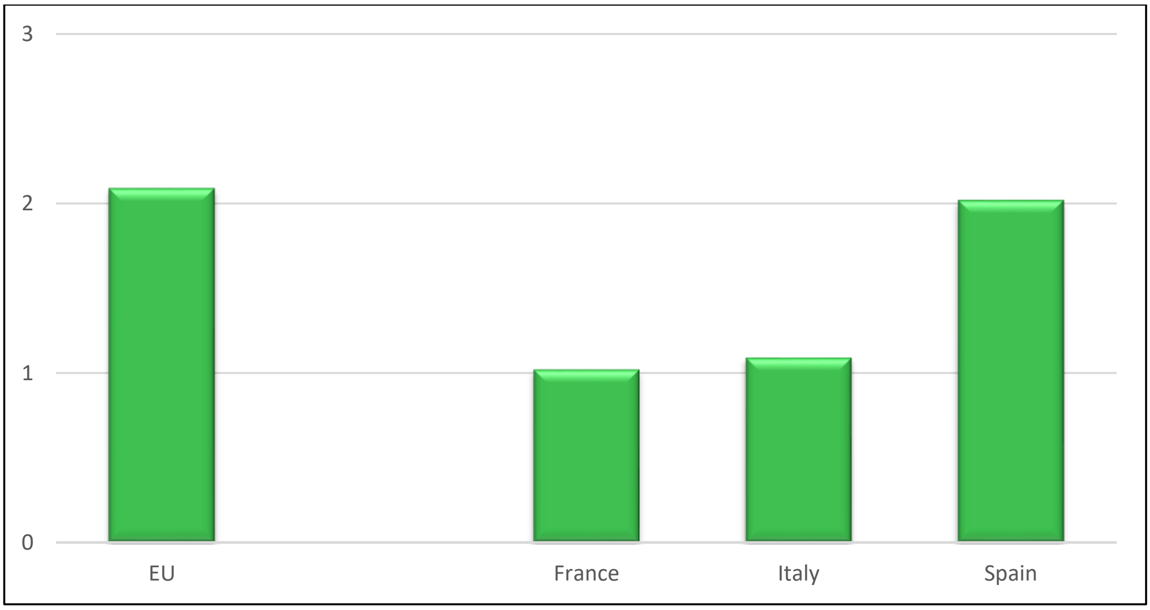
Primary production impacts

Basic requirements for the analysis are to examine the yield development in EU tomato farming and to determine a land productivity impact that can solely be related to the specific plant breeding in the EU respectively the three selected member states. This can be achieved by using the same gradual approach as applied in Noleppa and Cartsburg (2021) which looks at yield growth in tomato production first, calculates an innovation-induced yield growth in terms of hectare-related total factor productivity (TFP) growth for this crop then, and finally determines the plant breeding-induced yield growth of the speciality crop based on the share of plant breeding in innovation-induced yield growth. Applying this straightforward concept for the EU as a whole and the selected three member states leads to the following results.

Yield growth

Based on FAO (2021) data, figure 2.1 displays the yield growth rates in European tomato farming since the year 2000 for the EU in total as well as for the selected three EU member states being in the focus of this study.

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



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

It turns out that the yield development is rather unequal. The EU as a whole and Spain have obviously been able to increase tomato yields by more than 2.0 percent per annum since the year 2000. In opposite to that, land productivity in French and Italian tomato production has increased by around 1.0 percent only. Nevertheless, tomato yields have increased more than yields on average in arable farming in the EU in total as well as in France, Italy, and Spain (see Noleppa and Cartsburg, 2021).

Innovation-induced yield growth

Considering the complexity of managerial and technological processes, 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 can be minimized (although not entirely excluded), but yield growth can still be induced by agricultural intensification or innovation, respectively. Economic assessments use TFP analysis to demonstrate which parts of an observable change in productivity are induced by what here is called innovation and, thus, should not be related to increased (or decreased) factor use intensities. This study again counts on the rather straightforward and comparably few data demanding TFP calculation approach originally developed by Lotze-Campen et al. (2015). Consequently, developments in land-based factor use need to be identified and incorporated into the analysis by subtracting them from statistically measurable yields leading to innovation-induced yield growth. In full accordance with Noleppa and Cartsburg (2021), the changes in land-related factor use displayed in figure 2.2. are applied.

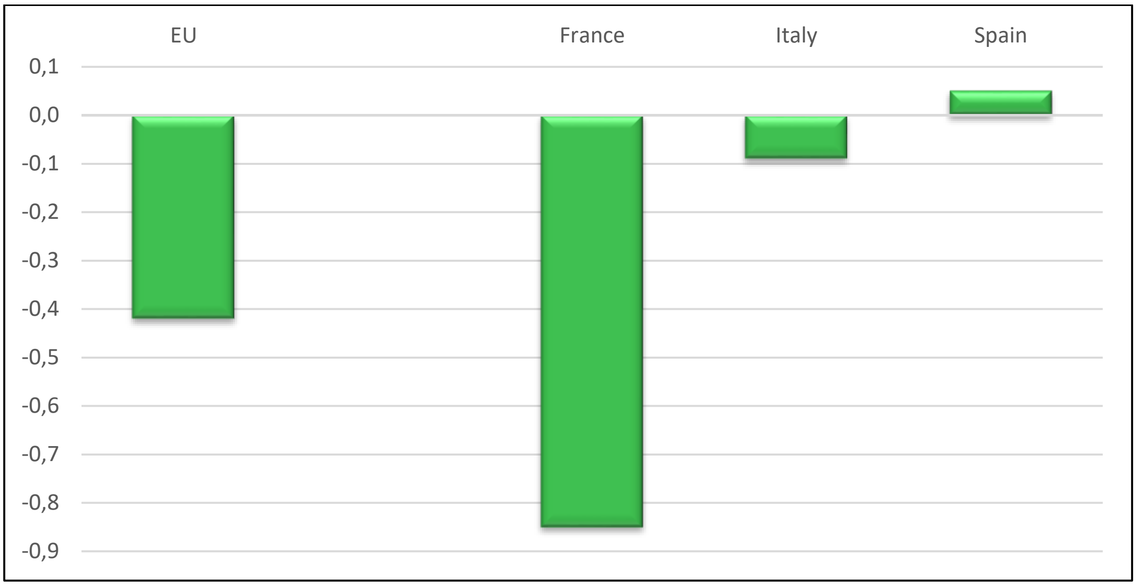
Figure 2.2: **Annual growth rates of the use of inputs per hectare in the EU and selected member states since the year 2000 (in percent)**

Input/Region	EU	FR	IT	ES
Fertilizers	0.4	-1.9	-2.5	-0.8
PPP	0.3	-1.2	-1.1	3.5
Seeds	-0.7	0.3	-0.6	0.6
Labour	-2.3	-1.7	-1.2	-1.2
Capital	1.2	0.5	1.3	1.4

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

Weighting the various change rates of the three intermediate inputs (fertilizers, plant protection products (PPP) and seeds), 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 (2019a) and KTBL (2021) results in the average growth rates of the overall input use displayed in figure 2.3. Accordingly, it can be stated that the aggregated use of variable and fixed production factors in the EU in total have changed at an annual rate of -0.42 percent. France (with -0.85 percent) and Italy (with -0.09 percent) have also experienced a decline of input use. Spain, however, has implemented a very small and almost negligible annual increase of overall input use since the year 2000 (0.05 percent).

Figure 2.3: **Annual growth rates of the overall input use in crop farming of the EU and selected member states since the year 2000 (in percent)**



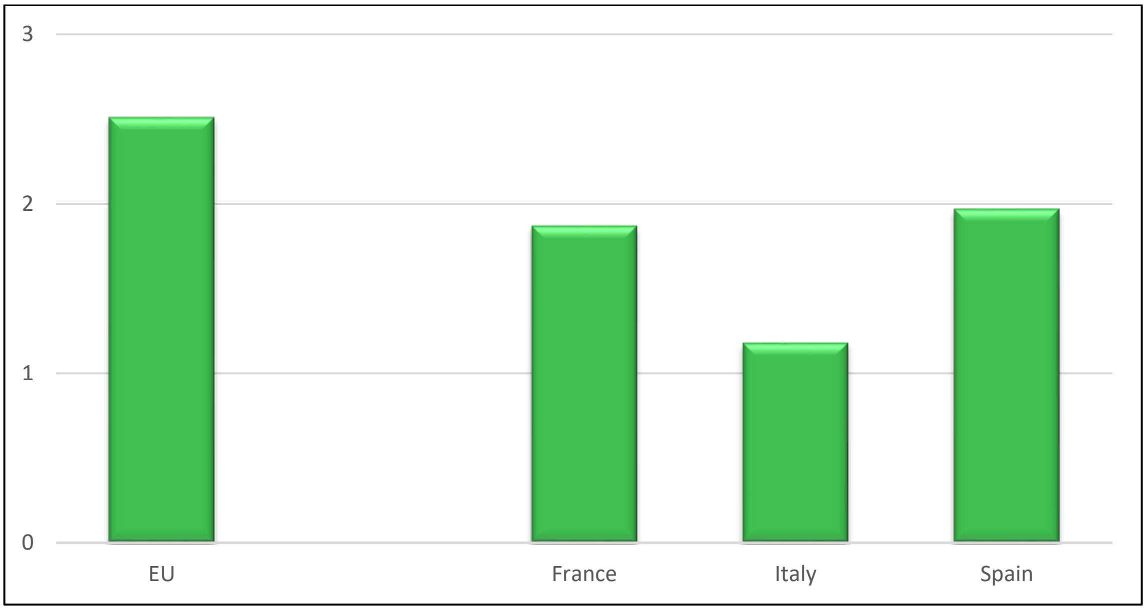
Source: Own calculations and figure.

According to Lotze-Campen et al. (2015) and as also applied in Noleppa and Cartsburg (2021), these share-weighted annual growth rates of the overall input use must be subtracted from the yield growth rates displayed in figure 2.1 to calculate meaningful annual innovation-induced yield growth rates for tomato farming in the EU and its member states. Figure 2.4 shows the results. Accordingly, it can be stated that innovations in tomato farming have enabled an EU yield growth since the turn of the millennium of 2.51 percent per annum which is well above the 1.68 percent per annum and hectare of EU arable farming in total (see Noleppa and Cartsburg, 2021).

In the three selected EU member states being in the focus of this study, the innovation-induced yield growth in tomato farming is partly higher and partly lower than the innovation-induced yield growth in the entire country-specific arable farming (see again Noleppa and Cartsburg, 2021). The following can be stated in particular:

- It is around 1.9 percent per annum in French tomato production (compared to less than 1.3 percent in arable farming in this EU member state),
- It amounts to around 1.2 percent per year in Italian tomato farming (compared to also less than 1.3 percent in the country's arable farming), and
- It is almost 2.0 percent per annum in Spanish tomato production (compared to just approximately 0.9 percent in arable farming of Spain).

Figure 2.4: **Annual innovation-induced yield growth rates of tomato farming in the EU and selected member states between 2000 and 2019 (in percent)**



Source: Own calculations and figure.

Plant breeding-induced yield growth

Determining the plant breeding-induced yield growth requires the definition of the share of plant breeding in innovation-induced yield growth. Therefore, Noleppa and Cartsburg (2021) provide a very substantial analysis squeezing out more than 100 scientific sources and expert statements. Accordingly, the share of plant breeding in innovation-induced productivity must be within the range of 50 to 90 percent, and the mean value is 66.8 percent. Unfortunately, the data do not allow for an explicit statement on the share with respect to tomato. The number of identified sources and statements is simply too low in terms of sound statistical analysis. Nevertheless, a best guess on the "location" of a tomato-related share within the above-mentioned interval can be given.

HFFA Research (2016), based on Fooland (2007) and Nikolla et al. (2012), argues that this share is at least 50 percent. Other sources point at a similar or even higher importance of plant breeding for innovation in tomato production:

- Causse et al. (2020) for instance argue that in times of climate change, breeding is the major determinant of tomato yield (development).
- Also van der Ploeg et al. (2007) claim that plant breeding is the main contributor to tomato yield development.

- More particularly, Lecompte and Causse (2014) – referring to a developed country context – state that 67 percent of yield progress in tomato can be attributed to genetic crop improvements.
- Finally, Balaguer (2017) shall be mentioned. Following the arguments of the author, almost all tomato yield development in Spain should be considered to come from plant breeding.

Using this as a base, the likely share of plant breeding for innovation-induced yield growth must be between 50 and (almost) 100 percent. A conservative assumption is made. Consequently, it is assumed hereafter, that two thirds of the annual innovation-induced yield growth rates of tomato farming in the EU and selected member states between 2000 and 2019 as displayed in figure 2.4 can be allocated to plant breeding. Figure 2.5 displays the values used hereafter for further analyses.

Figure 2.5: **Annual plant breeding-induced yield growth rates of tomato farming in the EU and selected member states between 2000 and 2019 (in percent)**

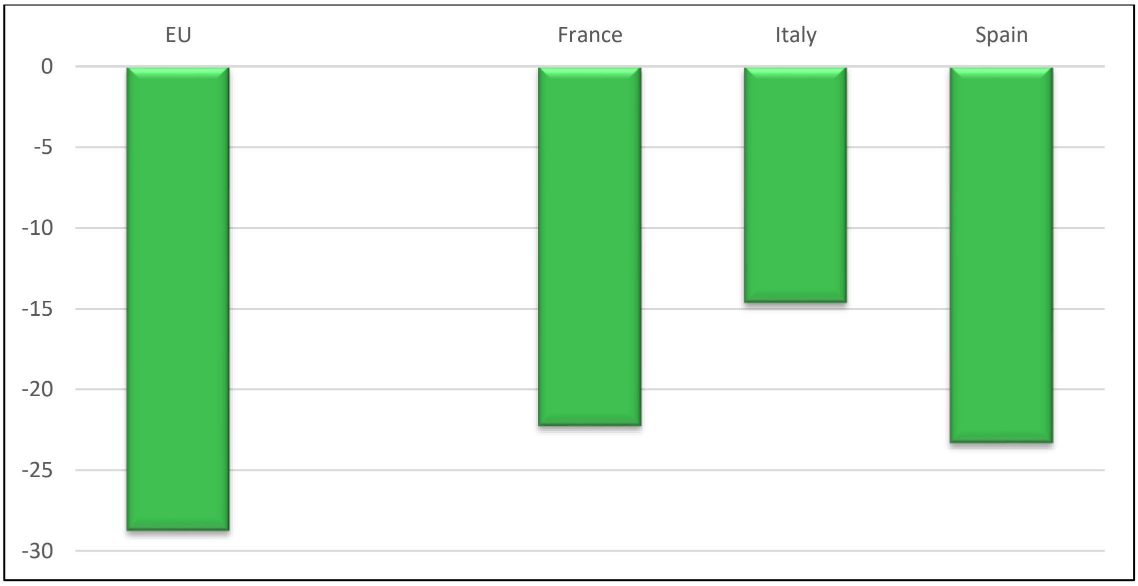
EU	FR	IT	ES
1.68	1.25	0.79	1.32

Source: Own calculations and figure.

Secondary socio-economic consequences

Defined shift factors

Figure 2.6: **Simulated yield loss for tomato in 2020 without plant breeding progress between 2000 and 2019 in the EU and selected member states (in percent)**



Source: Own calculations and figure.

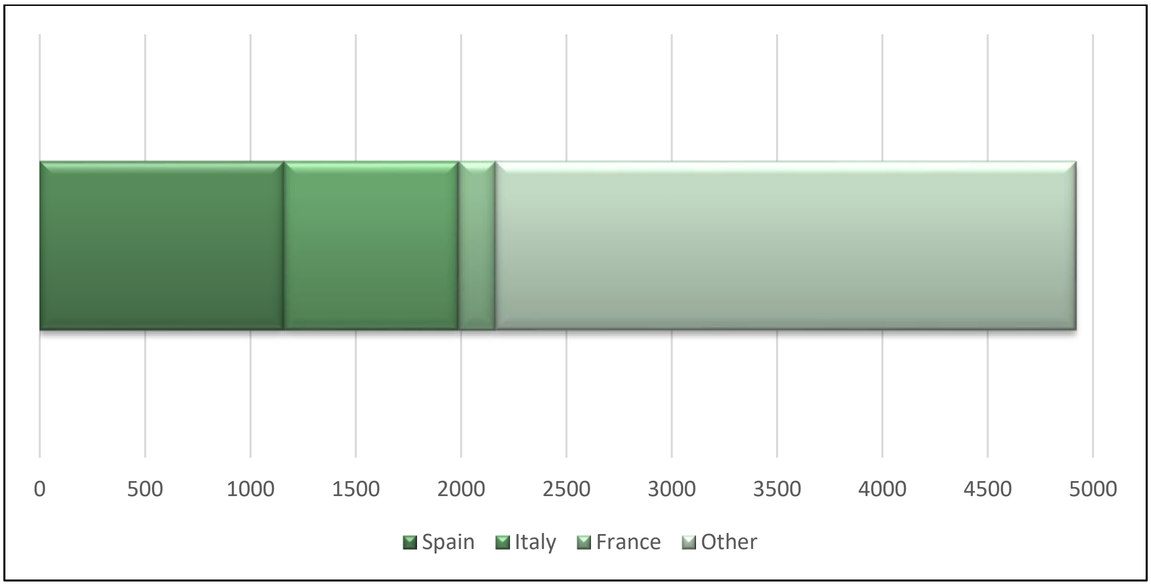
Analysing the value tomato-related plant breeding in and for the EU and its member states has had since the turn of the millennium requires to specify a scenario on the status quo without yield increases induced by plant breeding efforts in the past 20 years. More particularly, the scenario definition 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 analytical target indicators (see again Noleppa and Cartsburg, 2021). Especially this shock parameter simulates a relative yield change per region expressed as the percentage to be calculated by accumulating the average annual plant breeding-induced yield growth rates (see figure 2.5) for the entire time horizon between 2000 and 2019 using the compound interest approach.

Consequently, figure 2.6 above displays the simulated currently experienced yield loss in tomato production without plant breeding in the EU and selected member states in the last two decades. Accordingly, remarkable yield losses would have to be envisaged today if plant breeding for tomato in the EU had terminated in the year 2000. With respect to the chosen regional spectrum of this study, the apparent yield loss would have been between almost 15 percent in Italy and around 28 percent for the EU in total.

Impact on market supply

Facing lower tomato yields without plant breeding progress in the past two decades, the market supply in the EU would be lower today. In this respect, figure 2.7 shows the impact of plant breeding progress in the EU since 2000 on current market supply. Data from EC (2020d) is used to calculate the specific impact.

Figure 2.7: **Extra market supply for tomato in 2020 with plant breeding progress between 2000 and 2019 in the EU and selected member states (in 1,000 tons)**



Source: Own calculations and figure.

From the modelling exercise it can be concluded that plant breeding since the year 2000 has allowed the EU in total to supply an additional tomato volume in 2020 – expressed in terms of fresh tomato equivalents – of almost 5 million tons. Plant breeding for tomato in Spain alone contributes almost 1.2 million tons, and genetic crop improvements in Italy add more than 0.8 million tons. Plant breeding in France provides further 175,000 tons. Thus, the plant breeding progress of the past 20 years in the three selected EU member states is responsible for almost half the plant breeding-induced extra market supply in the tomato sector of the EU.

Impact on net trade

It is rather challenging to measure the net trade impact of plant breeding as regards tomato since not only fresh tomatoes, but manifold processed products (e.g., peeled tomatoes) as well as mixed goods (e.g., sauces) are subject of international trade. It is far beyond the scope of this research to look at all these markets in detail. In addition, publicly available statistics of the international tomato markets are often not detailed enough for the purpose of this study. Nevertheless, a meaningful assessment distinguishing the fresh tomato market from the market for "other" tomatoes is possible for the EU in total.

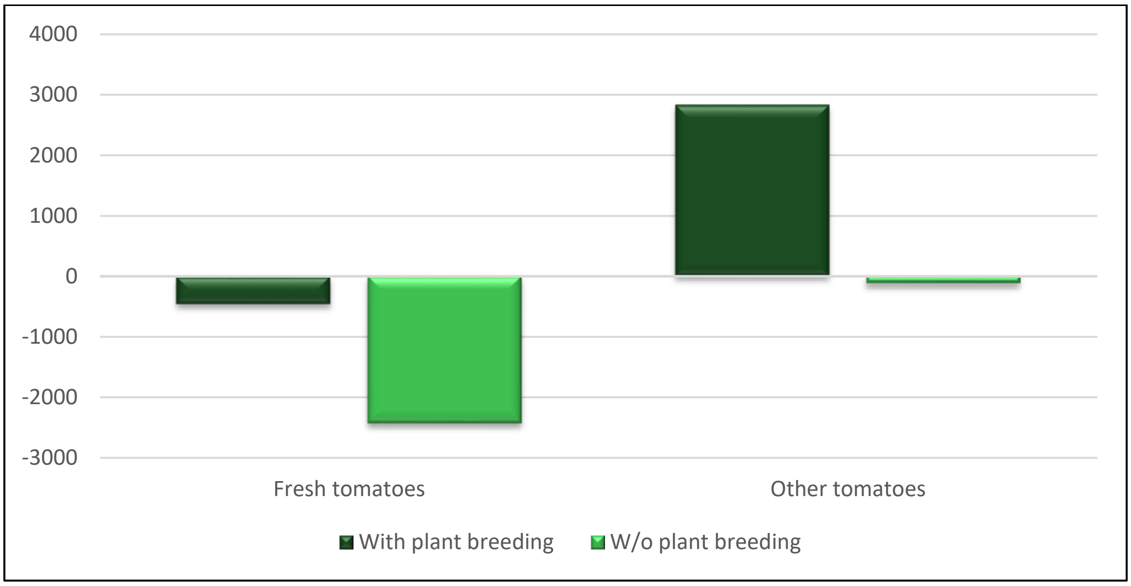
According to DG Agri (2021), most recent extra-EU trade amounts to 579,000 tons of fresh tomatoes imported and 117,000 tons of the fresh tomatoes exported. Hence, the EU currently net imports 462,000 tons of fresh tomatoes. Subtracting these amounts from aggregated trade data on tomato and products thereof provided by FAO (2021) additionally allows to determine the volume of the market for "other" tomatoes. With respect to this unspecific market, the EU extra trade is positive. This means a net trade export of more than 2.8 million tons (of fresh tomato equivalents) is currently achieved with plant breeding.

