The future of crop protection in Europe

Appendix 1 – Overview of current and emerging crop protection practices

STUDY

Panel for the Future of Science and Technology

EPRS | European Parliamentary Research Service
Scientific Foresight Unit (STOA)
PE 656.330 – February 2021

EN

The future of crop protection in Europe

Appendix 1:
Overview of current and emerging crop protection practices

Crop protection in prevailing agricultural systems in the EU is highly dependent on plant protection products (PPPs) to protect plants against harmful weeds, pests and diseases. The use of PPPs is a cause of health, environmental and public concerns, and a key question is whether their use can be reduced while maintaining adequate yields.

This study provides an overview and description of current and new crop protection practices, including mechanical techniques, plant breeding, biocontrol, induced resistance, applying ecological principles, precision agriculture (PA), and emerging plant protection products. The potential and impact of the new crop protection practices is assessed.

It may be feasible to design resilient systems that are economically viable, have limited environmental impact and help improve biodiversity. Diverse cropping systems would have a natural resilience to weeds, pests, and diseases, and potentially reduce the dependency on PPPs, enabled by PA technologies. The main challenge is to integrate new varieties, mechanisation, and biocontrol tools in these systems. Continuous development of all crop protection practices is needed to ensure sufficient control of pests, weeds and diseases.

The drivers and enablers for implementing alternative crop protection practices are identified, and an analysis of key legislation to support their use is presented.

AUTHORS

This study has been written by Marleen Riemens, Bas Allema, Johan Bremmer, Dirk van Apeldoorn, Yuling Bai, Corne Kempenaar, Machiel Reinders and Marcel Wenneker of Wageningen University and Research (WER) at the request of the Panel for the Future of Science and Technology (STOA) under the EPRS/STOA/17/004 framework contract led by VetEffecT and managed by the Scientific Foresight Unit, within the Directorate-General for Parliamentary Research Services (EPRS) of the Secretariat of the European Parliament.

ADMINISTRATORS RESPONSIBLE

Lieve Van Woensel and Nera Kuljanic, Scientific Foresight Unit (STOA)
To contact the publisher, please e-mail stoa@ep.europa.eu

LINGUISTIC VERSION

Original: EN
Manuscript completed in December 2020

DISCLAIMER AND COPYRIGHT

PE 656.330
ISBN: 978-92-846-7685-9
doi: 10.2861/044114
QA-02-21-005-EN-N

http://www.europarl.europa.eu/stoa (STOA website)
http://www.eprs.ep.parl.union.eu (intranet)
http://www.europarl.europa.eu/thinktank (internet)
http://epthinktank.eu (blog)

Executive summary

The world population is growing continuously and will require an ever-increasing supply of food. This can be achieved by using more farmland, but this would be detrimental to the global environment. It can also be achieved by raising crop yields per hectare. Another, complementary, approach is to change dietary habits and consume less animal products, which would release land used for livestock production and make it available for growing crops for direct human consumption.

Half of the total cultivated area in the EU (i.e. all the grassland and grazing, plus 50 % of the cereal area) is used for livestock production. Potentially, at least some of this land could be released from livestock production and used to grow plants for human consumption.

This study report focuses on the use of new, improved, crop protection practices as a means of maintaining the efficiency of food production, while at the same time protecting the environment.

Plant protection products (PPPs) are one of the most effective tools for achieving high crop yields. Herbicides, insecticides and fungicides protect crops against harmful weeds, insects and diseases.

However, there are societal concerns about PPPs, which have led to public debate, various controversies and increased demands for reducing their use. These concerns have been reflected in current EU legislation. A key question is whether the use of PPPs can be reduced, while maintaining or increasing yields. This question relates not only to global crop production, with its wide range in yields; but also to the EU, with its generally high levels of productivity.

EU agriculture still relies on pesticides for crop protection. A transition is needed towards more sustainable farming systems to reduce this reliance. It is suggested that three stages of transition can be distinguished: efficiency, substitution and redesign (the ERS paradigm). Until now, the focus has been on two out of three stages in the transition to sustainability: efficiency and substitution. An increased focus on the redesign of farming systems is needed.