EC (2021) also states that 40 percent of the tomato production in the EU is for fresh consumption. If also 40 percent of the extra market volume due to plant breeding since the turn of the millennium displayed in figure 2.7 relate to fresh tomatoes and the remaining 60 percent refer to "other" tomatoes, the following can be stated:

If the respective volumes were missing today, the already negative net trade position of the EU with respect to fresh tomatoes and the yet still positive net trade position of the EU with respect to other tomatoes would substantially deteriorate as figure 2.8 illustrates. In particular:

- The net import volume of fresh tomatoes would be more than 400 percent higher without plant breeding progress in the past 20 years; and
- In the case of other tomatoes, the EU would have lost its currently given net export position and would have become a net importer if plant breeding for tomato had terminated in 2000.
- In total, the EU today would thus not be able to net export an equivalent of almost 2.4 million tons of tomatoes but would be required to net import approximately 2.6 million tons of this agricultural commodity.

Figure 2.8: Net trade volume of the EU for fresh and other tomatoes in 2020 with and without plant breeding progress between 2000 and 2019 (in 1,000 tons)



Source: Own calculations and figure.

Impact on food availability

Plant breeding in the EU proves to increase tomato production. A substantial part of this production via market supply is used as food. Hence, plant breeding also tends to increase food availability as regards tomato. In the following the increase of food availability as of today that can be attributed to plant breeding progress between 2000 and 2019 shall be analysed. Therefore, a tomato basket is constructed which is filled with an average amount of the crop that is consumed per capita and year at EU level and global scale. FAO (2021) data is used therefore as the source also determines the share of food in total market supply.

Consequently, figure 2.9 displays the number of people worldwide and alternatively in the EU that can additionally be provided with a basket full of tomatoes for one year in 2020 due to plant breeding progress between 2000 and 2019.

Figure 2.9: Additionally available tomato 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	FR	IT	ES
EU citizens	175.2	6.2	29.5	41.3
Global population	211.5	7.4	35.6	49.9

Source: Own calculations and figure.

As figure 2.9 visualizes, plant breeding progress in the EU in total since the turn of the millennium has remarkably increased global food availability as regards tomato. In 2020, food baskets filled with the produce for an additional more than 200 million people became available worldwide. Alternatively, more than 175 million additional Europeans could be provided with the vegetable for food consumption. Spanish (Italian) plant breeding progress alone fills approximately 50 (35) million global tomato baskets or around 40 (30) million European tomato baskets.

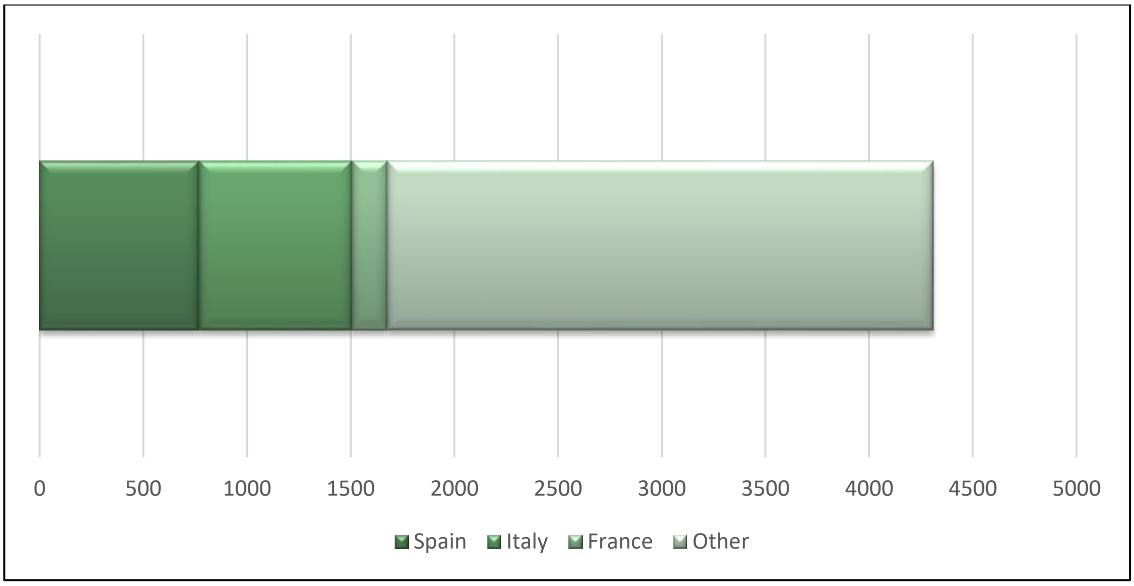
Impact on market prices

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. Applying a single market model for tomato as described in HFFA Research (2016) and already used to calculate the market supply impacts above, it turns out that prices at international tomato markets would have been 6.7 percent higher without plant breeding in the EU during the last two decades than they are at present. This is within the range of 2 to 12 percent, which has been calculated by Noleppa and Cartsburg (2021) for major arable crops.

Impact on sectoral income

The current sectoral income effect – from an analytical and modelling perspective the sum of so-called producer surpluses (producer income) and consumer surpluses (consumer savings) (see again Noleppa and Cartsburg, 2021) – of plant breeding progress in the EU between 2000 and 2019 for tomato is depicted in figure 2.10. Thereby, current price levels were obtained from EC (2021).

Figure 2.10: **Additional sectoral income for tomato in 2020 with plant breeding progress between 2000 and 2019 in the EU and selected member states (in million EUR)**



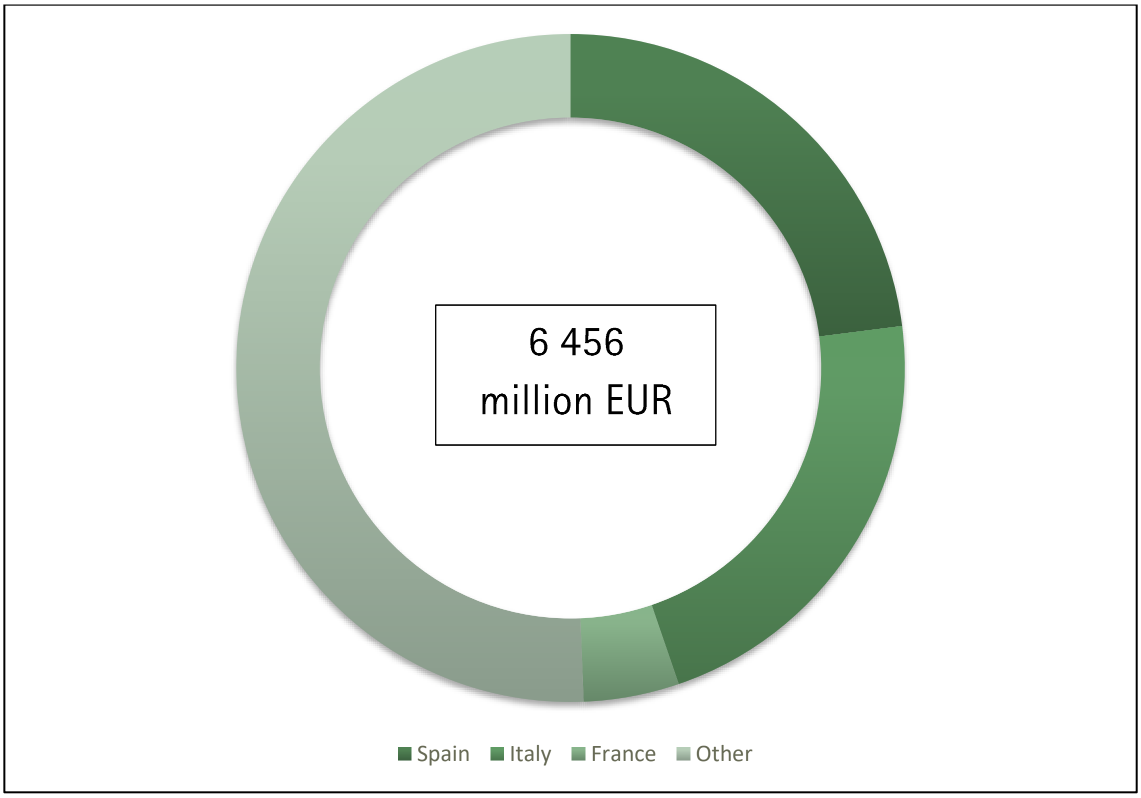
Source: Own calculations and figure.

The total social welfare gain of tomato-related plant breeding progress since the year 2000 in the EU amounts to more than EUR 4.3 billion in 2020. Approximately EUR 750 million of this amount is generated in Spain and France each, while the sectoral income has increased by almost EUR 170 million in France. Thus, the plant breeding progress of the past 20 years in the three selected EU member states is responsible for approximately 40 percent of the plant breeding-induced extra sectoral income of the EU in total.

Impact on GDP

It becomes clear that genetic crop improvements with respect to tomato have a strong sectoral economic impact in the EU and its member states. However, 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 tomatoes 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 2.10 must be linked to GDP multipliers (see again Noleppa and Cartsburg, 2021). Figure 2.11 provides the results of this exercise for the EU and its selected member states.

Figure 2.11: Additional GDP attributable to tomato in 2020 with plant breeding progress between 2000 and 2019 in the EU and selected member states (in million EUR)



Source: Own calculations and figure.

Accordingly, the overall GDP impact of 20 years of plant breeding for tomato should be valued almost EUR 6.5 billion in 2020 for the EU in total. Plant breeding in Spain alone accounts for EUR 1.5 billion, and genetic crop improvements in Italy provide EUR 1.4 billion. Together with France (EUR 0.3 billion), the three selected EU member states generate almost 50 percent of this extra GDP.

Impact on farm income and labour

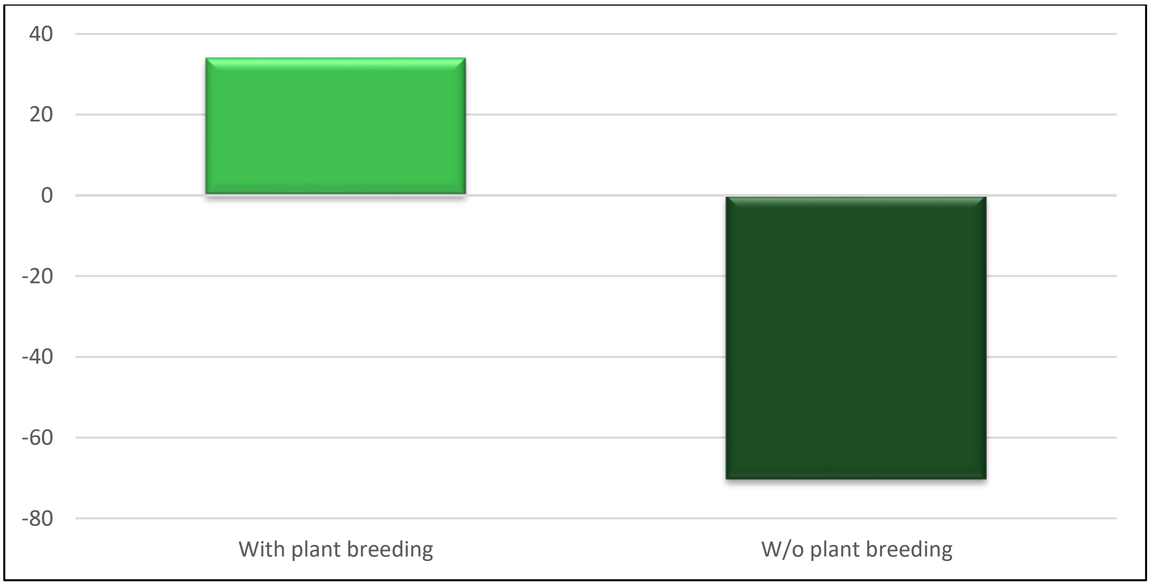
Noleppa and Cartsburg (2021) also analysed farm income and labour impacts of plant breeding for arable crops. Tomato is a specialty crop and the farm level data which were used by the authors are unfortunately not publicly available. Therefore, the specific analyses cannot be carried out.

Tertiary environmental effects

Impact on virtual land trade

The obvious developments in EU-extra trade in case of missing plant breeding activities for tomato since 2000 (see, again, figure 2.8) would subsequently change the balance of EU net imports of virtual agricultural land. Based on a similar methodology as applied in Noleppa and Cartsburg (2021)[1], the net virtual land trade in 2020 at global scale with and without plant breeding progress since 2000 and the subsequent change that can be attributed to the EU in total for an absence of plant breeding progress since the turn of the millennium is visualized in figure 2.12.

Figure 2.12: **Net virtual land trade attributable to tomato in 2020 with and without plant breeding progress between 2000 and 2019 in the EU (in 1 000 hectares)**



Source: Own calculations and figure.

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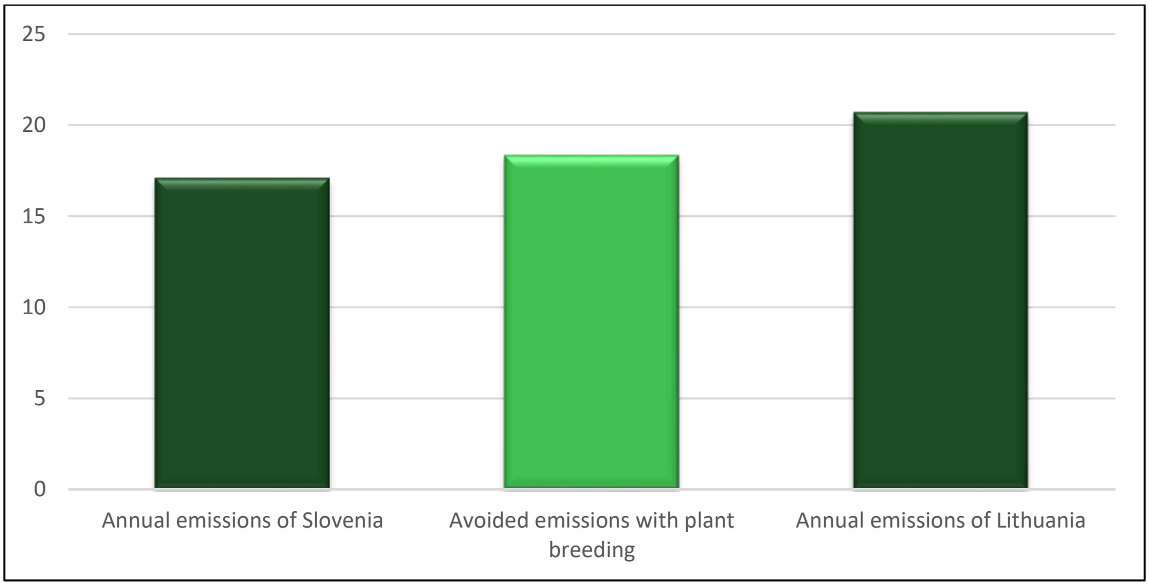
[1] Since the net trade balance is available for the EU in total only, the change in virtual land trade and consequently all other environmental analyses can also be drawn for the EU in total only.

Looking at figure 2.12, the EU implements today a virtual net export of land (34 000 hectares). If plant breeding in the EU had terminated in 2000, 70 000 hectares should have been virtually net imported in 2020. Hence, global land use with respect to tomato would have increased by almost 105 000 hectares. These are more than 1 000 square kilometers and, hence, as large as six times the surface of Lake Mar Menor in Spain or seven times the surface of Lake Como in Italy.

Impact on GHG emissions

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 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 Noleppa and Cartsburg (2021) and yields 18.3 million tons. This is almost as large as the entire annual GHG emissions in Slovenia or Lithuania (EEA, 2020) as figure 2.13 shows.

Figure 2.13: Avoided GHG emissions until 2020 attributable to tomato plant breeding progress between 2000 and 2019 in the EU – a comparison (in million tons)

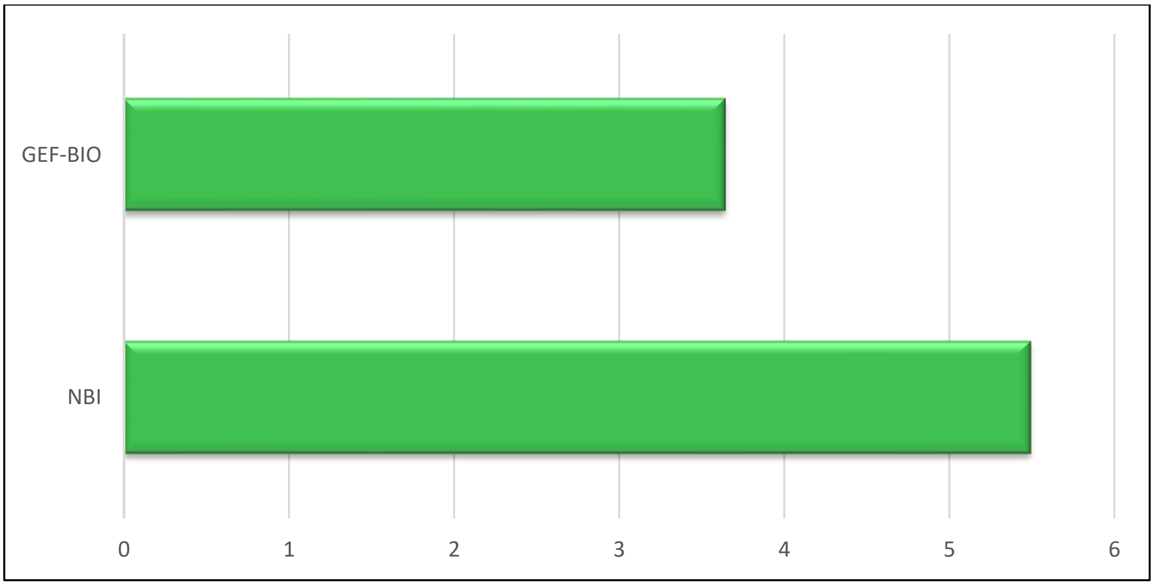


Source: Own calculations and figure.

Impact on global biodiversity

Repeating that plant breeding efforts in the EU related to tomato since the year 2000 have avoided a conversion of grassland and natural habitats of more than 100 000 hectares at global scale (see again figure 2.12), it is also worth quantifying the associated "biodiversity preserving" effect of genetic crop improvements. As outlined in Noleppa and Cartsburg (2021), two methods for capturing this effect are applied: First, the Global Environment Facility Benefits Index of Biodiversity (GEF-BIO) is used, and second, the National Biodiversity Index (NBI) is employed. The results with respect to the biodiversity loss of the two separate analyses for the EU in total are depicted in figure 2.14.

Figure 2.14: **Avoided global biodiversity loss until 2020 with tomato plant breeding progress between 2000 and 2019 in the EU (in million points)**



Source: Own calculations and figure.

Looking at figure 2.14, 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 3.6 million biodiversity points would have been lost until today by neglecting plant breeding for tomato 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 36 000 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 tomato in the EU between the years 2000 and today has compensated for almost three weeks 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 5.5 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 tomato 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 55 000 hectares of Indonesian natural habitats, i.e., as much as the loss of biodiversity that can be attributed to one and a half months of cutting rainforests in Indonesia at current deforestation intensity.

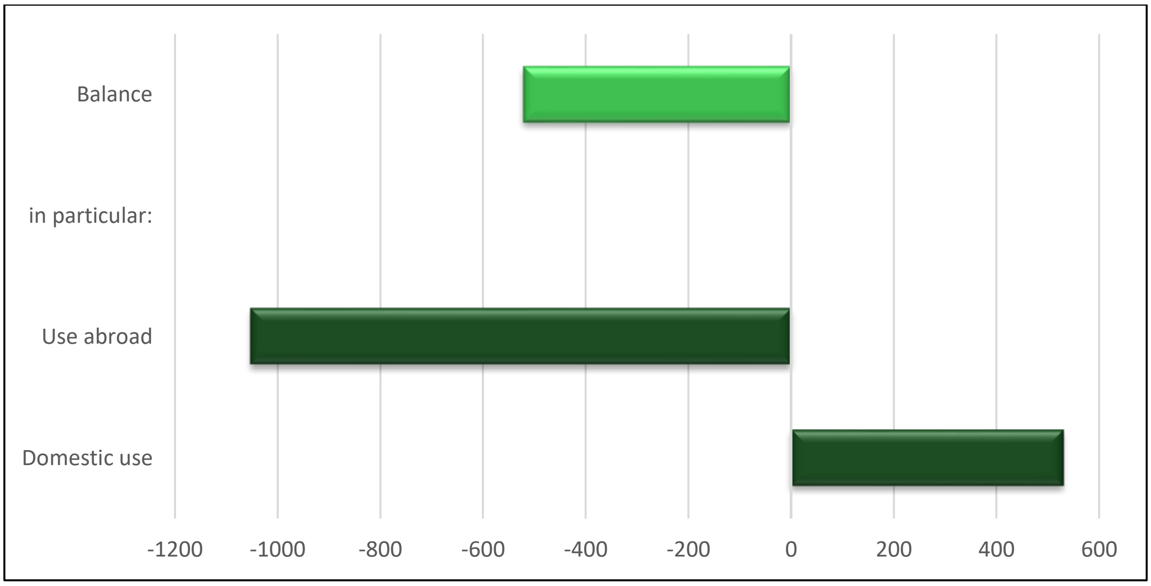
Impact on water use

Analyzing the impact of tomato 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 tomato (see above), more water is used domestically to do so. However, via higher exports and/or lower imports of the EU due to tomato 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 2.15.

Figure 2.15: **Global and regional water use balances in 2020 with tomato plant breeding progress between 2000 and 2019 in the EU (in million m³)**



Source: Own calculations and figure.

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 more than 530 million m^3. Higher crop production in the EU, however, allows to export more and/or import less. Subsequently, production incentives in foreign countries have shrunk and water is currently saved abroad due to plant breeding activities in the EU in the past two decades. In total, more than 1.0 billion m^3 of water are saved this way. On balance, a net saving of more than 520 million m^3 occurs.

2.2 Ex-ante assessment

This research does not only aim at discussing the various benefits European plant breeding for tomato 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. 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 for tomato in the EU until 2030 and 2040 also considering the EU's "Farm to Fork" and "Biodiversity" strategies with a specific scenario.

Definition of the scenarios for further analysis

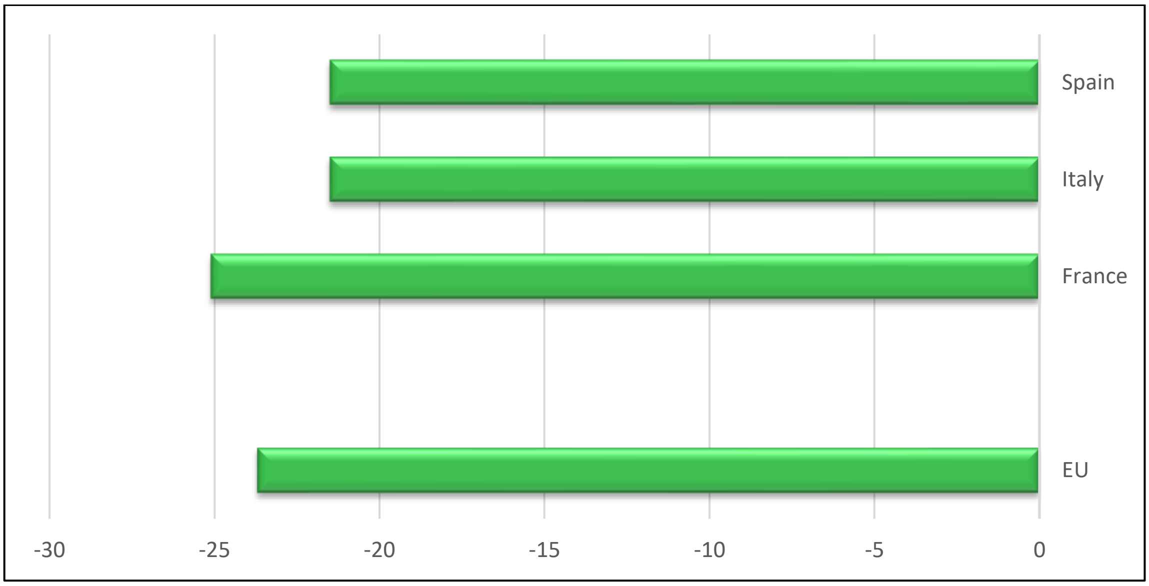
The basic scenario

In the following, EC (2020c) is used to forecast tomato market developments until 2030 and 2040 and to define the market environment by then. Accordingly, the specific market in the EU in total and its member states until 2030 (2040) is projected to develop into the following directions since 2020: It will be confronted with a production increase of 5.2 (10.4) percent and a decrease in net trade of 19.4 (38.8) percent. The market price will not change.

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

The two strategies (see EC, 2020a; b) aim at considerable changes along the 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. This particularly applies to specialty crops, such as tomato. For the purpose of this study, the "average" impacts as regards four important aspects of the two strategies – namely (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 plant protection products (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 – reported in Noleppa and Cartsburg (2021) for arable farming in total are included in the calculation of the potential partial outcome of implementing these strategies in the tomato sector. Figure 2.16 shows the then chosen production cut assumptions.

Figure 2.16: Assumed tomato production cuts in 2030 of a full implementation of the two strategies in the EU and selected member states (in percent)



Source: Own calculations and figure.

These scenario definitions and assumptions will now be used, ceteris paribus, to showcase the various socio-economic and environmental benefits in 2030 of tomato-related plant breeding progress at current pace between 2020 and 2029 as well as in 2040 of respective plant breeding progress at current pace between 2020 and 2039. Thereby, the various partial benefits of ongoing and future plant breeding activities will be compared with the potential partial impacts of just the production losses due to an enforcement of the two strategies until 2030.

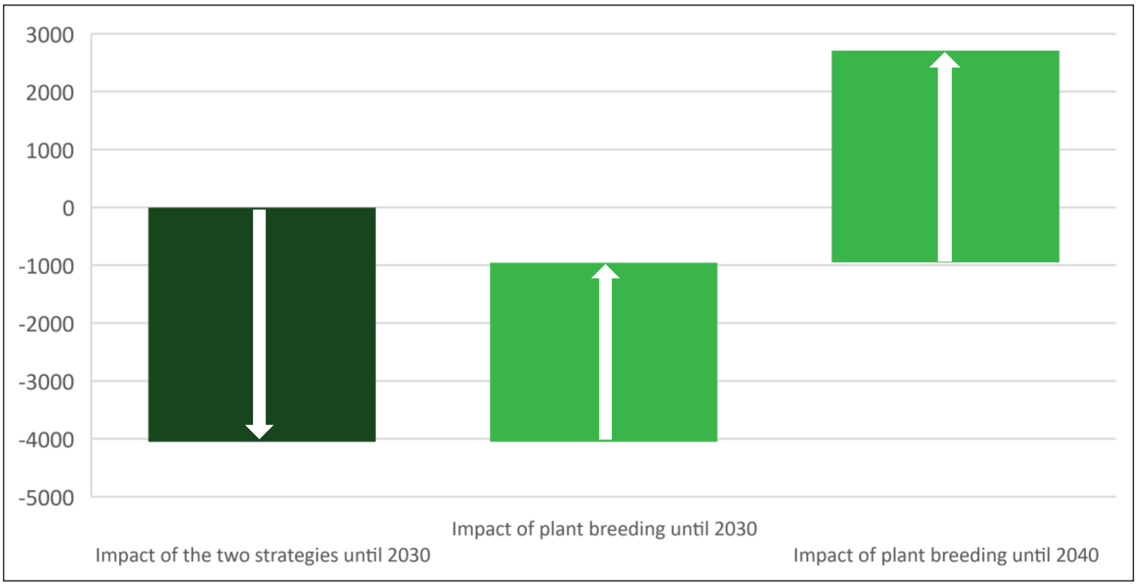
Future socio-economic consequences

Impact on market supply

Using the annualized plant breeding-induced yield growth referring to 2000-2019 (see again figure 2.5) also as a proxy to describe the expectable plant breeding-induced yield growth per year until 2030 and 2040 and the relative production losses due to the two strategies until 2030 (see again figure 2.16), figure 2.17 visualizes the comparison of the partial impacts – all other factors being constant – on tomato market supply for the EU in total while figure 2.18 provides detailed numbers for the three selected EU member states as well.

As can be seen by looking at figure 2.17, the potential plant breeding-induced additional market supply in 2030 (2040) will be lower (higher) than the market supply loss that can be attributed in the year 2030 to the full implementation of two strategies (as defined above) for the EU in total.

Figure 2.17: Comparing and balancing partial market supply effects of the two strategies until 2030 with tomato plant breeding until 2030 and 2040 in the EU (in 1 000 tons)



Source: Own calculations and figure.

A similar conclusion can also be drawn with respect to France and Spain, while even 20 years of future tomato-related plant breeding progress until 2040 contributing to 962 000 tons) will potentially be not enough to compensate for Italian market supply losses (of more than 1.2 million tons) embedded in the enforcement of the two strategies until 2030 (see figure 2.18)

Figure 2.18: Partial market supply effects of the two strategies until 2030 as well as of tomato plant breeding until 2030 and 2040 in the EU (in 1 000 tons)

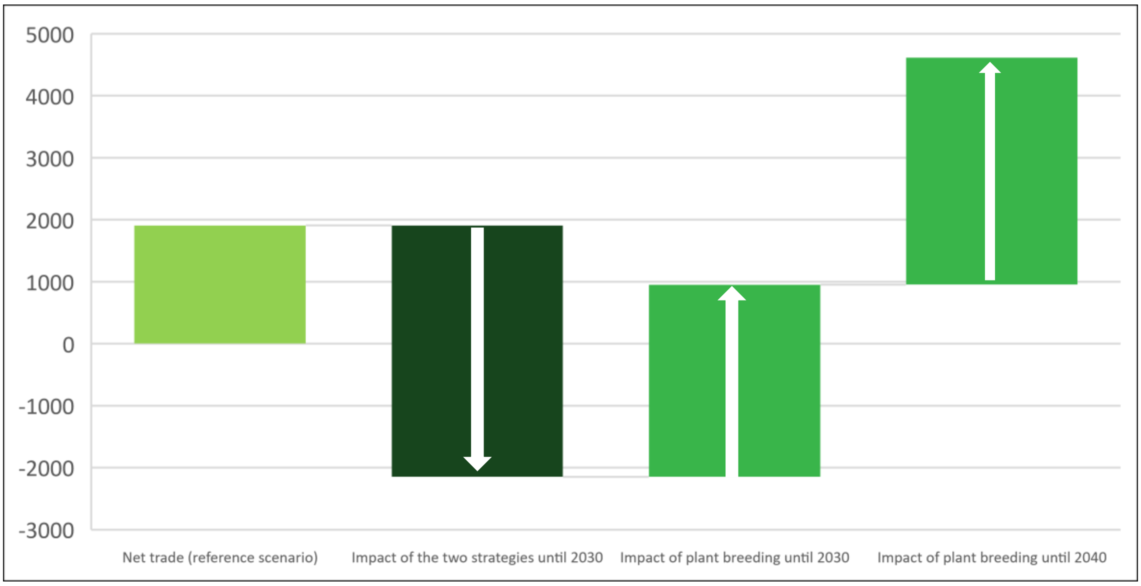
Impact of ...	EU	FR	IT	ES
Two strategies 2030	-4055	-195	-1214	-1070
Plant breeding 2030	3102	103	462	697
Plant breeding 2040	6766	219	962	1493

Source: Own calculations and figure.

Impact on net trade

Changing market supply does affect trade volumes. The resulting changes (again in terms of the potential EU-extra trade incorporating the basic scenario as well as the implementation of the two strategies) in the case of missing plant breeding progress as regards tomato between 2020 and 2030 (2040) for the EU in total are depicted in figure 2.19.

Figure 2.19: Comparing and balancing partial net trade effects of the two strategies until 2030 with tomato plant breeding until 2030 and 2040 in the EU (in 1 000 tons)



Source: Own calculations and figure.

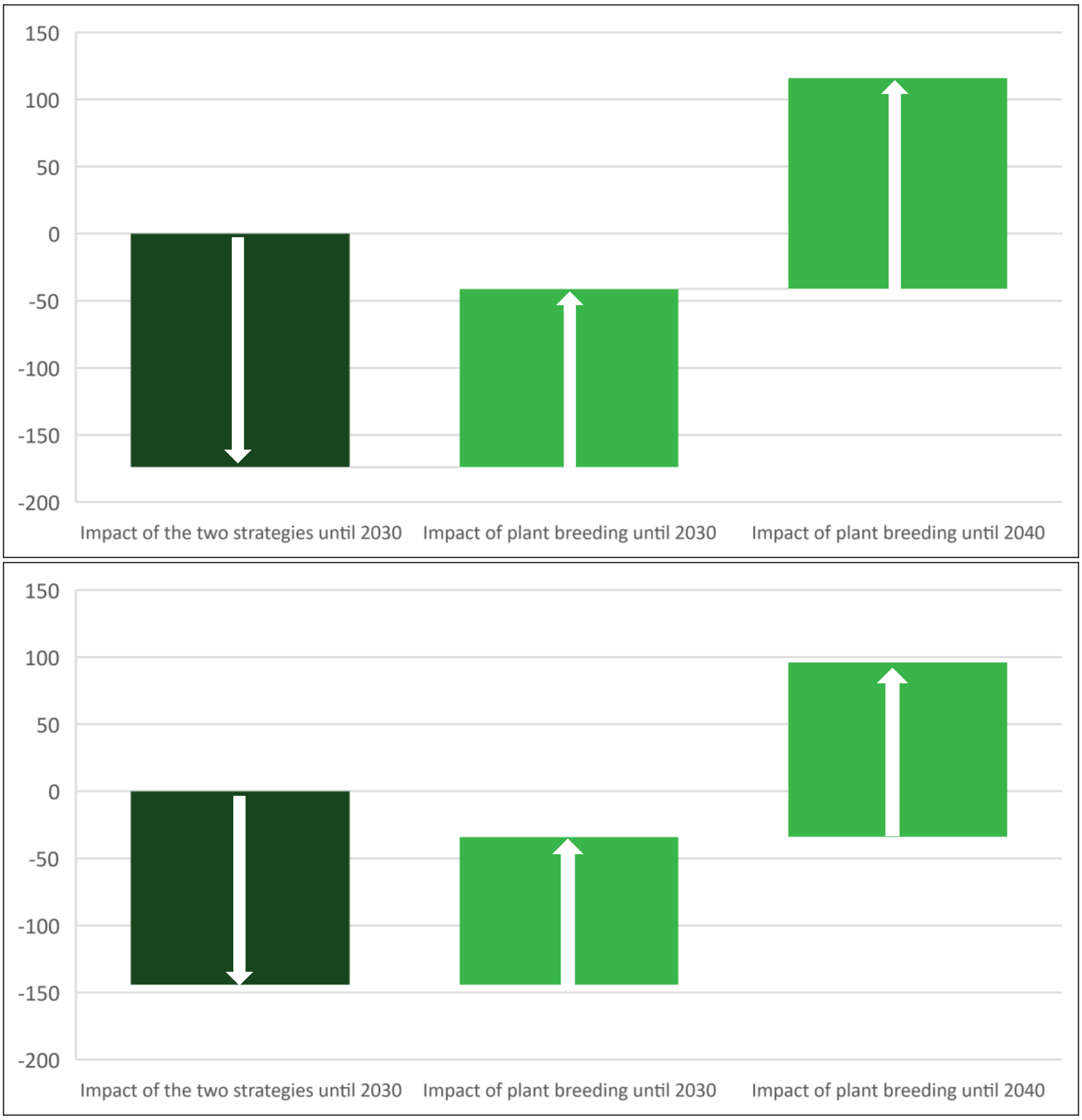
Starting with a forecasted net trade balance in 2030 of 1.9 million tons of tomato (fresh equivalents), the implementation of the two strategies until then – ceteris paribus – would lead to a switch from a net export to a net import situation for the EU in total. This partial impact cannot fully be compensated through plant breeding for tomato at current pace until 2030. Still a net import situation would be the most likely outcome in a decade from now. However, 20 years of plant breeding would be enough to bring the EU into a substantial net export situation as regards tomato by 2040.

Impact on food availability

Since plant breeding in the EU will also act in future to increase tomato production, a substantial part of this additional production can be used as food. Accordingly, plant breeding will increase food availability (and with that food security). 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 two strategies add to lower tomato production and, hence, shrinking food availability. This becomes obvious by looking at figure 2.20. With respect to global population, the two strategies (if fully implemented until 2030) would lead to a food shortage equivalent to 174 million food baskets filled with tomato. In opposite to that, plant breeding progress with respect to tomato in the EU at current pace would be able to refill 133 million of these food baskets in the next decade, and two decades of upcoming genetic crop improvements will potentially be able to refill 290 million food baskets full of tomato. 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

144 million tomato food baskets which can potentially be refilled in part (in full) due to plant breeding progress until 2030 (2040) as enough additional tomatoes for 110 (240) million EU citizens would become available.

Figure 2.20: **Comparing and balancing partial food availability effects of the two strategies until 2030 with tomato plant breeding until 2030 and 2040 in the EU for global population (above) and EU citizens (below) (in tomato for million people)**



Source: Own calculations and figure.

More details, also per EU member state being in the focus of this study, can be obtained from figure 2.21.

Figure 2.21: **Partial food availability effects of the two strategies until 2030 as well as of tomato plant breeding until 2030 and 2040 in the EU (in tomato for million people)**

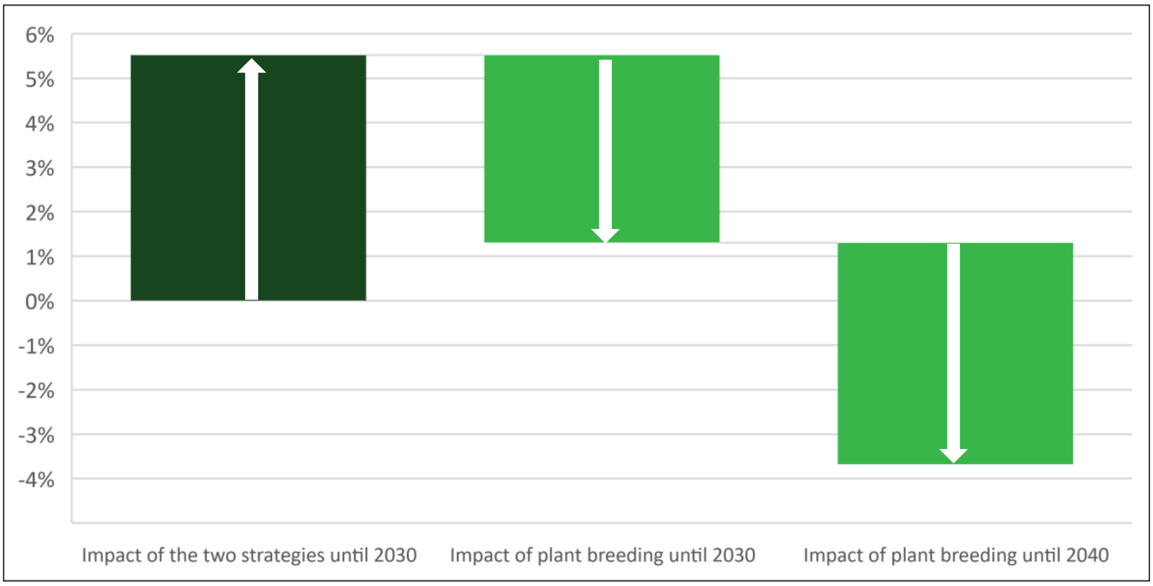
Impact of ...	EU	FR	IT	ES
		Global population		
Two strategies 2030	-174.0	-8.4	-52.1	-46.1
Plant breeding 2030	132.9	4.4	19.9	30.0
Plant breeding 2040	290.1	9.4	41.4	63.3
		EU Citizens		
Two strategies 2030	-144.2	-6.9	-43.1	-38.2
Plant breeding 2030	110.1	3.6	16.5	24.8
Plant breeding 2040	240.3	7.8	34.3	53.2

Source: Own calculations and figure.

Impact on market prices

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 2.22 displays the tomato market price effects of plant breeding until 2030 and 2040 in the EU and sets these impacts into perspective by comparing them with respective impacts that can be attributed to a full implementation of the two strategies.

Figure 2.22: **Comparing and balancing partial market price effects of the two strategies until 2030 with tomato plant breeding until 2030 and 2040 in the EU**



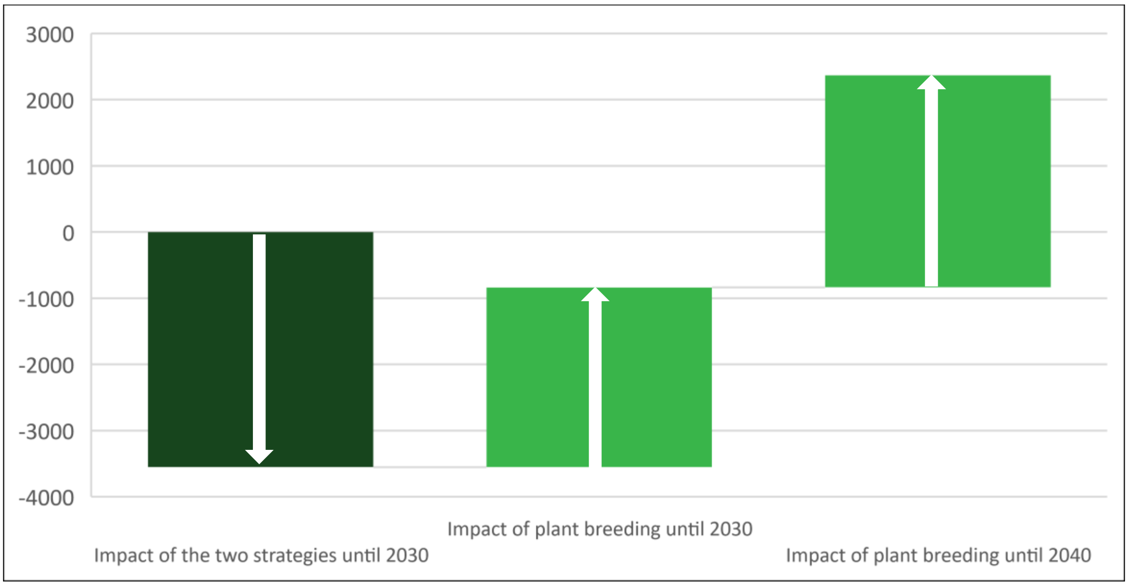
Source: Own calculations and figure.