New and emerging crop protection practices covered in this report include mechanical techniques, plant breeding, biocontrol, induced resistance, applying ecological principles, precision agriculture, and new plant protection products. These practices can all contribute to the development of sustainable farming systems, with the greatest impact being achieved when they are used together in the most suitable combinations.

Of the various new and emerging practices, **precision agriculture** is one of the most promising; with benefits on all productivity, sustainability, health and economic indicators. Its use in conventional farming is growing steadily, and further uptake is favoured by two trends in EU agriculture: decreasing numbers of people working on farms, and; increases in the average size of farm holdings. Another factor in its favour is that it may be easier for farmers (particularly large-scale) to incorporate into their existing practices, compared to other emerging techniques. Ease of uptake is likely to be particularly beneficial in the short-term.

An additional benefit of precision agriculture is that it has complementary beneficial effects on the other new and emerging practices, thus justifying the approach of combining various practices.

A potential drawback are the new, non-agricultural skills that farmers need to learn to implement precision agriculture technologies. Secondly, the interoperability of farming equipment needs improvement.
Current EU legislation does not adequately address all the legal, social and ethical considerations raised by developments in precision agriculture.

New **plant breeding** techniques also show widespread benefits for crop protection on all indicators apart from biodiversity, where a neutral impact is indicated. However, there is a need to update EU legislation to cover the latest technical developments in directed mutagenesis (or genome editing), which are potentially safer than earlier techniques of random (or conventional) mutagenesis.

It is also necessary to address the issue of competitiveness between EU producers and producers elsewhere. Tight regulation of new plant breeding techniques in the EU may put EU farmers at a competitive disadvantage with producers in other countries who are able to export to the EU.

Taking into account the strongly held views of the public on genetically modified organisms (GMOs), the European Commission Group of Chief Scientific Advisors[1] has proposed that the GMO Directive (Directive 2001/18/EC) should be revised to take into account current knowledge and scientific evidence as part of a dialogue with relevant stakeholders and the general public.

Biocontrol is one of just three of the new and emerging crop protection practices with potential to make a positive contribution to biodiversity (the others are 'applying ecological principles' and precision agriculture). Biocontrol entails all methods, tools, measures and agents of plant protection that rely on the use of beneficial organisms as well as their natural mechanisms and interactions. It shows a high potential for improving crop yields and also shows positive impacts for public health and food safety. However, it may be costlier to use than conventional pesticides and there are currently a number of barriers limiting uptake worldwide.

Applying ecological principles shows a strong benefit for biodiversity and also for crop yield per hectare, although the impact on farmer income is likely to be neutral in the short-term due to higher costs. Applying ecological principles increases plant diversity in and around crop fields through methods including crop rotation, green manure, undersowing, hedgerows, mulching and mixed cropping.

All diversification strategies benefit biodiversity, although combined diverse and conventional systems are likely to be the most resilient and bring the greatest environmental and economic benefits.

Induced resistance involves the use of biotic (living) or abiotic (non-living) agents to prime plant defence mechanisms. The practices include soil amendment, seed treatments, foliar spray elicitors and root drench elicitors. This is an emerging area of research and has not yet been adopted as a commercial crop protection practice, but could be beneficial for reducing the need for other crop protection treatments.

---

[1] https://ec.europa.eu/info/news/commissions-chief-scientific-advisors-publish-statement-regulation-gene-editing-2018-nov-13_en

Improved **mechanical techniques** show small positive impacts on public health and food safety, but a negative impact on climate change. Effectiveness may increase when coupled with precision agriculture techniques, such as automated guidance based on global positioning systems (GPS).

New and emerging **plant protection products** show positive (or 'less-negative') benefits for environmental and safety factors in comparison to existing PPPs. This is because new pesticides are safer, due to strict regulation and controls on the way they are used, and they are more specific. Also, they are applied more effectively, due to advances in application technology.

Reduction in their use may be assisted by precision farming techniques, but they are likely to be replaced only when other techniques achieve acceptable levels of yield and food quality.

Drivers and enablers are needed to encourage farmers to adopt alternative crop protection practices – drivers trigger change, enablers facilitate change.

A literature review on policy instruments for reducing pesticide use in Europe (Lee et al., 2019) found that farmers face a number of barriers to reducing their reliance on conventional pesticides. As well as concerns over crop yields, productivity and profitability, "Employing alternative crop protection methods is more time, labour, information and knowledge intensive than conventional farming systems."