It turns out that a full implementation of the "Farm to Fork" and "Biodiversity" strategies (as defined above) would increase the market price for tomato until 2030 by 5.5 percent. Plant breeding progress between 2020 and 2029 does already have the potential to partially counteract this development as the partial effect will be able to "delete" 4.2 percentage points of this price increase due to the strategies. In 2040, thanks to altogether 20 additional years of plant breeding for tomato at current pace, the strategies-related price increase might be overcompensated and a net price decrease of more than 3.5 percent might occur.

Impact on sectoral income

The future social welfare effects being a proxy for the agricultural income generated by future plant breeding activities until 2030 and 2040 as well as by the enforcement of the two strategies until 2030 with respect to tomato are now listed in figure 2.23 for the EU in total, while figure 2.24 provides more detailed information also for the selected three EU member states.

Figure 2.23: Comparing and balancing partial sectoral income effects of the two strategies until 2030 with tomato plant breeding until 2030 and 2040 in the EU (in million EUR)



Source: Own calculations and figure.

Looking at figure 2.23, it can be stated that a negative sectoral income effect can be associated with the implementation of the two strategies and the subsequent production losses. In fact, it can be shown that the two strategies would lead to a partial sectoral (tomato-related) income loss of more than EUR 3.5 billion. Plant breeding progress with respect to tomato until 2030 will have the potential to partly compensate this loss (with an additional sectoral income of approximately EUR 2.7 billion), and in 2040, a net surplus (of more than EUR 2.0 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 combined.

This – an aggregated positive sector income impact until 2040 – also applies to tomato production and breeding in France as well as in Spain, as figure 2.24 shows, whereas net income loss would still occur in the case of Italy as even 20 years of tomato plant breeding would not be enough to fully compensate the considerable sector income loss embedded in the full implementation of the two strategies as defined above.

Figure 2.24: **Partial sectoral income effects of the two strategies until 2030 as well as of tomato plant breeding until 2030 and 2040 in the EU (in million EUR)**

Impact of ...	EU	FR	IT	ES
Two strategies 2030	-3552	-190	-1082	-709
Plant breeding 2030	2713	100	413	462
Plant breeding 2040	5920	213	860	990

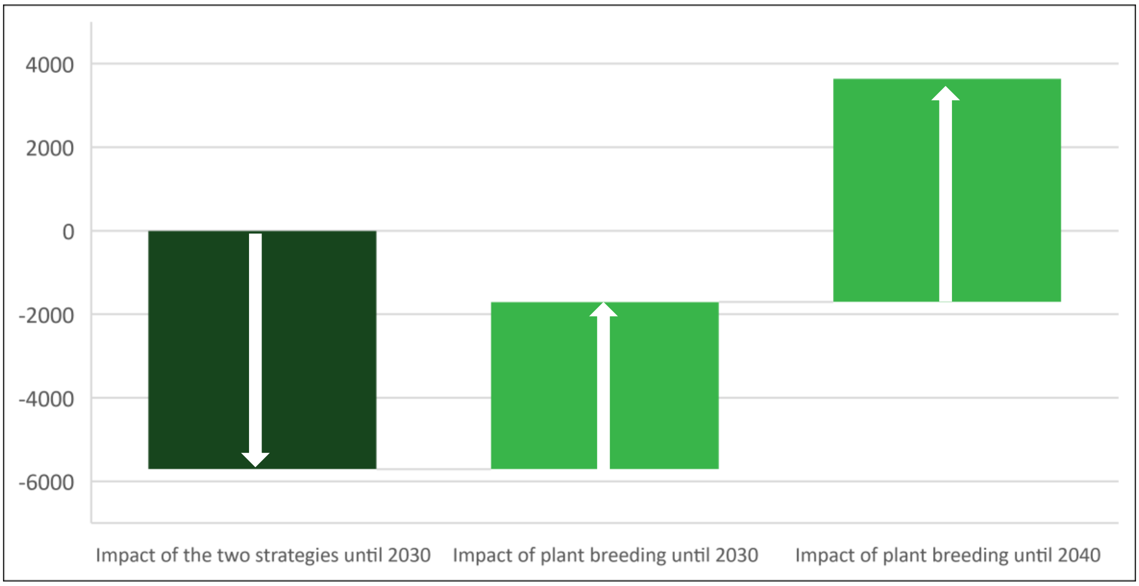
Source: Own calculations and figure.

Impact on GDP

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, here tomato, must be transported, stored, processed, traded, retailed, etc. This tends to increase the generation of income in other sectors. Therefore, the producer surplus additionally generated through plant breeding being a substantial part of the future societal welfare (or sectoral income) effect displayed in figure 2.23 and figure 2.24 must be linked to GDP multipliers as described in Noleppa and Cartsburg (2021). Accordingly, figure 2.25 gives an overview on the various partial impacts discussed in this chapter for the EU in total while figure 2.26 provides the region-specific results in detail.

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 with respect to tomato 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 2.25. The full implementation of the two strategies – as defined above – would lead to a GDP loss of more than EUR 5.7 billion. Plant breeding progress until 2030 has already the potential to substantially reduce this loss since EUR 4.0 billion could be added to the European GDP. In 2040, the GDP loss attributable to the two strategies would potentially be overcompensated by more than EUR 3.5 billion due to plant breeding for tomato in the next two decades.

Figure 2.25: **Comparing and balancing partial GDP effects of the two strategies until 2030 with tomato plant breeding until 2030 and 2040 in the EU (in million EUR)**



Source: Own calculations and figure.

A positive GDP impact until 2040 on aggregate can also be stated with respect to tomato production and breeding in France as well as in Spain, as figure 2.26 shows, whereas a net GDP loss would still occur in the case of Italy as even 20 years of tomato plant breeding would not be enough to fully compensate the GDP loss embedded in the implementation of the two strategies as defined above.

Figure 2.26: **Partial GDP effects of the two strategies until 2030 as well as of tomato plant breeding until 2030 and 2040 in the EU (in million EUR)**

Impact of ...	EU	FR	IT	ES
Two strategies 2030	-5711	-336	-2058	-1367
Plant breeding 2030	4009	177	785	890
Plant breeding 2040	9351	378	1637	1908

Source: Own calculations and figure.

Impact on farm income and labour

It shall be repeated here, that in opposite to Noleppa and Cartsburg (2021), the farm income and labour impacts of plant breeding for tomato being a specialty crop cannot be carried out due to missing publicly available farm level data.

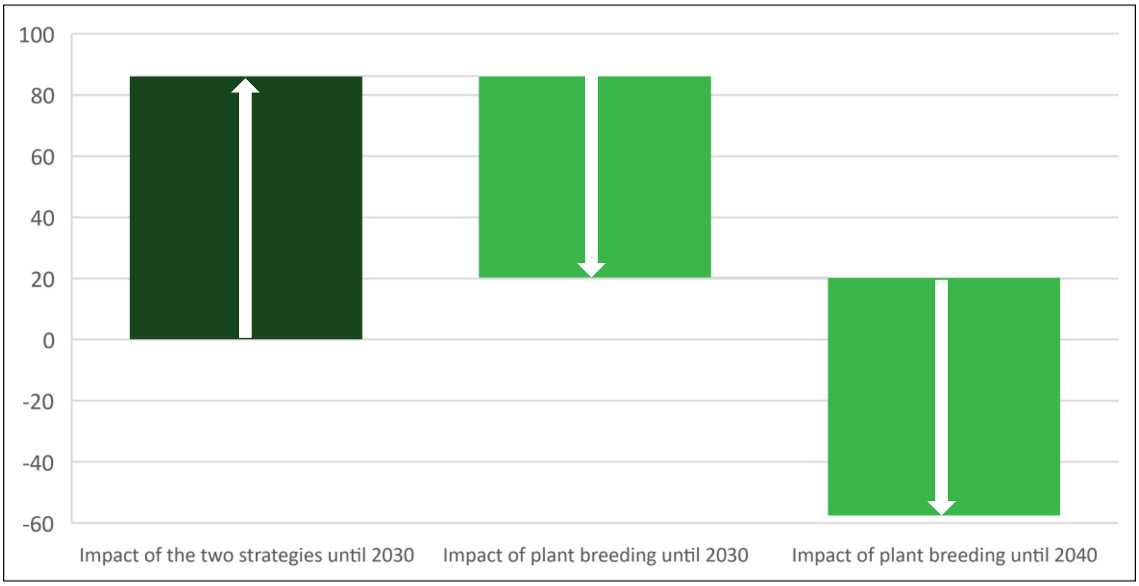
Future environmental effects

Before the environmental effects as well are discussed for the future scenarios in more detail, it shall be repeated that the methodology to receive the various results does not allow to derive results for specific EU member states due to data restrictions (see above). Hence, only impacts with respect to the EU in total are discussed in the following.

Impact on virtual land trade

Obviously, tomato-related plant breeding activities from now would also increase the EU-extra exports and/or decrease the EU-extra imports in future. This contributes to a positive net trade balance (see again figure 2.19), whereas the full implementation of the two strategies potentially leads to a worsening of the net trade balance. This has implications for the net virtual land trade of the EU that can be attributed to tomato (see also figure 2.12). In fact, the net virtual land trade effect of future plant breeding for tomato in the EU can again be compared with the specific impact which would result from a full implementation of the "Farm to Fork" and "Biodiversity" strategies. Figure 2.27 shows the result and firstly indicates that the partial effect of the strategies would be to use more land abroad to satisfy domestic tomato demand in the EU with production losses here due to the strategies. However, figure 2.27 secondly signals that this negative environmental effect can be compensated in part due to plant breeding in the next decade and overcompensated with tomato plant breeding at current pace between 2020 and 2039. The net effect of the two partial future developments, if added, would indicate a land saving of almost 60 000 hectares at global scale.

Figure 2.27: **Comparing and balancing partial net virtual land effects of the two strategies until 2030 with tomato plant breeding until 2030 and 2040 in the EU (in 1 000 hectares)**



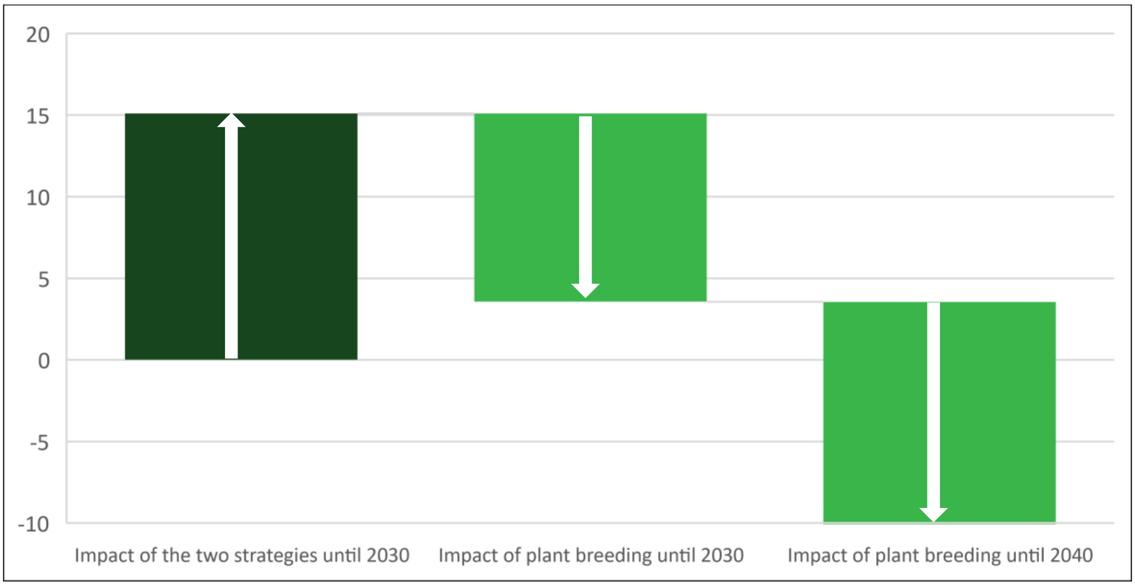
Source: Own calculations and figure.

Impact on GHG emissions

The arable land additionally needed at global scale without plant breeding for tomato 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 does yet still sequester 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 was to be used for farming. In this respect, 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 tomato demand.

The partial GHG emission effects from respective land use changes of the two strategies on the one hand and future tomato-related plant breeding progress in the EU on the other hand are visualized in figure 2.28.

Figure 2.28: **Comparing and balancing partial GHG emission effects of the two strategies until 2030 with tomato plant breeding progress until 2030 and 2040 in the EU (in million tons)**



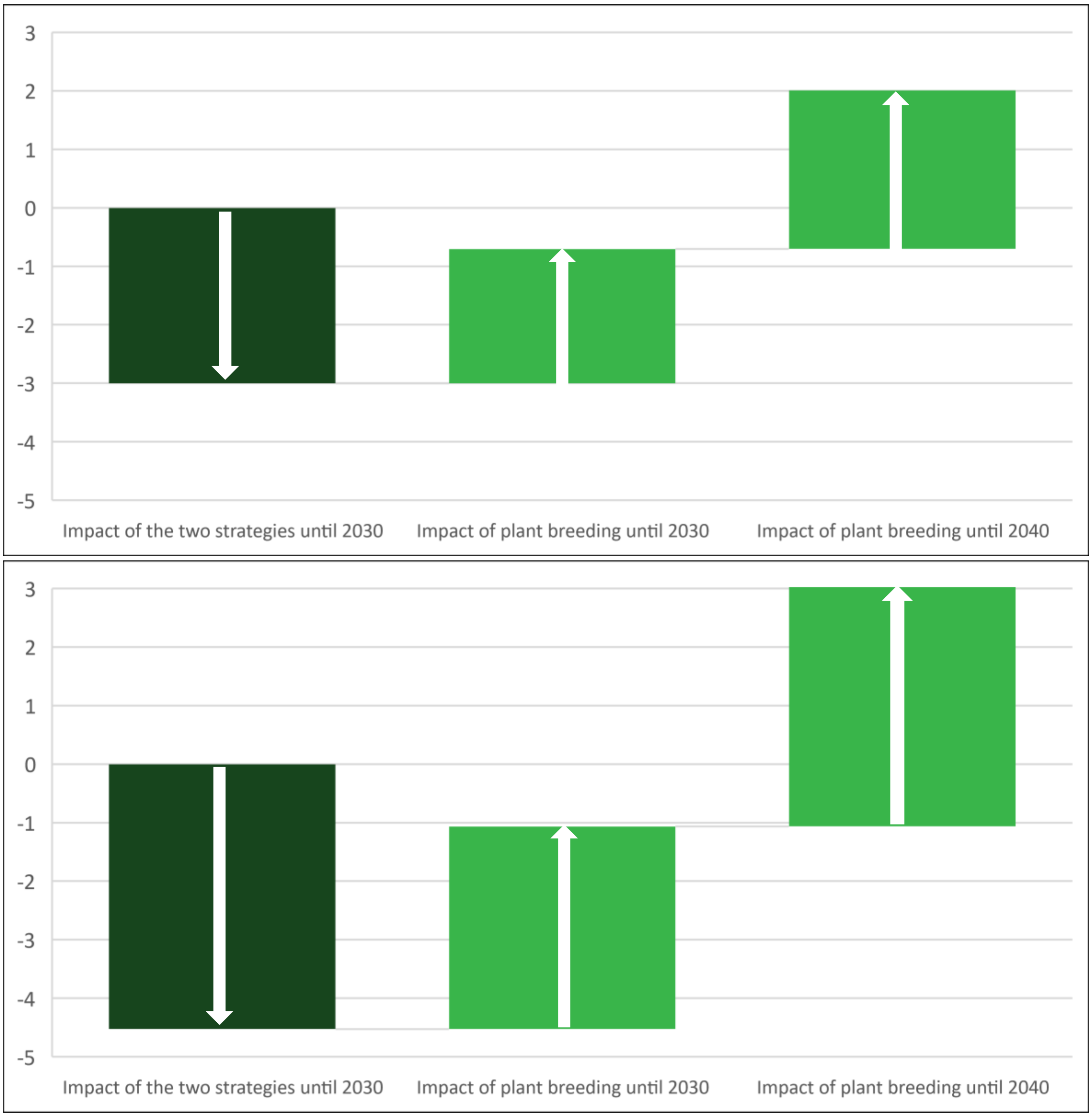
Source: Own calculations and figure.

It turns out, that an enforcement of the two strategies would potentially cost 15 million tons of GHG emissions measured in terms of CO_2 equivalents which can be related to the tomato farming sector. To a substantial part, this extra emission level can be reduced by tomato-related plant breeding in the next decade. Twenty years of these EU plant breeding efforts would even allow to overcompensate, and a net saving of approximately 10 million tons of GHG emissions can be achieved until 2040 on balance if the partial effects are aggregated.

Impact on biodiversity

Repeating that future plant breeding efforts as regards tomato in the EU will avoid a conversion of natural or nature-like habitats, while the implementation of the two strategies as defined above acts in exactly the opposite way, it is also worth quantifying the associated potential biodiversity effect of respective future developments based on the two methods outlined above. The results of the separate analyses for the EU in total are depicted in figure 2.29.

Figure 2.29: Comparing and balancing partial biodiversity effects based on the GEF-BIO (above) and NBI (below) of the two strategies until 2030 with tomato plant breeding until 2030 and 2040 in the EU (in million points)



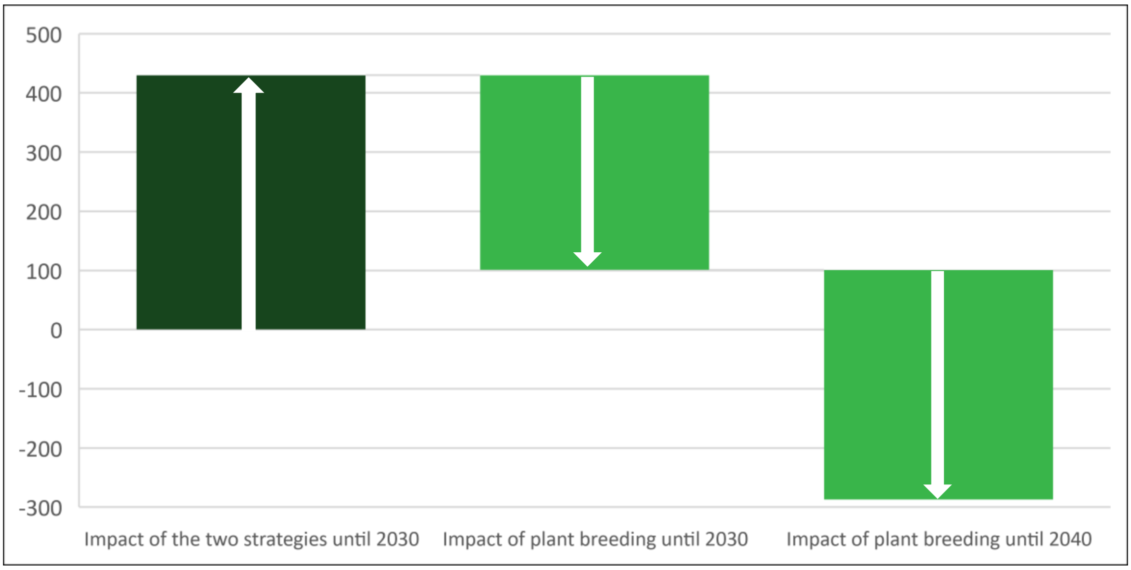
Source: Own calculations and figure.

Based on the GEF-BIO (NBI), approximately 3.0 (more than 4.5) million biodiversity points attributable to tomato farming would be lost by an implementation of the two strategies in the EU in the next decade on top of what will most probably be lost in terms of global species richness anyway due to other reasons. This is equivalent to the biodiversity currently found in 30 (45) million hectares of Brazilian (Indonesian) ecosystems. Three quarters of this loss can be compensated through tomato-related plant breeding in the next decade, and two decades of EU plant breeding with respect to tomato are able to more than fully compensate the biodiversity loss attributable to the two strategies (as defined above). In the case of combining the partial effects, a net gain of approximately 2.0 (3.0) biodiversity points can potentially be envisaged.

Impact on water use

What has been analyzed with respect to water use in the past can also be examined for the future. Using the same methodology as above, two effects – domestic water use changes due to developments in EU production and water use changes abroad due to international trade implications – can be aggregated to a net water use balance. The partial tomato-related changes of this balance which can be attributed to an implementation of the two strategies until 2030 on the one hand and plant breeding until 2030/2040 on the other hand are displayed in figure 2.30. Accordingly, the full implementation of the two strategies would cause an additional global water use of 430 million m^3. Plant breeding for tomato in the next decade in the EU would already be able to substantially reduce this partial effect, and the partial water saving effect of plant breeding for tomato 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 almost 300 million m^3 might occur if the effects are aggregated.

Figure 2.30: Comparing and balancing partial water balance effects of the two strategies until 2030 with tomato plant breeding progress until 2030 and 2040 in the EU (in million m^3)



Source: Own calculations and figure.

3 The importance of alfalfa plant breeding in the EU

3.1 Ex-post evaluation

Primary production impacts

As in the case of tomato, basic requirements for the analysis are to examine the yield development in EU alfalfa farming and to determine a land productivity impact that can solely be related to the specific plant breeding in the EU respectively the three selected member states. This can normally be achieved by using the gradual approach as applied in Noleppa and Cartsburg (2021) which looks at yield growth in alfalfa production first, calculates an innovation-induced yield growth in terms of hectare-related TFP growth for this crop then, and finally determines the plant breeding-induced yield growth of the fodder crop based on the share of plant breeding in innovation-induced yield growth.

However, applying this straightforward concept for the EU as a whole and the selected three member states is impossible due to severe data restrictions. In fact, consistent and comparable statistics on alfalfa yield developments between the turn of the millennium and today are not available. Only partial data could be found, which allow for the determination of alfalfa yield growth since the year 2000.

Yield growth

Based on data obtained from Gnis (2018), it can be stated that alfalfa yields in France increased by just 0.32 percent per annum between the years 2002 and 2017. Beguier et al. (2018) as well look at alfalfa yield developments in France. Accordingly, it can be concluded that this yield increased by not more than 0.11 percent per annum between the years 2000 and 2016. Finally, Julier et al. (2017) argue that European alfalfa yields increased by 0.15 percent per annum.

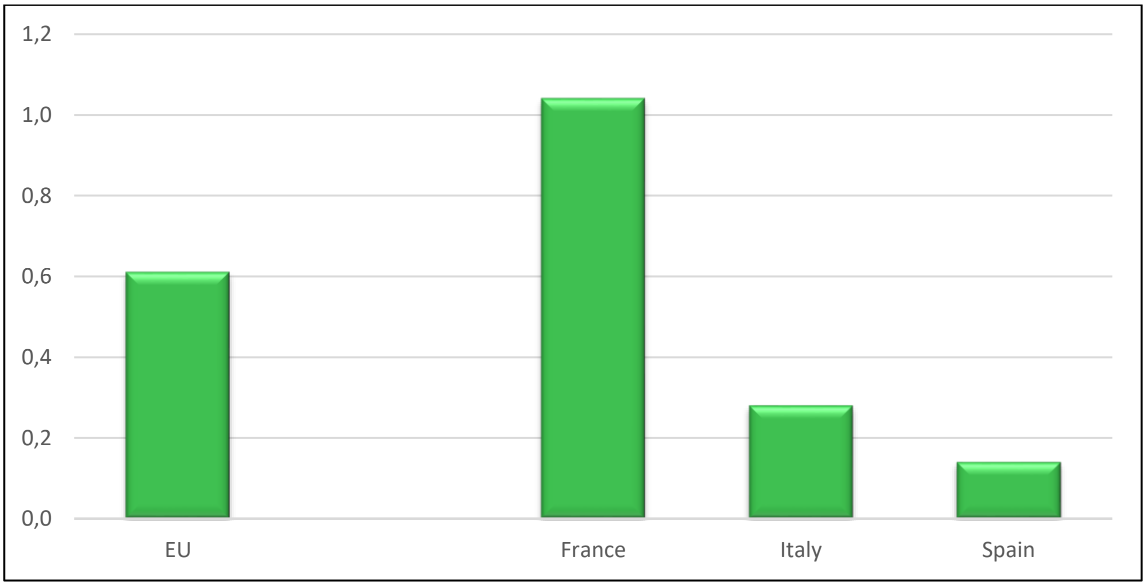
The weak data background and the embedded uncertainty do not allow to profoundly determine a statistically observable yield growth with respect to alfalfa in the EU in total and the three selected EU member states. Instead, a meaningful assumption must be made. Accordingly, it is assumed in the following that alfalfa yields have increased in all four regions being in the focus of this study by 0.19 percent per annum since the turn of the millennium. This is simply the mean value of the three specific quantitative arguments just briefly discussed and as such remarkably lower than the yield progress of the past 20 years on average in arable farming in the EU in total as well as in France, Italy, and Spain (see Noleppa and Cartsburg, 2021). In this respect, the consideration of a rather low yield growth rate for alfalfa is also supported by Annicchiarico et al. (2015) stating that yield (and also genetic) progress for the specific crop is definitely (much) lower than in the case of major arable crops due to its perennial nature, particular long breeding cycles and other more technical reasons.

Innovation-induced yield growth

At this stage of the analysis, developments in land-based factor use need to be identified and incorporated into the analysis again by subtracting them from statistically measurable yields leading to innovation-induced yield growth. In full accordance with Noleppa and Cartsburg (2021), figure 2.2 (see above) already displays the changes in land-related factor use to be applied.

Again, weighting the various change rates of the specific three intermediate inputs (fertilizers, plant protection products (PPP) and seeds), as well as of capital and labour with the individual input shares of these production factors in the entire input obtained from EC (2019a) and KTBL (2021) results in the average growth rates of the overall input use already displayed in figure 2.3. According to Lotze-Campen et al. (2015) and as also applied in Noleppa and Cartsburg (2021), these share-weighted annual growth rates of the overall input use must be subtracted from the annual yield growth rates referring to the past 20 years that have to be allocated to alfalfa to calculate meaningful annual innovation-induced yield growth rates for alfalfa farming in the EU and its member states. Figure 3.1 shows the results.

Figure 3.1: Annual innovation-induced yield growth rates of alfalfa farming in the EU and selected member states between 2000 and 2019 (in percent)



Source: Own calculations and figure.

Accordingly, it can be stated that innovations in alfalfa farming have enabled an EU yield growth since the turn of the millennium of 0.61 percent per annum, which is well below the 1.68 percent per annum and hectare of EU arable farming in total (see Noleppa and Cartsburg, 2021). In the three selected EU member states being in the focus of this study, the innovation-induced yield growth in alfalfa farming is also lower than the innovation-induced yield growth in the entire country-specific arable farming (see again Noleppa and Cartsburg, 2021). It is around 1.0 percent per annum in French alfalfa production (compared to less than 1.3 percent in arable farming), it amounts to almost 0.3 percent per year in Italian alfalfa farming (compared to also less than 1.3 percent in the country's arable farming), and it is just 0.14 percent per annum in Spanish alfalfa production (compared to approximately 0.9 percent in arable farming of this specific EU member state).

Plant breeding-induced yield growth

Determining the plant breeding-induced yield growth requires the definition of the share of plant breeding in innovation-induced yield growth. Therefore, Noleppa and Cartsburg (2021) provide a very substantial analysis squeezing out more than 100 scientific sources and expert statements. Accordingly, the share of plant breeding in innovation-induced productivity must be within the range of 50 to 90 percent, and the mean value is around two thirds. Unfortunately, the data do not allow for an explicit statement on the share with respect to alfalfa as no crop-specific sources and statements could be identified.

However, considering alfalfa as both, a (non-dry) pulse and a green fodder crop, the shares identified in Noleppa and Cartsburg (2021) with respect to (dry) pulses and green maize may serve as a best guess. Interestingly, both shares are always in the same range allowing to assume hereafter that the plant breeding shares in innovation-induced yield growth are 67 percent in the cases of the EU in total as well as Italy and Spain, whereas this share is around 83 percent in the case of France. Consequently, figure 3.2 displays the annual plant breeding-induced yield growth rates used hereafter for further analyses.

Figure 3.2: **Annual plant breeding-induced yield growth rates of alfalfa farming in the EU and selected member states between 2000 and 2019 (in percent)**

EU	FR	IT	ES
0.41	0.86	0.19	0.10

Source: Own calculations and figure.

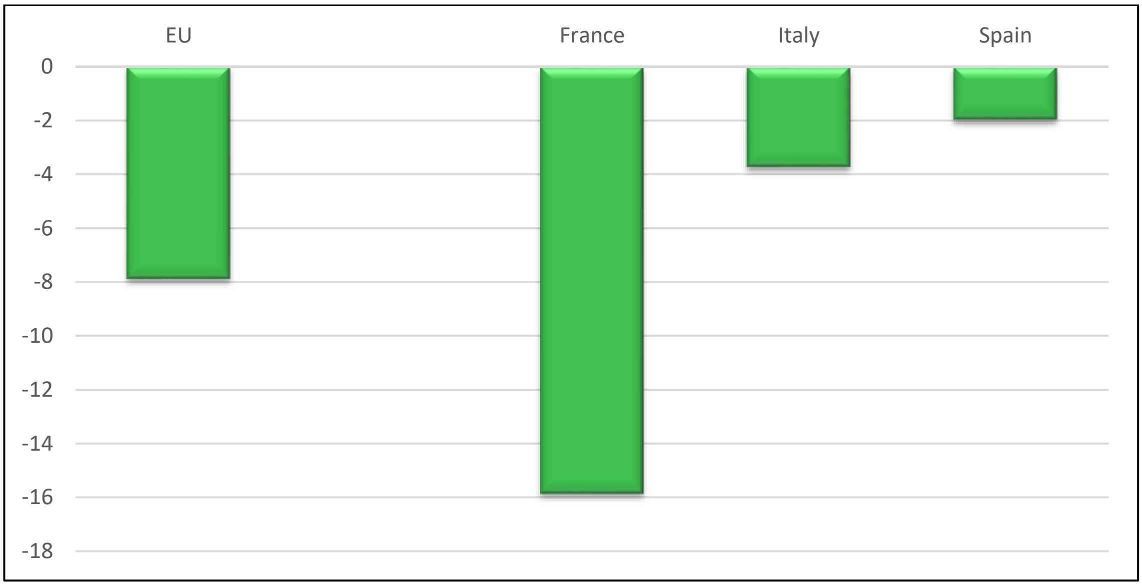
Secondary socio-economic consequences

Defined shift factors

Analysing the values alfalfa-related 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 without yield increases induced by plant breeding efforts in the past 20 years. As in the case of tomato, 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 the target indicators of this study. Therefore, the shift factor must be expressed as the percentage to be calculated by accumulating the average annual plant breeding-induced yield growth rates (see figure 3.1) for the entire time horizon between 2000 and 2019 using the compound interest approach.

Consequently, figure 3.3 displays the simulated currently experienced yield loss in alfalfa production without plant breeding in the EU and selected member states in the last two decades. Accordingly, partly remarkable yield losses would have to be envisaged today if plant breeding for alfalfa in the EU had terminated in the year 2000. With respect to the chosen regional spectrum of this study, the apparent yield loss would have been between 2.0 percent in Spain and almost 16 percent in France.

Figure 3.3: **Simulated yield loss for alfalfa in 2020 without plant breeding progress between 2000 and 2019 in the EU and selected member states (in percent)**

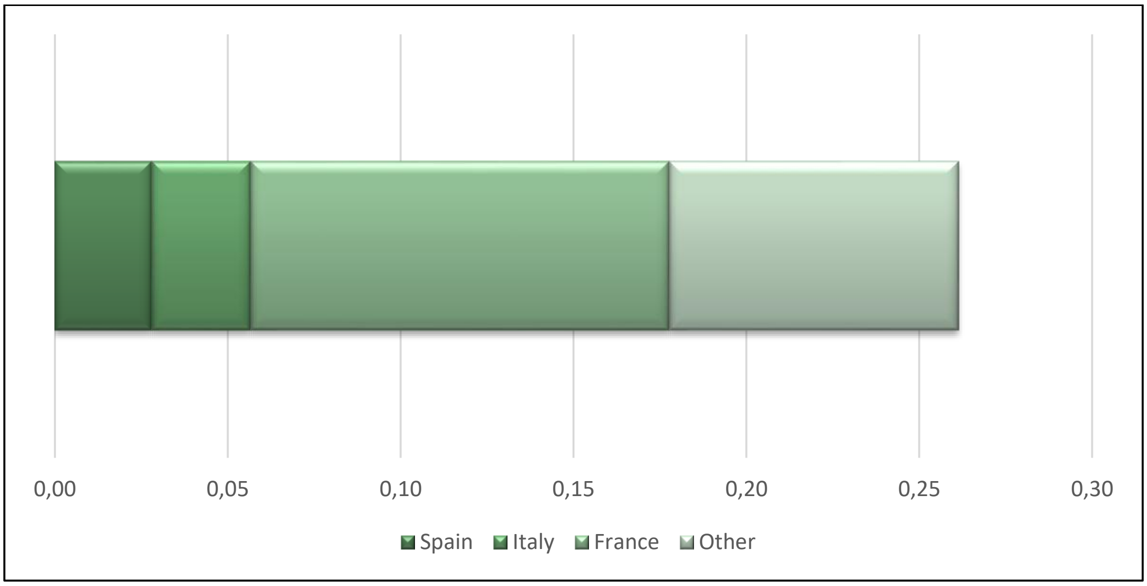


Source: Own calculations and figure.

Impact on market supply

Facing lower alfalfa yields without the plant breeding progress of the past two decades, the market supply in the EU would be lower today. In this respect, figure 3.4 shows the impact of plant breeding progress in the EU since 2000 on current market supply. Data on dehydrated alfalfa and green forage from Duursema (2018) is used to calculate the specific impact. Accordingly, it can be concluded that plant breeding since the year 2000 has allowed the EU in total to supply an additional alfalfa volume in 2020 of more than 250 000 tons. Plant breeding for alfalfa in France alone contributes more than 120 000 tons, and genetic crop improvements in Italy and Spain add almost 30 000 tons each. Thus, the plant breeding progress of the past 20 years in the three selected EU member states is responsible for almost 70 percent of the plant breeding-induced extra market supply in the alfalfa sector of the EU.

Figure 3.4: **Extra market supply for alfalfa in 2020 with plant breeding progress between 2000 and 2019 in the EU and selected member states (in million tons)**



Source: Own calculations and figure.

Impact on net trade

Figure 3.5: **Net trade volume of the EU for alfalfa and products thereof in 2020 with and without plant breeding progress between 2000 and 2019 (in 1 000 tons)**

Source: Own calculations and figure.

It is also rather challenging to measure the net trade impact of plant breeding as regards alfalfa since international trade in this crop and products thereof is only rudimentarily covered within the data bases used to apply the same or at least a similar methodology as applied in Noleppa and Cartsburg (2021). Nevertheless, a meaningful assessment is possible for the EU in total if specific data on aggregated crop trade provided by FAO (2021) is used.

Accordingly, most recent extra-EU trade amounts to 699 000 tons of alfalfa (and products thereof) exported and 382 000 tons of this agricultural commodity imported. Hence, the EU does currently net export 317 000 tons of alfalfa. If the market supply volume shown in figure 3.4 was missing today, the still impressive positive net trade position of the EU with respect to alfalfa and products thereof would substantially deteriorate as figure 3.5 above illustrates. More particularly, the net export volume would shrink by 83 percent without the plant breeding progress of the past 20 years.

Impact on food availability

Alfalfa is not used for human consumption. Hence, such an analysis will not be included into this study.

Impact on market prices

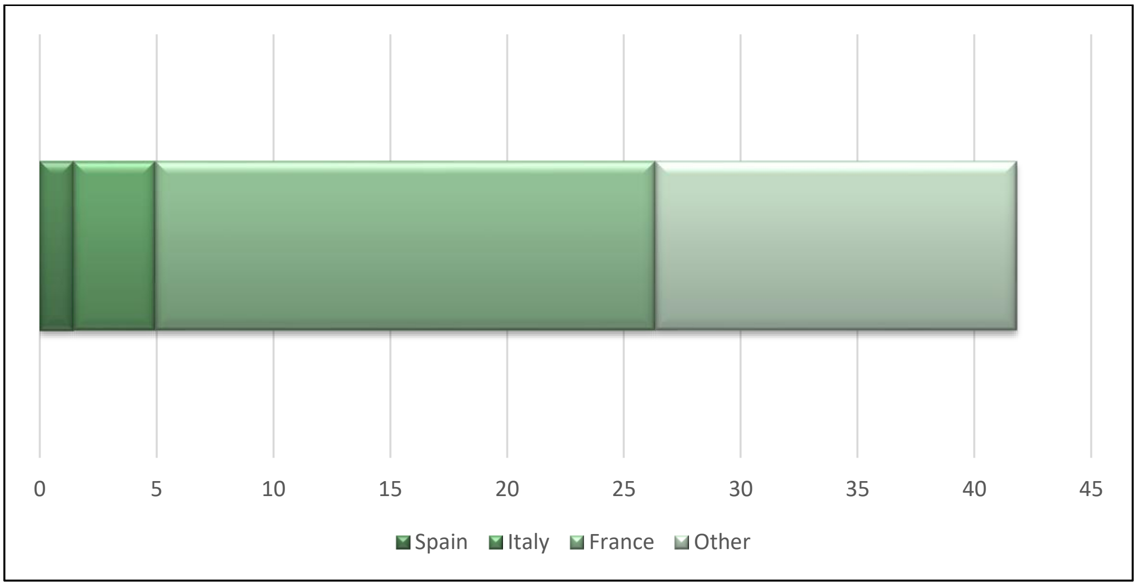
In the case of alfalfa, also a rather high market supply volume with plant breeding does not only create a benefit in terms of the trade balance as already discussed, but additionally enables consumers in the EU and around the globe to buy the agricultural raw materials at affordable prices. Applying again a single market model for alfalfa (as already described and used to calculate the market supply impacts for tomato), it turns out that prices at international alfalfa markets would have been 2.2 percent higher without plant breeding in the EU during the last two decades than they are at present.

Impact on sectoral income

The current sectoral income effect – from an analytical and modelling perspective the sum of so-called producer surpluses (producer income) and consumer surpluses (consumer savings) (see again Noleppa and Cartsburg, 2021) – of plant breeding progress in the EU between 2000 and 2019 for alfalfa is depicted in figure 3.6. Thereby, price levels describing the status quo were obtained from FAO (2021).

Accordingly, it can be stated that the total social welfare gain of alfalfa-related plant breeding progress since the year 2000 in the EU amounts to more than EUR 40 million in 2020. More than EUR 20 million of this amount is generated in France alone, while the sectoral income increased only a bit in Spain and Italy (due to the comparably low progress as can be seen in figure 3.2 and figure 3.3.). Nevertheless, the plant breeding progress of the past 20 years in the three selected EU member states on aggregate is responsible for more than 60 percent of the plant breeding-induced extra sectoral income of the EU in total while the rest can mainly be attributed to Germany, The Netherlands and the Czech Republic as well as the UK (as a former EU member state).

Figure 3.6: **Additional sectoral income for alfalfa in 2020 with plant breeding progress between 2000 and 2019 in the EU and selected member states (in million EUR)**



Source: Own calculations and figure.

Impact on GDP

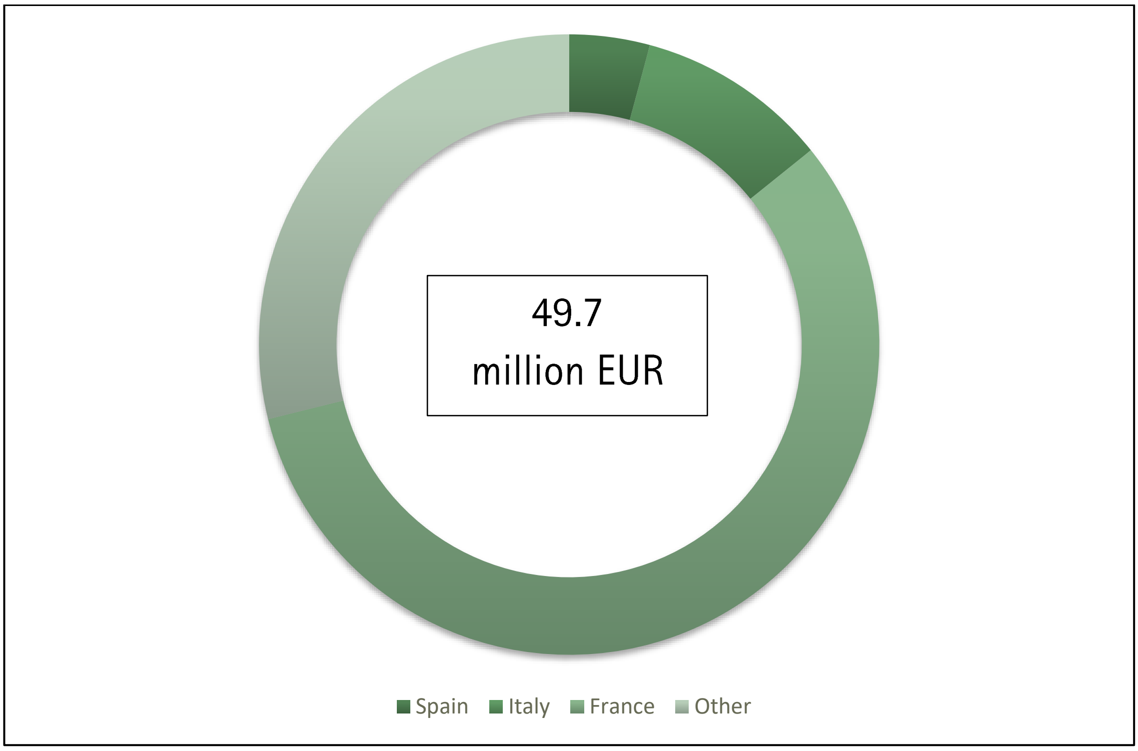
It becomes clear that genetic crop improvements with respect to alfalfa have a positive sectoral economic impact in the EU and its member states. However, plant breeding does not only benefit the primary agricultural sector but the society in total. It particularly creates an economic value not only for farmers but for (mainly rural) citizens upstream and downstream the value chain because the additionally produced alfalfa must be transported, stored, traded, retailed, fed to livestock, etc. This tends to increase the generation of income in other primary and non-primary sectors. Accordingly, the producer surplus additionally generated through plant breeding being a substantial part of the societal welfare effect displayed in figure 3.7 must be linked to GDP multipliers (see again Noleppa and Cartsburg, 2021).