Lee et al. (2019) found that behavioural change by farmers depends on them being sufficiently enabled, legitimised, demanded and motivated. When choosing the most suitable drivers and enablers (or mixtures of these instruments) it is necessary to address these change factors, as well as the social, environmental and economic characteristics of the farmers being targeted.

The main **regulatory issues** concerning the adoption of alternative crop protection practices described in this report concern: new plant breeding techniques; the registration of microbial biocontrol agents; privacy and autonomy issues regarding precision agriculture, and; continuous updating of EU legislation regarding plant protection products.

The **main challenge** is to integrate the new varieties, mechanisation, and biocontrol tools in new cropping systems that are enabled by precision agriculture technologies, such as autonomous robots, sensing devices and decision support tools. Breeding programmes take at least 10 to 15 years, the development of a biocontrol agent takes 5-10 years, and designing diversified cropping systems including addressing underlying research questions, will all take significant time. Continuous development of all crop protection practices is needed to better disrupt the life cycle of pests, diseases and weeds, and to improve non-chemical control methods and application of chemical control using intelligent application technologies adapted to local circumstances, including the knowledge and skills of operators.

Table of contents

List of figures

List of tables

1. Introduction

1.1. Context and background

The world population is growing continuously. By the end of the 21st century, it is expected that around 11 billion people will need to be fed. This will require an increase in food production. Growth in food production can be achieved by using more land for farming, and also by increasing yields per hectare.

Extending the area of land used for food production contributes significantly to the loss of biodiversity, which is highly undesirable for the sustainability of the environment. As a consequence, the pressure to improve productivity per hectare increases.

Another – complementary – approach is to change the type of food we eat, essentially by consuming less animal products. This would release land used for animal production to grow crops for direct human consumption. This approach would require significant changes in dietary habits, and may not be universally desirable or feasible. Nevertheless, it seems likely that changes in dietary habits will be an important factor for food supply in the future.

This report focuses on the use of new, improved, crop protection practices as a means of maintaining or increasing the efficiency of food production per hectare, while at the same time protecting the environment.

Plant protection products (PPPs) are among the most effective tools for achieving high crop yields. Herbicides, insecticides and fungicides protect crops against harmful weeds, insects and diseases. However, the use of PPPs is subject to societal concerns because of their possible impacts on human health (of producers, consumers and in some cases bystanders) and the environment (through loss of biodiversity). Recent examples of concerns are debates about the relation between the use of glyphosate and cancer, and the use of neonicotinoids and the decline of pollinators.

These concerns have led to public debate, various controversies and an increased demand for reducing the use of PPPs, which has been reflected in current EU legislation. A key question is whether the use of PPPs can be reduced while maintaining or increasing yields. This question relates not only to global crop production with its wide range in yields, but also to the EU with its generally high levels of productivity.

The concerns were the reason for STOA to organise a workshop 'Farming without agro-chemicals' on 6 March 2019 (STOA, 2019). The aim was to give participants a better understanding of the impact of PPPs on food production and explore the perspectives of different stakeholder groups.

To stimulate further discussion, at the request of STOA, researchers from KU Leuven produced a scientific background report[2]. The report explored whether it is possible to grow plants without using herbicides, fungicides and insecticides. It concluded that a policy aimed at reducing the use of PPPs on its own will have negative trade-offs if the yield reduction is compensated by an expansion of farmland. This would lead to more biodiversity loss.

The report found that, despite the doubling of PPP use since 1980, the environmental impact has been significantly reduced by: application of more strict registration policies; replacement of broad-acting PPPs by more specific PPPs; avoiding impacts on non-target organisms, and; the use

---

[2] https://www.europarl.europa.eu/cmsdata/185760/EPRS_IDA(2019)634416_EN.pdf

of more advanced application technology. Without PPPs, including biopesticides[3], the food security of 11 billion people would be threatened.

Based on the outcomes of the workshop and the scientific background report, STOA commissioned this study to explore options for European farmers to work in a sustainable manner while securing overall food production, preserving biodiversity and supporting farm incomes.

1.2. Objectives

Overall objective

The overall objective of *The Future of Crop Protection in Europe* project is to present an overview of crop protection options for European farmers to work in a sustainable manner while securing overall food production, preserving biodiversity and supporting farmer's incomes.