Figure 3.7 provides the results of this exercise for the EU and its selected member states. Hence, it can be argued that:

- The overall GDP impact of 20 years of plant breeding for alfalfa should be valued almost EUR 50 million in 2020 for the EU in total, and
- Crop-specific plant breeding in France alone accounts for more than EUR 28 million.

Together with Italy and Spain, the three selected EU member states generate approximately 70 percent of this extra GDP.

Figure 3.7: **Additional GDP attributable to alfalfa in 2020 with plant breeding progress between 2000 and 2019 in the EU and selected member states (in million EUR)**



Source: Own calculations and figure.

Impact on farm income and labour

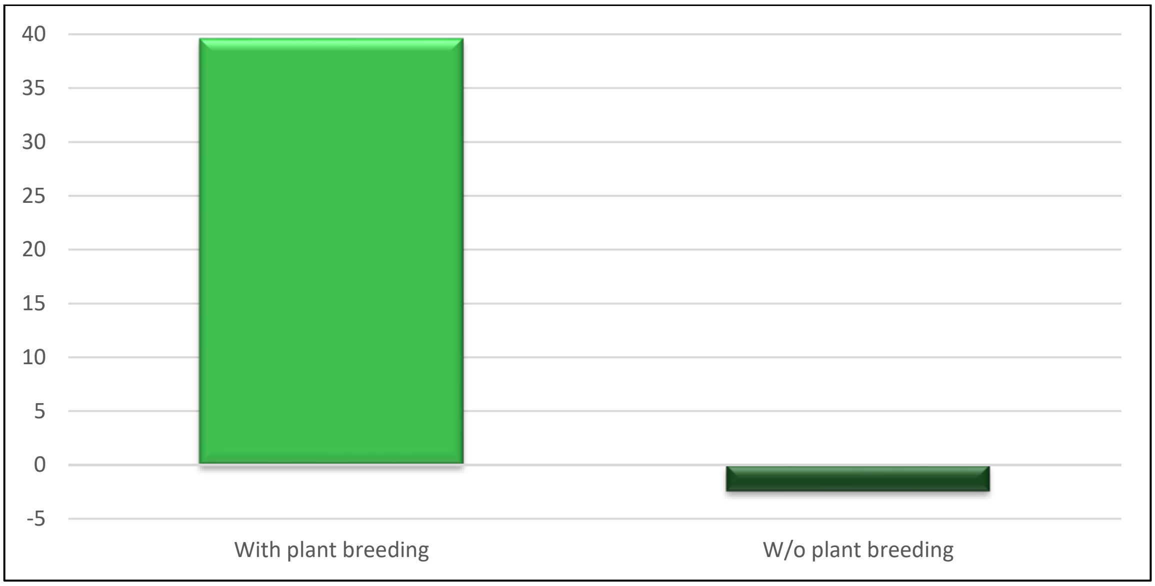
Noleppa and Cartsburg (2021) also analysed farm income and labour impacts of plant breeding for major arable crops. As in the case of tomato the necessary farm level data to apply the same or at least a similar approach is unfortunately not publicly available. Therefore, the specific analyses cannot be carried out.

Tertiary environmental effects

Impact on virtual land trade

The obvious developments in EU-extra trade in the case of missing plant breeding activities for alfalfa since 2000 (see, again, figure 3.5) would subsequently change the balance of EU net imports of virtual agricultural land. Based on a similar methodology as applied in the case of tomato, the net virtual land trade in 2020 at global scale with and without plant breeding for alfalfa since 2000 and the subsequent change that can be attributed to the EU in total for an absence of crop-specific plant breeding progress since the turn of the millennium is visualized in figure 3.7.

Figure 3.7: **Net virtual land trade attributable to alfalfa in 2020 with and without plant breeding progress between 2000 and 2019 in the EU (in 1 000 hectares)**



Source: Own calculations and figure.

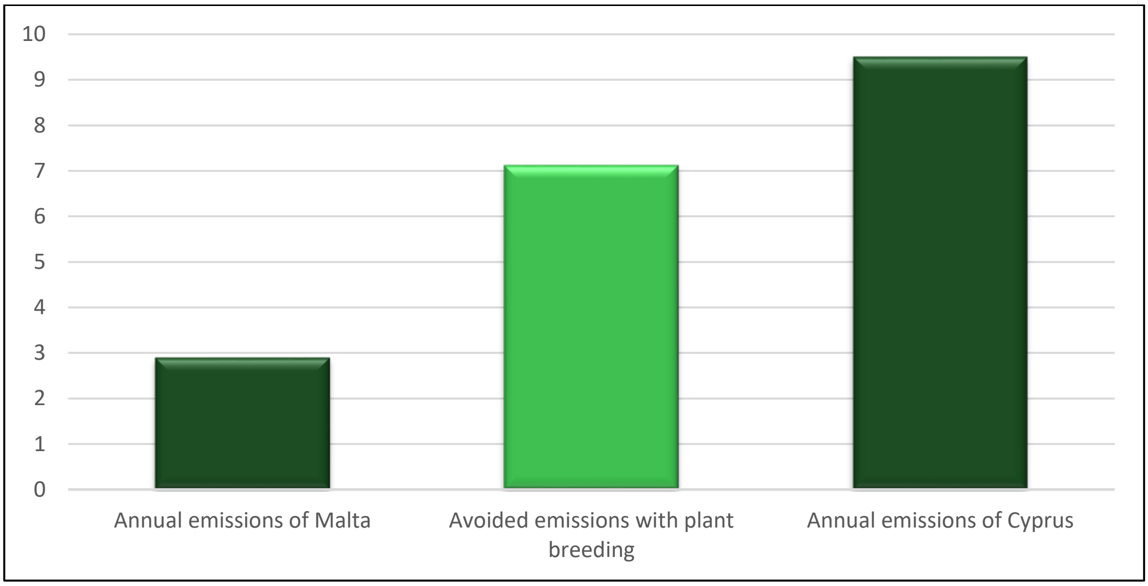
Accordingly, the EU today achieves an alfalfa-based virtual net export of land (almost 40 000 hectares). If plant breeding in the EU had been terminated in 2000, more than 2 000 hectares should have been virtually net imported in 2020. Hence, global land use with respect to alfalfa production would have increased by approximately 42 000 hectares in the past 20 years. These are more than 400 square kilometers and hence larger than the surface of Lake Garda in Italy.

Impact on GHG emissions

This arable land globally needed extra without plant breeding for alfalfa in the EU in the last two decades is not available *per se*. In fact, it needs to be additionally converted from grassland or natural habitats. However, all this land does yet sequester carbon both above and below ground. This means, a tremendous part of this carbon would be released into the atmosphere as a GHG if the land was used for farming.

The amount of mainly CO_2 to be emitted in such a situation, and currently avoided due to lasting genetic crop improvements, can again be calculated by using the approach described in Noleppa and Cartsburg (2021) and yields 7.1 million tons of extra GHG emissions at global scale due to land use changes triggered by lower alfalfa production in the EU due to an absence of plant breeding for that crop since the turn of the millennium. To compare: This one-time-only effect should not be considered "low" as it is between the entire annual GHG emissions of Malta and Cyprus (EEA, 2020) as figure 3.8 visualizes.

Figure 3.8: **Avoided GHG emissions until 2020 attributable to alfalfa plant breeding progress between 2000 and 2019 in the EU – a comparison (in million tons)**



Source: Own calculations and figure.

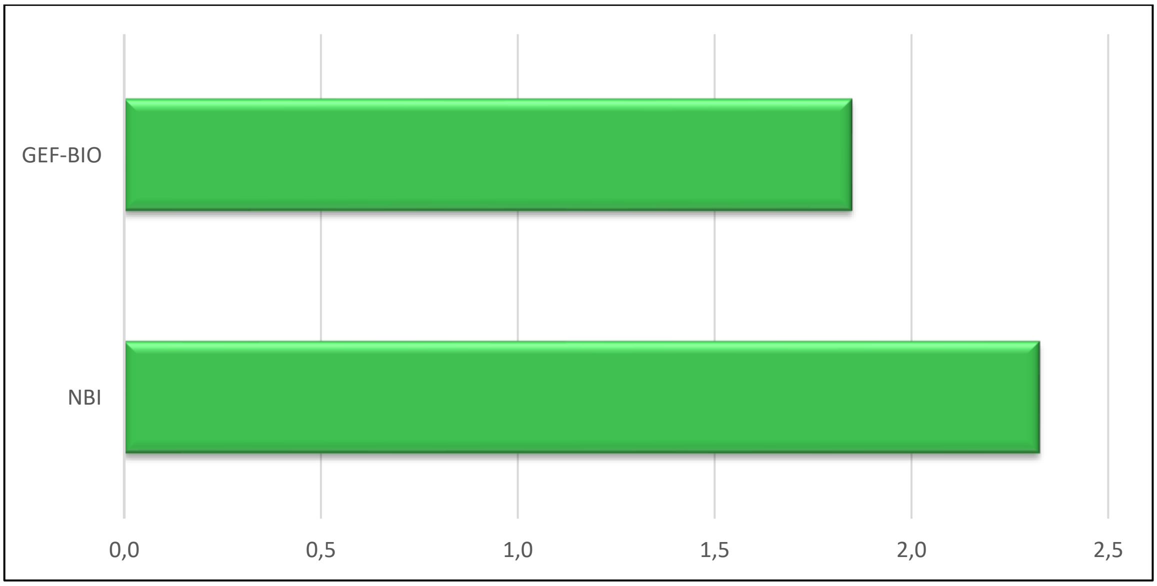
Impact on global biodiversity

Repeating that plant breeding efforts in the EU related to alfalfa since the year 2000 have avoided a conversion of grassland and natural habitats of more than 40 000 hectares at global scale (see again figure 3.7), it is also worth quantifying the associated "biodiversity preserving" effect of genetic crop improvements. As outlined in Noleppa and Cartsburg (2021), two methods for capturing this effect can again be applied: First, the GEF-BIO approach is used, and second, the NBI concept is employed. The results regarding the biodiversity loss of the two separate analyses for the EU in total are depicted in figure 3.9. Looking at the figure, the following specific findings with respect to avoided biodiversity loss can be highlighted for the EU in total:

- Based on the GEF-BIO, more than 1.8 million biodiversity points would have been lost until today by neglecting plant breeding for alfalfa 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 18 000 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 alfalfa in the EU between the years 2000 and today has compensated for almost ten days 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 more than 2.3 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 alfalfa 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 23 000 hectares of Indonesian natural habitats, i.e., as much as the loss of biodiversity that can be attributed to approximately three weeks of cutting rainforests in Indonesia at current deforestation intensity.

Figure 3.9: Avoided global biodiversity loss until 2020 with alfalfa plant breeding progress between 2000 and 2019 in the EU (in million points)



Source: Own calculations and figure.

Impact on water use

Analyzing the impact of alfalfa plant breeding in the EU on global water demand is not possible due to data availability. The crop is unfortunately not covered by the global water footprint data base used in Noleppa and Cartsburg (2021).

3.2 Ex-ante assessment

Again, this research on alfalfa does not only aim at discussing the various benefits European plant breeding for the crop 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. Therefore, as in the case of tomato, also an *ex-ante* assessment will be carried out, which looks ahead and seeks to discuss socio-economic as well as environmental effects of plant breeding for alfalfa in the EU until 2030 and 2040 also considering the EU's "Farm to Fork" and "Biodiversity" strategies with a specific scenario.

Definition of the scenarios for further analysis

The basic scenario

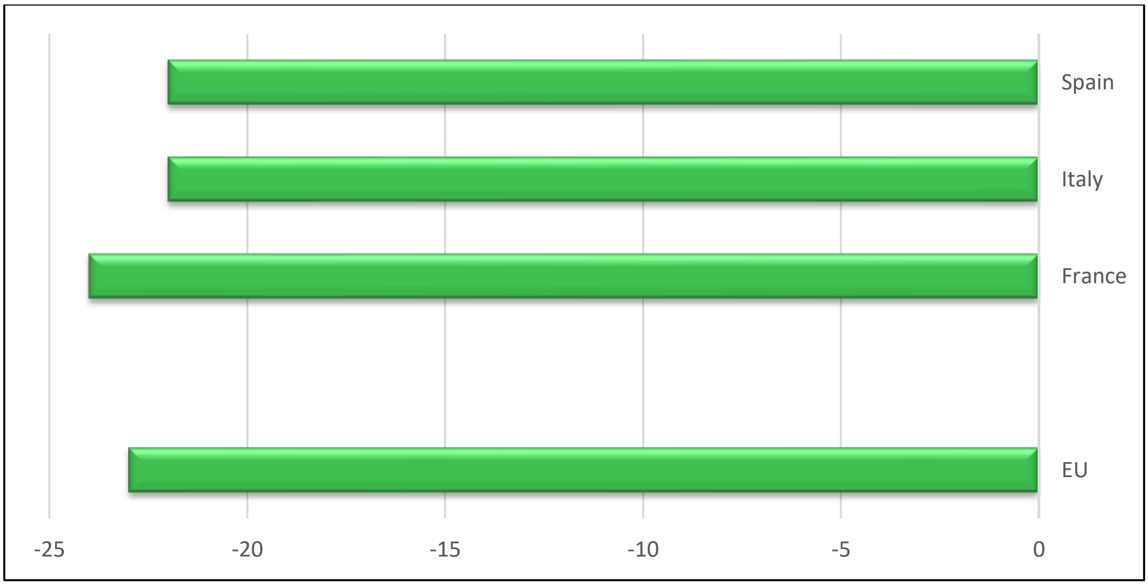
In the following, EC (2020c) and more particularly respective data on green fodder is used to forecast alfalfa market developments until 2030 and 2040 and to define the market environment by then. Accordingly, the specific market in the EU in total and its member states until 2030 (2040) is projected to not change in terms of supply, net trade, and prices.

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

The two strategies (see EC, 2020a; b) aim at considerable changes along the 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. This particularly applies to a crop such as alfalfa, which has a rather "tiny" importance for arable farming in total and, thus, might be subject to more uncertainty.

Nevertheless, for the purpose of the following analysis, initial regional production cut effects due the two strategies as displayed in figure 3.10 will be assumed.

Figure 3.10: **Assumed alfalfa production cuts in 2030 of a full implementation of the two strategies in the EU and selected member states (in percent)**



Source: Own calculations and figure.

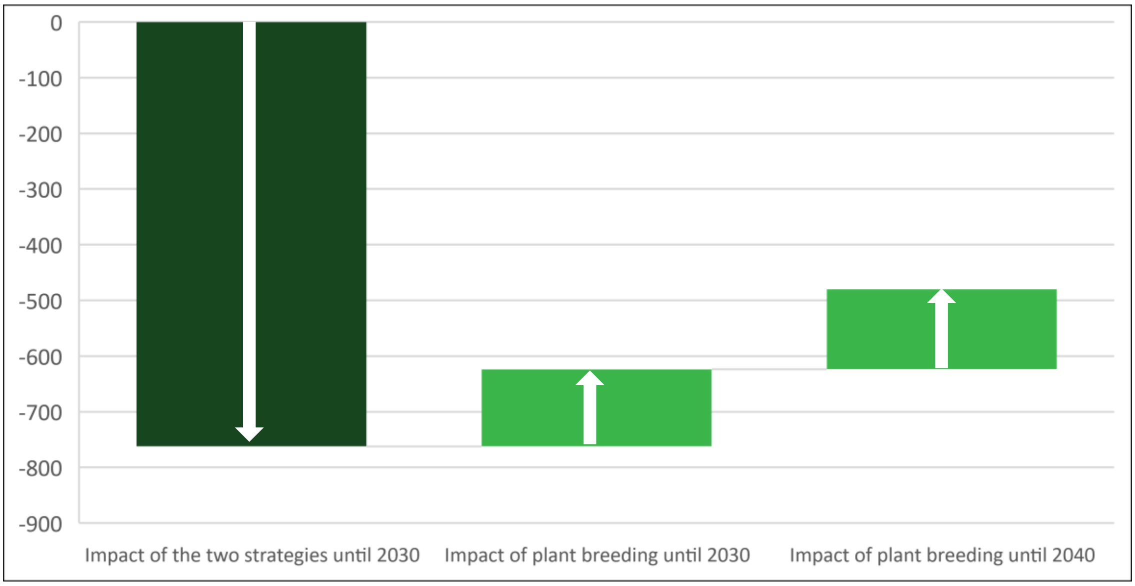
These impacts are the result of four aspects of the two strategies – (1) an inclusion of non-productive land: 10 percent of all agricultural land by 2030, (2) an increase of the area under organic farming: 25 percent of all agricultural land by 2030, (3) a reduction of the use of chemical plant protection products (PPP): 50 percent reduction by 2030 vs. the status quo, and probably mostly irrelevant for alfalfa as a nitrogen-fixing crop (4) a reduction of nitrogen fertilizers: 20 percent reduction by 2030 vs. the status quo – and have been reported in Noleppa and Cartsburg (2021) for green maize (being a green fodder crop). They are included hereafter in the estimates of the potential outcome of implementing the strategies in the alfalfa sector. These scenario definitions and assumptions will now be used, ceteris paribus, to showcase the various socio-economic and environmental benefits in 2030 of alfalfa-related plant breeding progress at current pace between 2020 and 2029 as well as in 2040 of respective plant breeding progress at current pace between 2020 and 2039. Thereby, the various partial benefits of ongoing and future plant breeding activities will be compared with the potential partial impacts of just the production losses due to an enforcement of the two strategies until 2030.

Future socio-economic consequences

Impact on market supply

Using the annualized plant breeding-induced yield growth referring to alfalfa and 2000-2019 (see again figure 3.1) also as a proxy to describe the expectable plant breeding-induced yield growth per year until 2030 and 2040 and the relative production losses due to the two strategies until 2030 (see again figure 3.10), figure 3.11 visualizes the comparison of the partial impacts – all other factors being constant – on alfalfa market supply for the EU in total.

Figure 3.11: **Comparing and balancing partial market supply effects of the two strategies until 2030 with alfalfa plant breeding until 2030 and 2040 in the EU (in 1 000 tons)**



Source: Own calculations and figure.

As can be seen by looking at figure 3.11, the potential plant breeding-induced additional market supply in 2030 and also in 2040 will be considerably lower than the market supply loss that can be attributed in the year 2030 to the full implementation of the two strategies (as defined above) for the EU in total. In other words: Plant breeding for alfalfa at current pace is by far not enough to compensate when referring to the scenario defined above.

A similar conclusion can also be drawn with respect to the three selected EU member states as figure 3.12 displays. However, in France at least 20 years of future alfalfa-related plant breeding progress will potentially be enough to substantially compensate for market supply losses embedded in the enforcement of the two strategies until 2030 in this EU member state.

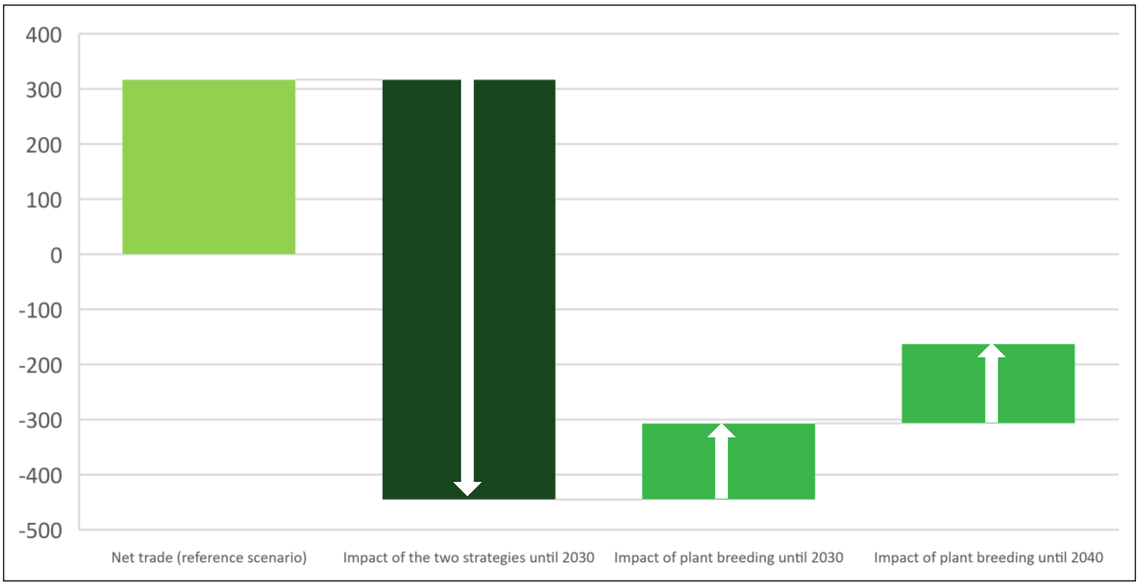
Figure 3.12: Partial market supply effects of the two strategies until 2030 as well as of alfalfa plant breeding until 2030 and 2040 in the EU (in 1 000 tons)

Impact of ...	EU	FR	IT	ES
Two strategies 2030	-762	-183	-169	-312
Plant breeding 2030	138	68	15	14
Plant breeding 2040	283	143	30	29

Source: Own calculations and figure.