This overall objective has been divided in four specific objectives. This report addresses the first objective listed below:

Specific objectives

The specific objectives consistent with the foresight approach, are:

- to review and assess current crop protection practices as well as possible alternative crop protection practices;
- to develop (four) scenarios (narratives of the future) based on the review serving the brainstorm about the potential impacts of possible courses of action regarding plant health protection;
- to analyse and report reflections on the public and other stakeholders' perception of the assessed crop protection practices;
- to provide a range of policy options justified by the combination of both the review of crop protection practices and the stakeholder analysis.

Chapter 2 of this report presents the main crops grown in Europe, PPP use on these crops, and potential alternative crops and cultivars.

Chapter 3 provides a description and assessment of existing and emerging crop protection practices.

Chapter 4 identifies drivers and enablers for implementing alternative crop protection practices.

Chapter 5 describes key legislation relevant to current and possible alternative protection practices.

1.3. Data sources

1.3.1. Cultivated area and average yield

Data on the major crops grown in the EU were obtained from the EUROSTAT apro_cpsh1 database[4] and combined for all Member States (MS). For most crops the data was from 2018. Any

---

[3] See Section 3.3 for an explanation of the term biopesticide.

[4] https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=apro_cpsh1&lang=en

gaps were filled with equivalent data from 2015. The data was accessed on 23 April 2020. In some cases, for example cereals, individual species have been grouped under one heading.

Yields are shown in tonnes per hectare (t/ha). Average yields were calculated as the sum of production for a crop species divided by the area cultivated. Cultivation area is expressed in 1 000 ha.

1.3.2. Plant Protection Products data

Eurostat data on sales of pesticides[5] were accessed on 17 June 2020 for the period 2011-2017, and were used to provide figures for the Member States. The data showed that four Member States accounted for two thirds of pesticide sales and more than half of the agricultural land in the EU.

Harmonised Risk Indicators (HRI) for the EU and for these four Member States were used as an indicator for the human health and environmental risks associated with plant protection products. Data on pesticide use per crop is unfortunately lacking.

---

[5] Note that the terms 'Plant Protection Product' (or PPP) and 'pesticide' are used interchangeably in this report. For an explanation of the distinction between the terms, see https://ec.europa.eu/food/plant/pesticides_en

2. Main crops in Europe: PPP use and alternative crops and cultivars

In the following sections, cultivated areas of arable crops, vegetable crops, fruit and nuts, and grapes and olives are shown for the EU. An overview of possible alternative cultivars and crops that are less vulnerable to pests and diseases is presented. Also, developments in plant breeding for these crops are discussed.

Section 2.1 shows the area of crops cultivated in the EU. Section 2.2 shows data on PPP use.

Sections 2.3 - 2.6 provide information on the husbandry practices used to grow arable crops; vegetable crops; fruits, berries and nut crops; and grape and olive crops.

In Section 2.7 the potential impact of alternative crops and cultivars is discussed.

2.1. Cultivated area of crops in the EU

Table 1 shows the total area of the main categories of crops grown in the EU. Temporary grassland and grazing are included in this table for completeness but are not further elaborated on the following sections.

Table 1: Cultivated area of crops in the EU (1 000 ha)

Crop category	Area (1 000 ha)	Area (%)
Arable crops	80 463	74.7
Vegetables	2 027	1.9
Fruits, berries and nuts	3 224	3.0
Grapes	3 034	2.8
Olives	5 092	4.7
Temporary grass and grazing	13 865	12.9
Total	**107 707**	**100**

Source: Eurostat

2.2. Use of Plant Protection Products

2.2.1. Sales of PPPs in the EU

Eurostat provides data on PPP sales per Member State. Regulation (EC) No 1185/2009 requires Member States to provide statistics on placing PPPs on the market and on their use in agriculture.

Statistics on the sale of pesticides have been publicly available on Eurostat since 2011. Data is collected by many Member States, but the completeness and quality of data provided by individual Member States varies between years.

The Eurostat data provide insight on sales of pesticides from 2011 to 2018 (Eurostat, accessed 17 June 2020). Figure 1 shows sales in the EU (in kg of active ingredients) for the different groups of pesticides:

- Fungicides and bactericides;
- Herbicides, haulm destructors and moss killers;
- Insecticides and acaricides;
- Plant growth regulators;
- Molluscicides;
- Other plant protection products.

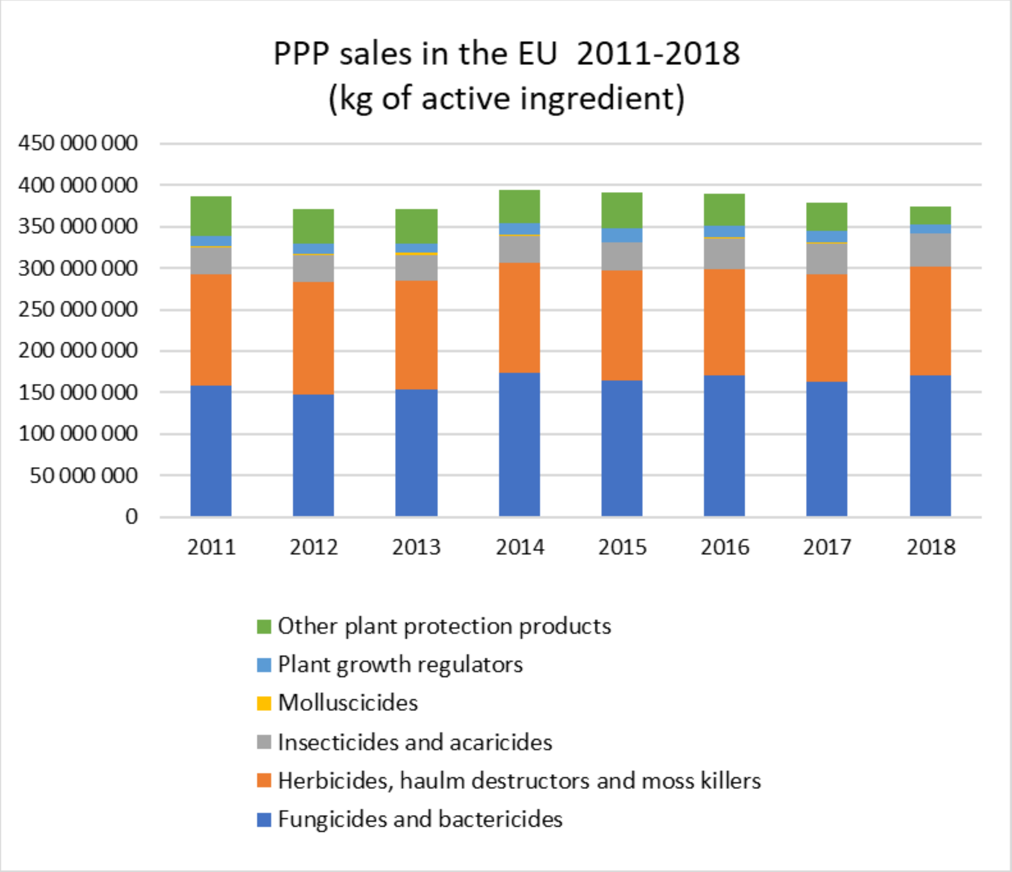


Figure 1. PPP sales in the EU between 2011 and 2018 for different pesticide groups
Source: Eurostat (accessed 17 June 2020)

Figure 1 shows that ‘Fungicides and bactericides’ make up the largest proportion of sales in all years (45 % in the latest year, 2018), followed by ‘herbicides, haulm destructors and moss killers’ (35 % in 2018). ‘Other plant protection products’ was the third largest group from 2011 – 2016 with approximately 10 % of sales, but was overtaken by ‘Insecticides and acaricides’ in 2017 and 2018.

PPP sales (kg of active ingredients) vary significantly between EU Member States. Sales in 2018 for the EU-28 plus Iceland, Norway and Switzerland are shown in Figure 2. Four EU Member States (France, Spain, Italy and Germany) accounted for over two thirds of the total. These four MS are also the main agricultural producers in the EU; together they represent 51 % of the total EU utilised agricultural area and 49 % of the total EU arable land (source: Eurostat).

Differences in PPP use between Member States correlates with differences in crop yield (STOA, 2019).