Impact on net trade

Figure 3.13: Comparing and balancing partial net trade effects of the two strategies until 2030 with alfalfa plant breeding until 2030 and 2040 in the EU (in 1 000 tons)



Source: Own calculations and figure.

Changing market supply does affect trade volumes. The resulting changes (again in terms of the potential EU-extra trade incorporating the basic scenario as well as the implementation of the two strategies) in the case of missing plant breeding progress as regards alfalfa between 2020 and 2030 (2040) for the EU in total are depicted in figure 3.13 above.

Starting with a forecasted net trade balance in 2030 of approximately 310 000 tons of alfalfa, the implementation of the two strategies until then – ceteris paribus – would lead to a switch from a net export to a net import situation for the EU in total. More than 400 000 tons of alfalfa would have to be net imported then. This devastating partial trade impact cannot fully be compensated through plant breeding for alfalfa at current pace until 2030. Still a net import situation would be the most likely outcome in one and even two decades from now. By 2040, the trade balance being the result of an aggregated effect of the three displayed partial impacts would indicate a net alfalfa import of still more than 150 000 tons.

Impact on food availability

Again, it shall be noted that alfalfa is not used for human consumption. Hence, such an analysis will not be included into this study.

Impact on market prices

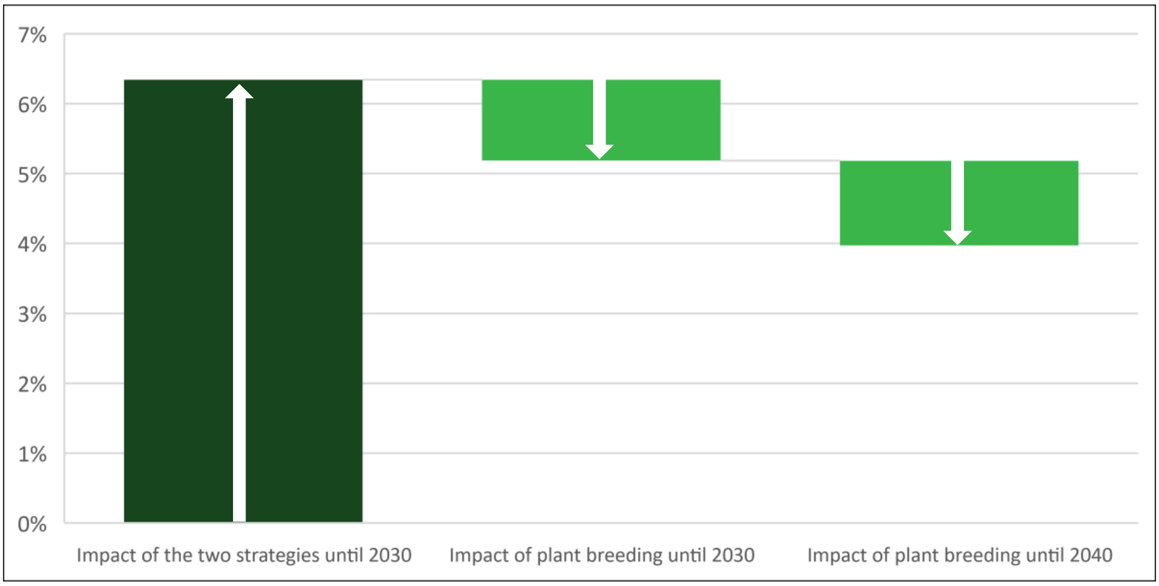
It has already been stated above that a rather high market supply volume with plant breeding does not only create a benefit in terms of the trade balance, but additionally enables consumers in the EU and around the globe to buy agricultural raw materials at affordable prices. Against this background, figure 3.14 below displays the alfalfa market price effects of plant breeding until 2030 and 2040 in the EU and sets these impacts into perspective by comparing them with respective impacts that can be attributed to a full implementation of the two strategies.

It turns out that a full implementation of the "Farm to Fork" and "Biodiversity" strategies (as defined above) would increase the market price for alfalfa until 2030 by approximately 6.3 percent. Plant breeding progress between 2020 and 2029 has the potential to partially counteract this development as the partial effect will be able to "delete" 1.2 percentage points of this price increase due to the strategies. By 2040, thanks to altogether 20 additional years of plant breeding for alfalfa at current pace, the strategies-related price increase might be further reduced. However, still a net price decrease of 4.0 percent might occur.

Impact on sectoral income

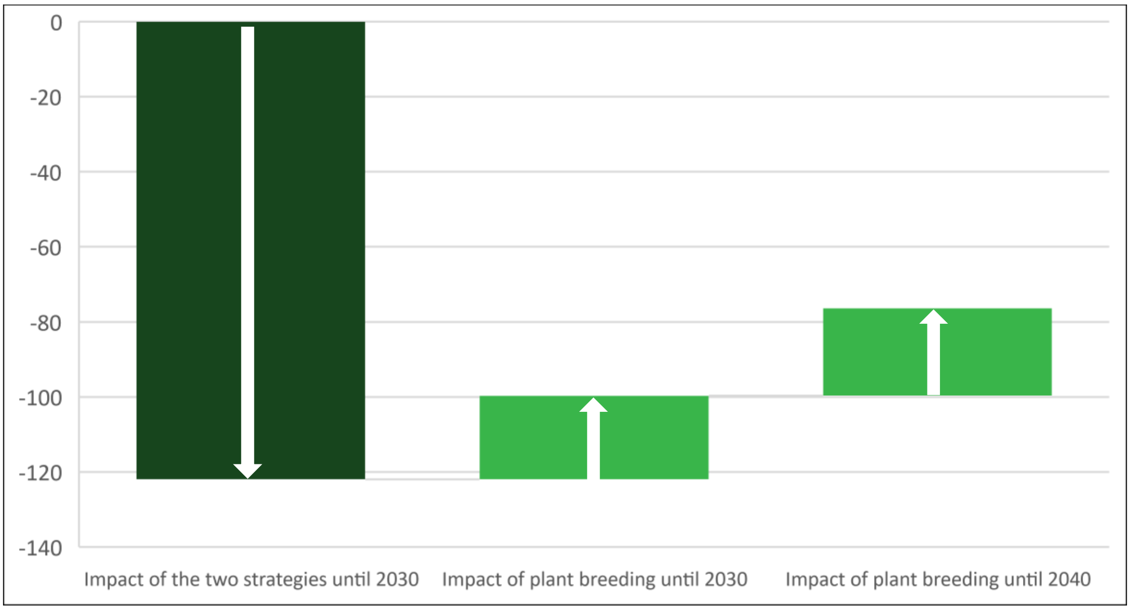
The future social welfare effects being a proxy for the agricultural income generated by future plant breeding activities until 2030 and 2040 as well as by the enforcement of the two strategies until 2030 with respect to alfalfa are now listed in figure 3.15 for the EU in total, while figure 3.16 provides more detailed information on the sectoral income effect also for the selected three EU member states.

Figure 3.14: Comparing and balancing partial market price effects of the two strategies until 2030 with alfalfa plant breeding until 2030 and 2040 in the EU



Source: Own calculations and figure.

Figure 3.15: Comparing and balancing partial sectoral income effects of the two strategies until 2030 with alfalfa plant breeding until 2030 and 2040 in the EU (in million EUR)



Source: Own calculations and figure.

Looking at figure 3.15, it can be stated that a negative sectoral income effect can be associated with the full implementation of the "Farm to Fork" and "Biodiversity" strategies and the subsequent production losses. In fact, it can be shown that the two strategies would lead to a partial sectoral (alfalfa-related) income loss of more than EUR 120 million. Plant breeding progress with respect to alfalfa until 2030 will have the potential to partly compensate this loss (with an additional sectoral income of approximately EUR 20 million), and in 2040, a net loss (of more than EUR 75 million) will still have to be envisaged if the aggregated effects of incorporating the partial impacts of an enforcement of the two strategies on the one hand and plant breeding progress at current pace between 2020 and 2039 on the other hand are combined.

This – an aggregated negative sector income impact until 2040 – also applies to alfalfa production and breeding in all the three selected EU member states, as figure 3.16 shows.

Figure 3.16: Partial sectoral income effects of the two strategies until 2030 as well as of alfalfa plant breeding until 2030 and 2040 in the EU (in million EUR)

Impact of …	EU	FR	IT	ES
Two strategies 2030	-122	-32	-21	-16
Plant breeding 2030	22	12	2	1
Plant breeding 2040	46	25	4	2

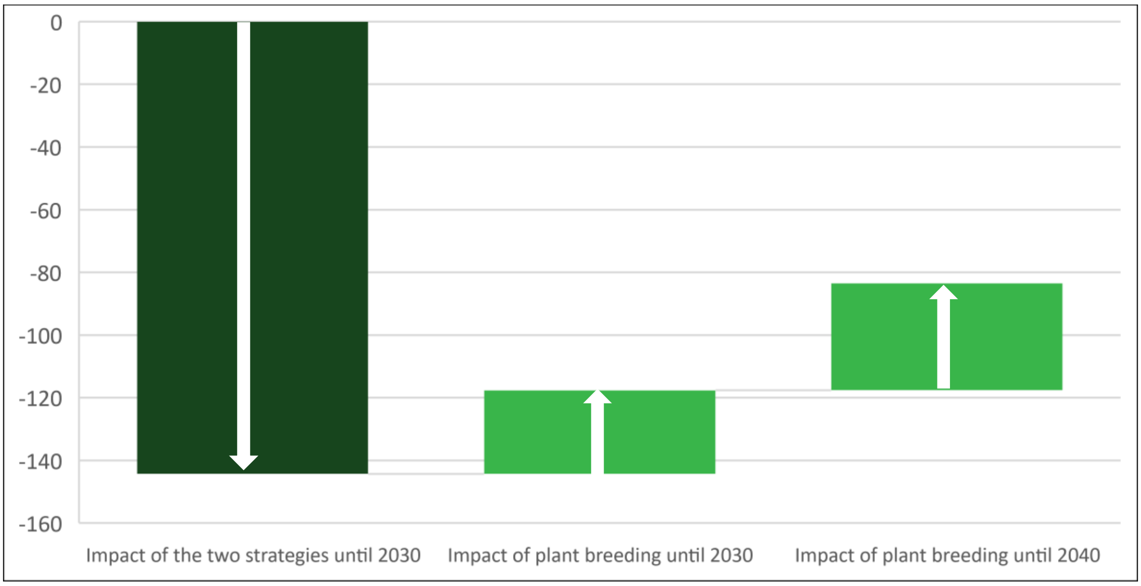
Source: Own calculations and figure.

Impact on GDP

It has already several times been stated above: Plant breeding does not only benefit the primary agricultural sector but the society in total as it creates an economic value upstream and downstream the value chain. This tends to increase the generation of income in other sectors. Therefore, the producer surplus additionally generated through plant breeding being a substantial part of the future societal welfare (or sectoral income) effect displayed in figure 3.15 and figure 3.16 must be linked to GDP multipliers as described in Noleppa and Cartsburg (2021). Accordingly, figure 3.17 gives an overview on the various partial impacts discussed in this chapter for alfalfa and the EU in total, while figure 3.18 provides the region-specific results in detail.

As in the case of the analysis regarding 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 with respect to alfalfa will not have the potential to compensate the negative GDP impact of the two strategies until 2030 and 2040. This becomes obvious by looking at figure 3.17. The full implementation of the two strategies – as defined above – would lead to a GDP loss of more than EUR 140 million. Plant breeding progress until 2030 has only the potential to reduce this loss by almost EUR 30 million. In 2040, the GDP loss attributable to the two strategies would potentially be counteracted by approximately EUR 60 million due to plant breeding for alfalfa in the next two decades. This is less than half the loss attributable to an enforcement of the two strategies.

Figure 3.17: **Comparing and balancing partial GDP effects of the two strategies until 2030 with alfalfa plant breeding until 2030 and 2040 in the EU (in million EUR)**



Source: Own calculations and figure.

A negative GDP impact until 2040 on aggregate can also be stated with respect to alfalfa production and breeding in the three selected EU member states being in the focus here, as figure 3.18 shows.

Figure 3.18: **Partial GDP effects of the two strategies until 2030 as well as of alfalfa plant breeding until 2030 and 2040 in the EU (in million EUR)**

Impact of ...	EU	FR	IT	ES
Two strategies 2030	-144	-43	-29	-23
Plant breeding 2030	27	16	3	1
Plant breeding 2040	61	33	5	2

Source: Own calculations and figure.

Impact on farm income and labour

It shall be repeated here that in opposite to Noleppa and Cartsburg (2021), the farm income and labour impacts of plant breeding for alfalfa cannot be carried out due to missing publicly available farm level data.

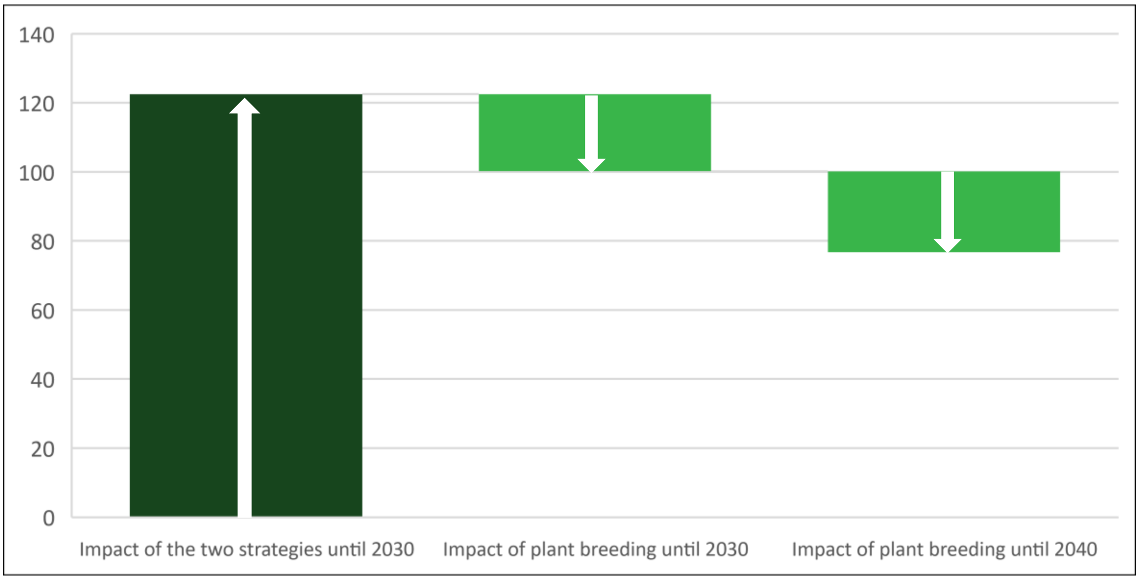
Future environmental effects

Before the environmental effects are also discussed for the future alfalfa scenarios in more detail, it shall be reiterated that the methodology to obtain the various results does not allow to derive results for specific EU member states due to data restrictions mentioned above. Hence, only impacts with respect to the EU in total are discussed in the following.

Impact on virtual land trade

Obviously, alfalfa-related plant breeding activities from now would also increase the EU-extra exports and/or decrease the EU-extra imports in future. This contributes to a positive net trade balance (see again figure 3.5), whereas the full implementation of the two strategies potentially leads to a worsening of the net trade balance. This has implications for the net virtual land trade of the EU that can be attributed to alfalfa (see also figure 3.7). The net virtual land trade effect of future plant breeding for alfalfa in the EU can again be compared with the specific impact which would result from a full implementation of the "Farm to Fork" and "Biodiversity" strategies. Figure 3.19 shows the result and firstly indicates that the partial effect of the strategies would be to use 120 000 hectares more land abroad to satisfy global alfalfa demand with production losses here due to an enforcement of the two strategies. Figure 3.19 secondly signals that this negative environmental effect can partly be compensated due to plant breeding in the next one (two) decade(s) by more than 22 000 (45 000) hectares with alfalfa plant breeding at current pace between 2020 and 2029 (2039). However, the net effect of the partial future developments, if added, would still indicate an additional land use of almost 80 000 hectares at global scale.

Figure 3.19: **Comparing and balancing partial net virtual land effects of the two strategies until 2030 with alfalfa plant breeding until 2030 and 2040 in the EU (in 1 000 hectares)**



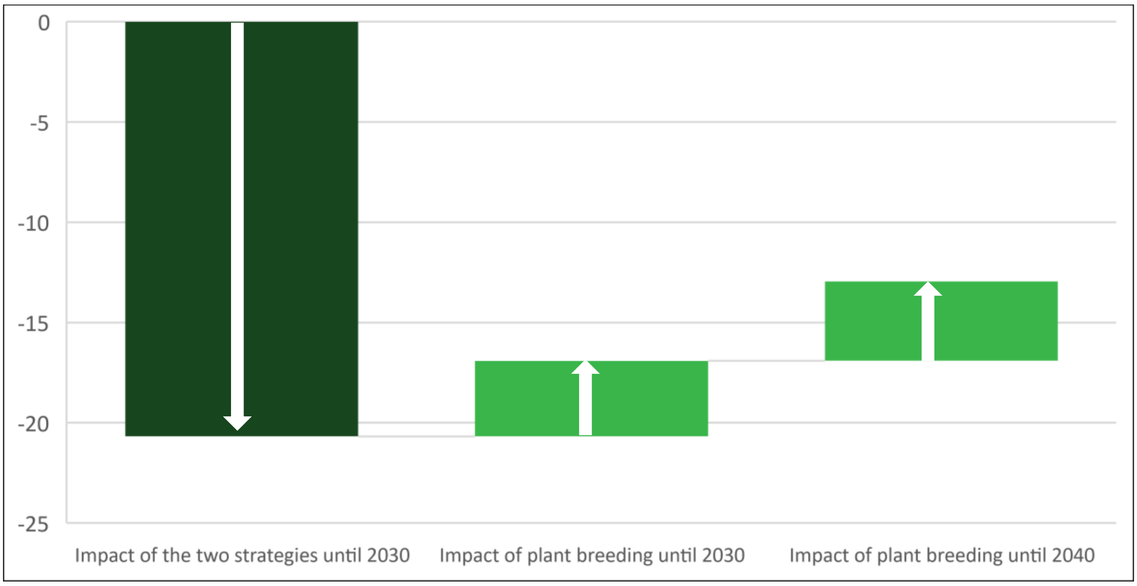
Source: Own calculations and figure.

Impact on GHG emissions

The arable land additionally needed at global scale without plant breeding for alfalfa in the EU in the next two decades will again not be available *per se* but would need to be converted from non-agricultural habitats still sequestering carbon. A substantial part of this carbon would be released into the atmosphere in the form of mainly CO_2 if the land was to be used for farming. 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 alfalfa demand.

The partial GHG emission effects from respective land use changes of the two strategies on the one hand and future alfalfa-related plant breeding progress in the EU on the other hand are visualized in figure 3.20.

Figure 3.20: **Comparing and balancing partial GHG emission effects of the two strategies until 2030 with alfalfa plant breeding until 2030 and 2040 in the EU (in million tons)**



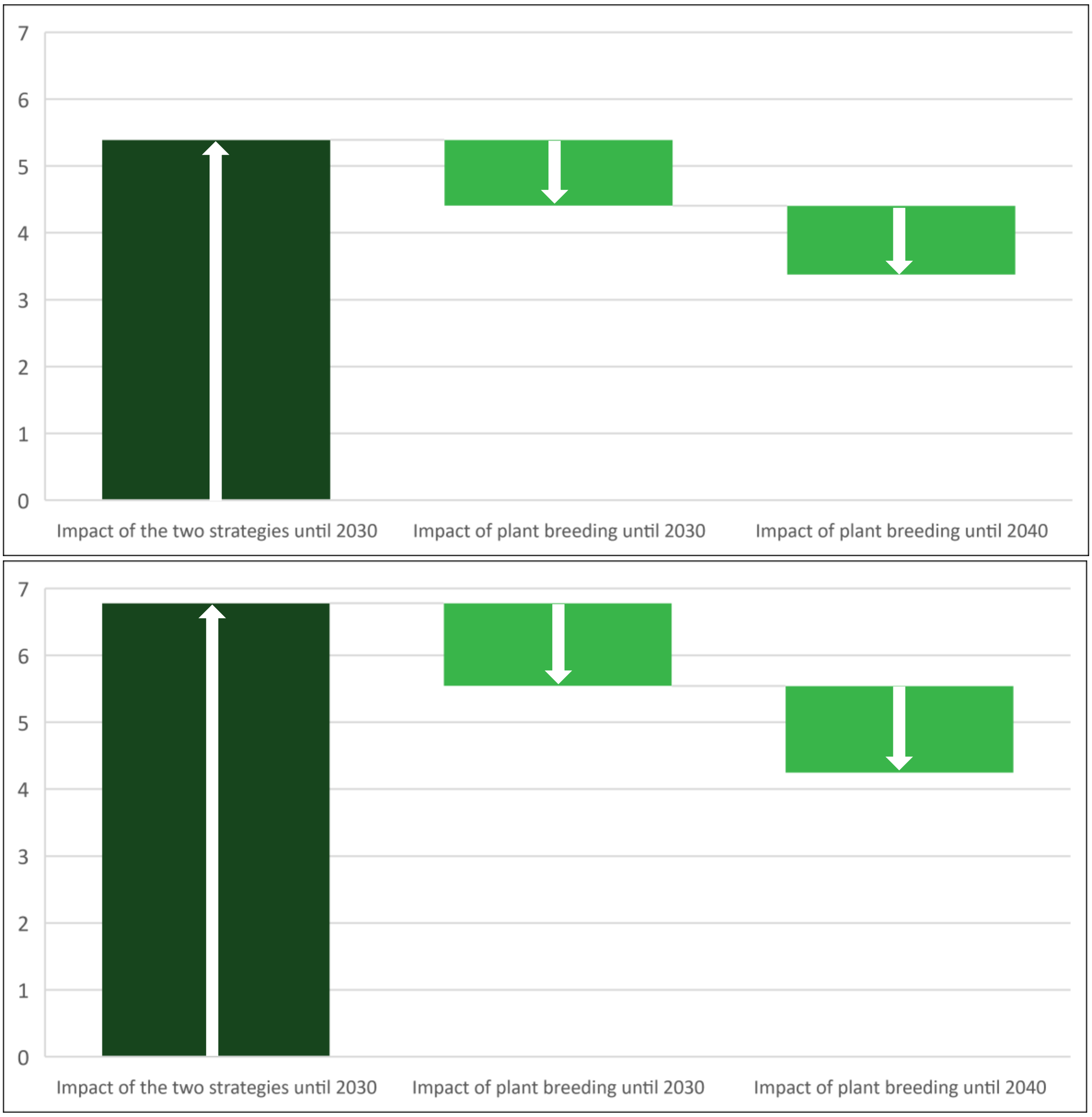
Source: Own calculations and figure.

It turns out that an enforcement of the two strategies would potentially cost more than 20 million tons of GHG emissions measured in terms of CO_2 equivalents which can be related to the alfalfa farming sector. Only in part, this potential extra emission can be reduced by alfalfa-related plant breeding in the next two decades. Even 20 years of these EU plant breeding efforts would only allow to compensate 7.7 million tons of these GHG emissions. Hence, a net emission of approximately 13 million tons of GHG would have to be envisaged until 2040 on balance if the discussed partial effects are aggregated.

Impact on biodiversity

Repeating that future plant breeding efforts as regards alfalfa in the EU will avoid a conversion of natural or nature-like habitats, while the implementation of the two strategies as defined above acts in exactly the opposite way, it is also worth quantifying the associated potential biodiversity effect of respective future developments based on the two methods outlined above. The results of the separate analyses for the EU in total are depicted in figure 3.21.

Figure 3.21: **Comparing and balancing partial biodiversity effects based on the GEF-BIO (above) and NBI (below) of the two strategies until 2030 with alfalfa plant breeding until 2030 and 2040 in the EU (in million points)**



Source: Own calculations and figure.

Based on the GEF-BIO (NBI), approximately 5.5 (more than 6.7) million biodiversity points attributable to alfalfa farming would be lost by an implementation of the two strategies in the EU in the next decade on top of what will most probably be lost in terms of global species richness anyway due to other reasons. This is equivalent to the biodiversity currently found in 55 (67) million hectares of Brazilian (Indonesian) ecosystems. Only a minor part of this loss can be compensated through alfalfa-related plant breeding in the next two decades. In the case of combining the partial effects, a net loss of approximately 3.5 (4.3) million biodiversity points must potentially be envisaged.

Impact on water use

Analyzing the impact of alfalfa plant breeding in the EU on global water demand is again not possible since the crop is unfortunately not covered by the global water footprint data base used in Noleppa and Cartsburg (2021).

4 Case study analysis: *Phytophthora*-resistant tomato

At a global scale, the most important vegetable crop is *Solanum lycopersicum*, better known as tomato (Chaudhary and Atamian, 2017). As such, tomatoes have diverse positive qualities that make it attractive for consumers as well as outdoor and indoor growing around the year - the crop has a high nutritional value, enables potentially high yields, has a rather short life cycle, and many partially very diverse varieties and cultivars are available. In recent years, around 180 million tons of tomatoes have been produced worldwide (FAO, 2021). Major global producers are China, India, the United States of America, Turkey, Egypt, and Iran (Pirondi et al., 2017). However, the EU is also important as each tenth tomato is harvested here. Among the EU member states, Italy and Spain play a particular role in tomato production: 33 percent and 29 percent respectively of all EU tomatoes are produced in these two countries. Together with France, these three EU member states being in the focus of this study alone account for more than 11.0 million tons of tomatoes, i.e., for two thirds of the domestic supply of this vegetable crop (FAO, 2021).

While various abiotic stress factors, like salinity and drought, can pose serious challenges to the cultivation of tomatoes (Cui et al., 2018), there are in addition several major biotic stress factors that require tomato farmers to find suitable preventive and reactive measures. In fact, it is estimated that around 200 diseases do exist that can have negative effects on the growth of the tomato plant and that are caused by fungi, bacteria, viruses, insects, and/or nematode pests. Among them, the most common as well as challenging disease is the so-called late blight caused by the foliar oomycete *Phytophthora infestans*. Being able to complete its disease cycle within just a few (often fewer than five) days, the specific pathogen produces approximately 300 000 sporangia per day and can, thus, quickly infect the mainly aboveground parts of the plant leading to – among others – leaf and stem necrosis, fruit rot and finally also plant death (Chaudhary and Atamian, 2017; Pirondi et al., 2017).

Phytophthora infestans also infects other plants belonging to the nightshade family, for instance potatoes. Hence, also the Great Famine in Ireland between 1845 and 1849, that caused around one million deaths in the country, was a result of the yield depressing effect of late blight being a "new" disease at that time for which little relevant crop management techniques were available for famers (Nowicki et al., 2012). Still today, the disease can lead to a crop loss of up to 100 percent, and this particularly applies to tomato if affected (see, for instance, Nowicki et al., 2012; Cooke et al., 2012; Pirondi et al., 2017).

In any case, the effects on fruit quality, yield reduction and resulting economic losses are severe if no appropriate control is accessible to the farmer. Yet, different agricultural practices can support the farmer to control the effects of the disease. As Damicone and Brandenberger (2016) stress: All available methods must be integrated into an overall management strategy, which includes amongst others cultural practices[2], the use of chemicals as well as the planting of disease-resistant varieties. However, so far, chemical control measures have been the main tool to tackle the disease at global scale (Pirondi et al., 2017).

In fact, fungicides are available for the proper management of late blight on tomato. Protectant as well as penetrant fungicides are an optional choice, the former one being applied before the presence of the disease, while the latter one has the capacity to fight the disease when it already appeared on the plant. However, the risk of penetrant – or also called curative or therapeutic – fungicides is to lead to the development of resistance of pathogens toward the chemicals[3]. Hence, fungicide applications should be made prior to infection when environmental conditions favour the disease to be most effective. In fact, late blight progresses very quickly under humid conditions, particularly when accompanied by cool temperatures plus rain, heavy dew, and/or fog (McGrath, 2019)[4].

Against this background, McGrath (2019) also states that late blight is most effectively managed with practices implemented before the disease starts to develop, or at the first sign. In this regard, the selection of resistant varieties is also a proper strategy for managing the disease since with fungi-resistant or more particularly *Phytophthora*-resistant varieties the management practice is in place before late blight starts to develop. Damicone and Brandenberger (2016) even argue that

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[2] An important cultural practice is to use commercial seed that has been thoroughly dried since seed infection is very unlikely then. Tomato transplants shall also be inspected for late blight symptoms prior to purchase and/or planting. If infections are found in a few plants within a field, infected plants should be removed, disced-under, or killed to avoid spreading through the entire field (Johnson et al., 2016).

[3] Due to the very targeted killing of specific enzymes or proteins of the fungi, already small changes of the pathogen can lead to less or an even complete stop of effective fungicide application (Pirondi et al., 2017).

[4] Because late blight disease development is so dependent on weather, also disease forecasting programmes have been developed to estimate when the pathogen is most active. The programmes use temperature, humidity, and rainfall data to determine whether a fungicide application is necessary or not. This may save several fungicide sprays per season while still providing good disease control (Johnson et al., 2016).

planting disease-resistant varieties could most likely be considered the most effective and economical method of disease control in tomato production.

However, a specific task must be considered in this respect. Tomato plants are constantly challenged by new pathogens and pest races or strains that can overcome the defence mechanisms of the crop. Regarding late blight, several studies could show that numerous severe epidemics could be associated with the emergence of "new" races of *Phytophthora infestans* with respective host resistance (Pirondi et al., 2017). Thus, the development of technologies that support to overcome such resistance breaks are now in the focus of current agricultural research (Chaudhary and Atamian, 2017)[5]. According to the author, genome-editing technologies can be a powerful tool to enhance plant resistance of tomato crops.

In fact, NPBT introduce new options to speed up these developments in the tomato sector. The CRISPR/Cas9 technology, for instance, was first applied in tomato already in 2014 and has since then been applied to overcome viral, fungal, and bacterial infection. It is particularly argued by Wang et al. (2019) that respectively bred immunity remained active across multiple generations, thereby indicating the utility of the CRISPR/Cas9 system for cultivating durable disease-resistant and environmental adaptive crops (see also Borelli et al., 2018).

In light of the high risk of resistance development against fungicides by *Phytophthora infestans* (see above) and the long timeframe for the approval of new active substances in the EU (and beyond), Pirondi et al. (2017) indeed argue that current research on NPBT have great chances to improve the management strategies of the disease and to minimize the risk of the development of resistant strains. Not surprisingly, such research efforts have clearly increased since late blight has become of growing significance for tomato cultivation, and significant progress could already be made with respect to the sequencing of the tomato gene and the developing of tomato breeding lines and hybrid cultivars with multiple late blight-resistant genes (see also Zhang et al., 2014)[6]. All in all, the scientific community has great hopes to apply CRISPR/Cas9 and other NPBT as successful tools for tomato crop improvement breeding – with the special focus, of course, on resistance breeding - to address the challenge of late blight (Cui et al., 2018).

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[5] Considering this, an additional challenge should be mentioned: So far, even a resistant variety will quite often show some late blight symptoms when conditions are highly favorable for the disease. In fact, levels of resistance vary between cultivars and may be more or less effective depending on the *Phytophthora infestans* clonal lineage present.

[6] NPBT do not only contribute or are expected to further contribute to breeding resistances against biotic stress factors such as *Phytophthora infestans* but are also considered to improve the fruit quality of the tomato including its size. In this regard, the application of the CRISPR/Cas9 technology has already successfully been applied to breed tomatoes that are larger in size, to enhance tomato fruit quality, as well as the shelf life of tomato plants (Wang et al., 2019; Li et al., 2018). Also, the cultivation of yellow, pink and purple tomatoes has been undertaken by scientists with the support of NPBT. Since colour and texture do play a role with respect to the consumer choice, such quality criteria matter as regards the sales options at a given market (Wang et al., 2019).

Despite first success stories, it is still too early to precisely determine the (potential) magnitude of impacts *Phytophthora*-resistant tomato varieties will have in future. However, expectations are high. Wang et al. (2019), for instance, state that NPBT will be able to revolutionise the improvement of tomato. Against this background and following Nowicki et al. (2012), the impact of Phytophthora-resistant tomato varieties may be measured in terms of yield and production costs, at least. Accordingly, approximately 7.0 percent of harvestable tomatoes can be considered having been subject to losses caused by *Phytophthora infestans* in the past two decades at broader regional scale[7] – despite the use of proper fungicides and already available fungi-resistant varieties via conventional breeding techniques. According to the authors, additional yield losses could only be avoided through higher fungicide applications: an increase by 25 percent and more seems plausible. Following Huub et al. (2019), six to ten fungicide applications per season have been carried out in recent years in tomato production to control the disease. Taking an average of eight applications, breeding for Phytophthora-resistant tomato varieties could thus lead to the saving of two (25 percent) fungicide applications per year.

On farm level, the successful meeting of these expectations – 7.0 percent avoided yield losses and 25 percent less fungicide use – linked to *Phytophthora*-resistant tomato varieties might create income improvements for tomato farmers in France, Italy and Spain as depicted in figure 4.1 using the resulting net margin (or farm profit) as a proper income indicator[8]. As can be seen, the farm income will potentially increase in all three cases. This is due to a higher market revenue (triggered by the increasing yield) and lower production costs (caused by using less fungicides[9]).

The country-specific income increases are as follows: In France, the net margin (being the result of subtracting all variable and fixed costs from market revenues excluding governmental transfer payments) will potentially increase from 2 548 EUR per hectare to 3 527 EUR per hectare if *Phytophthora*-resistant tomato varieties become available and provide the above-mentioned benefits. Accordingly, the farmer's income from tomato production would increase by 38 percent in this EU member state. In Italy, the farm income increase from tomato production would be 44 percent since the net margin in the reference system of 1 487 EUR per hectare will potentially increase by 660 EUR per hectare with a *Phytophthora*-resistant tomato variety. And in Spain, where in the reference system a net margin of 1 530 EUR per hectare can be generated with tomato production, the future use of *Phytophthora*-resistant tomato varieties might potentially be able to create a net margin of 2 239 EUR per hectare, which is equivalent to an income increase of 46 percent for a typical tomato-producing farmer in the country.

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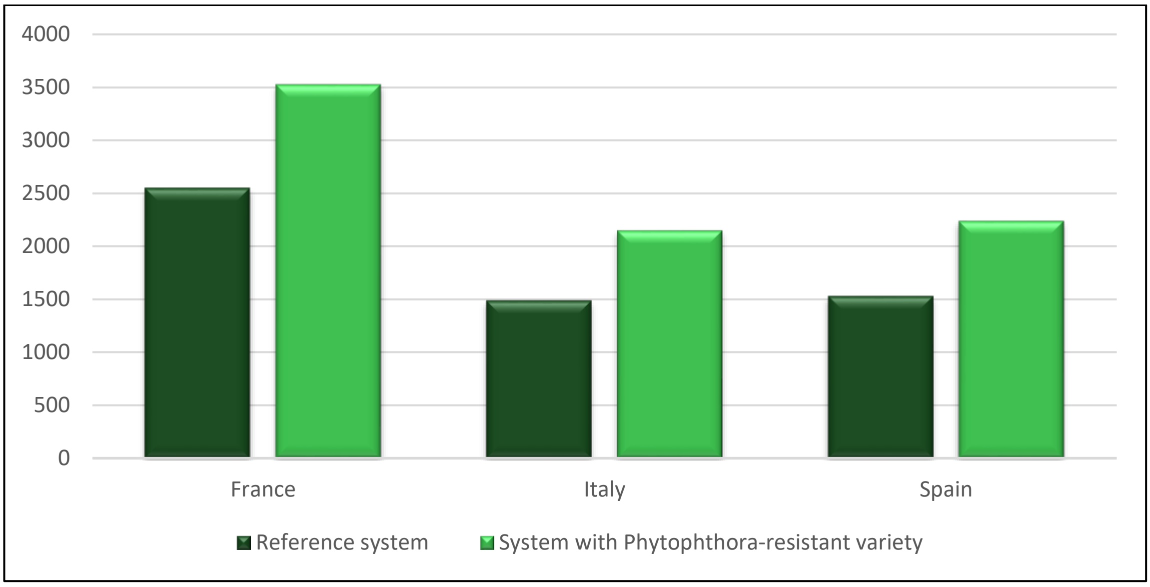
[7] If affected, losses of 12 to 100 percent have occurred on local scale.

[8] To determine the underlying market revenues and production costs, yield and price data as well as information on production costs were obtained from Agri Benchmark (2021), DG Agri (2021), EC (2020d) and Chiffoleau et al. (2015) and cross-checked by using FAO (2021) and Capobianco-Urlate et al. (2021).

[9] Changing seed costs are not considered hereafter as the past has not provided sufficient evidence for remarkable specific cost changes that should be related to resistant tomato varieties.

Figure 4.1: **Net margins of tomato production at the level of a typical farmer in France, Italy, and Spain without and with a *Phytophthora*-resistant variety developed through NPBT (in EUR per hectare)**



Source: Own calculations and figure.

Finally, the net effect of potentially using *Phytophthora*-resistant tomato varieties in future on fungicide applications in the three selected EU member states as well as in the EU in total shall be highlighted. The results are displayed in figure 4.2 based on the assumption that in the reference system eight fungicide applications per hectare and year are necessary and 25 percent less in the future system with *Phytophthora*-resistant tomato varieties. Thereby, FAO (2021) is used to determine the area for cultivating tomato. As can be seen, it turns out that at a European scale, more than 300 000 hectare-based applications of fungicides can potentially be avoided in future if *Phytophthora*-resistant tomato varieties developed through NPBT become available. This should be considered a specific environmental benefit of using such new and innovative techniques on top of what modern plant breeding is already able to provide.

Figure 4.2: **Number of applications of fungicides in tomato production in France, Italy, and Spain as well as the EU in total without and with a *Phytophthora*-resistant variety developed through NPBT**

	EU	FR	IT	ES
Reference system	1 266 656	30 400	500 880	301 520
System with *Phytophthora*-resistant variety	949 992	22 800	377 160	226 140
Change	*-316 664*	*-7 600*	*-123 720*	*-75 380*

Source: Own calculations and figure.

5 Conclusions and recommendations

This research shall be considered an addendum to previous research (Noleppa and Cartsburg, 2021) and as such also aims at analysing if and to what extent plant breeding in the EU contributes to increased yields and production and subsequently also to improved market and trade conditions, increased food supply, higher economic prosperity and increased social welfare, additional farm income, lower land use, reduced GHG emissions, preserved biodiversity, and the saving of water as well as PPP. The focus is thereby on tomato and alfalfa as well as on France, Italy, and Spain.

Again, it turns out that plant breeding-induced innovations in these two crop sectors and EU member states count a lot. With plant breeding for tomato and alfalfa in the past two decades not only yields per hectare have increased, but also arable production. Moreover, the higher yields per hectare have increased the supply of primary agricultural products on international markets. This has contributed to stabilising markets and reducing price volatility and has additionally improved the agricultural net trade balance. Specifically, plant breeding for tomato also improved food availability. Furthermore, plant breeding for the two crops has generated additional economic prosperity by increasing farm income and the GDP. The entire agricultural value chain from input suppliers to final consumers have benefited.

Plant breeding for tomato and alfalfa in the EU and the selected EU member states in the past two decades has not only brought about positive economic effects, but has also generated substantial environmental impacts. It has particularly helped save scarce land resources around the globe by generating higher yields. Therefore, it can be stated that plant breeding for these two crops has minimised the net virtual land imports of the EU. This has contributed to preserving natural habitats and reducing GHG emissions resulting from an expansion of the global acreage. Plant breeding for tomato and alfalfa, thus, has also secured less GHG being emitted by helping avoid negative land use change. In addition, it has generated a positive biodiversity effect. Finally, crop-specific plant breeding in the EU in the past contributed to saving scarce water resources around the globe.

It can preliminarily be summarised: Plant breeding for tomato and alfalfa in the EU has contributed a lot to yield progress since the turn of the millennium. This has surely created opportunities for the agrarian economy and the rural areas, and has additionally offered various environmental benefits. Looking ahead, this perspective does not change. This allows to condense that successfully innovated genetic crop improvements in the EU with respect to tomato and alfalfa have been and will be essential for economic 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. This does not only apply to plant breeding for major arable crops in general, but particularly to plant breeding for tomato and alfalfa.

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 this respect, a case study on potential impacts of *Phytophthora*-resistant tomato varieties developed through NPBT illustrates on an exemplified base that very specific genetic crop improvements may lead to remarkable partial economic and environmental benefits if successfully implemented. Against this background, also tomato and alfalfa plant breeders should be aware that their efforts have helped and – even more important – can continuously help create synergies and avoid trade-offs embedded in multiple objective settings bridging the economy and environment. This makes plant breeding an important area of research and development (R&D) and also tomato and alfalfa 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 disease resistance, other agronomic traits, product quality, crop adaptation and genetic diversity.

Plant breeders 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. Provided that the EU sees itself as a responsible actor that accepts emerging global and regional challenges in terms of the economy and environment and wants to play its part in meeting them, it follows that these respective considerations must be taken into account in a balanced way when making decisions on NPBT as well. In fact, to also encourage tomato and alfalfa 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 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.

More precisely, a proportionate and result-focussed regulatory framework is needed to establish clear and sustainable rules for the European plant breeding sector including plant breeding for tomato and alfalfa. 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, 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 must focus on the individual technique, how it is used and the characteristics of the resulting product. EU policy makers and regulators should take this into consideration when discussing potential future regulatory options because without accelerating plant breeding in the EU – particularly for the two crops having been in the focus of this study – in the future, the objectives of the "Farm to Fork" and "Biodiversity" strategies and, hence, the European Green Deal can hardly be achieved.

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

An addendum to prior research for tomato and alfalfa

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