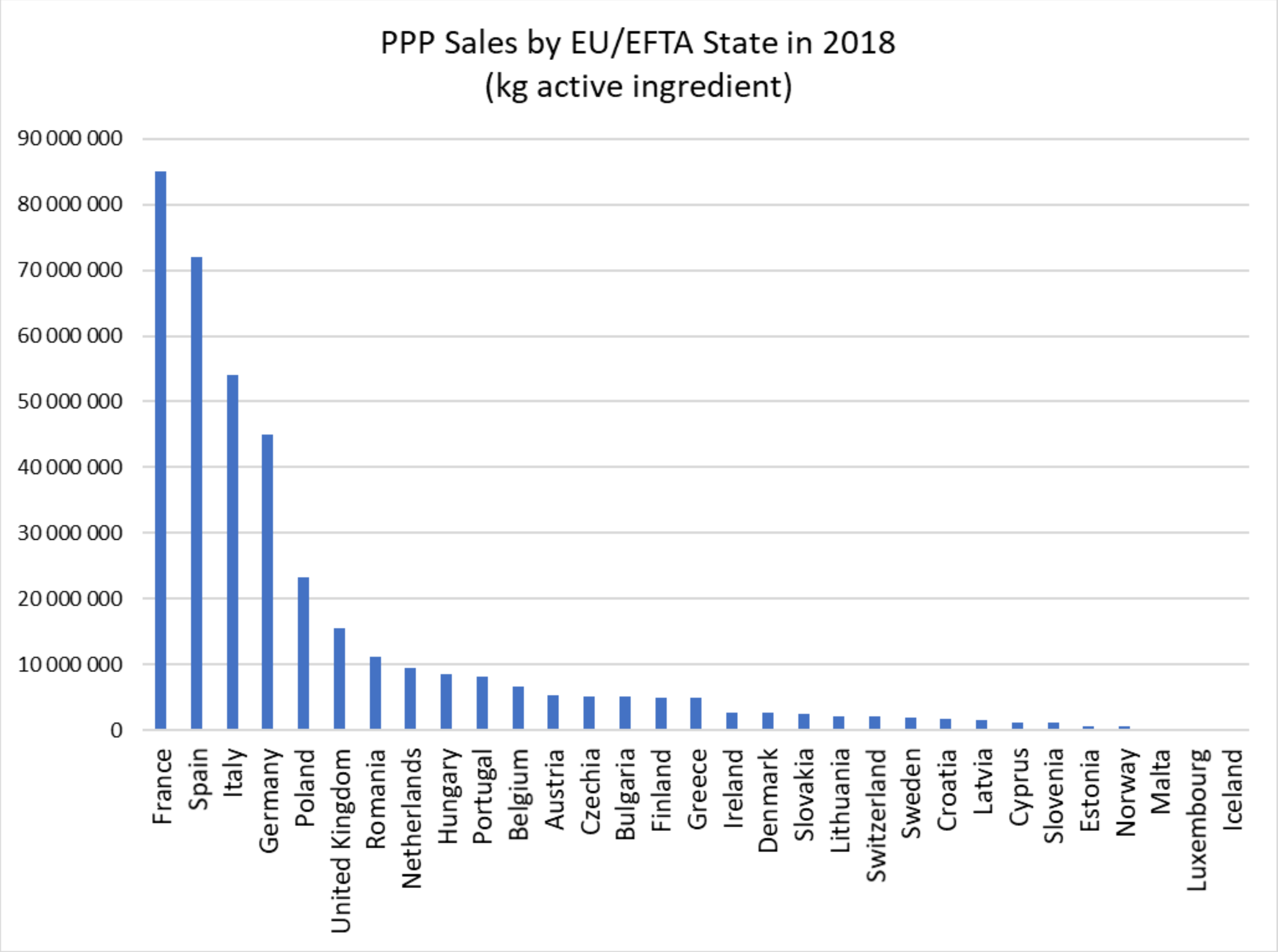


Figure 2. PPP sales for the EU-28 plus three EFTA States, 2018
Source: Eurostat (accessed 17 June 2020)

The pattern of PPP sales (kg of active ingredients) by group varies between the EU/EFTA States. The patterns for the four MS with the highest sales (France, Spain, Italy and Germany) are described below and shown in the following figures.

In France, ‘Fungicides and bactericides’ and ‘Herbicides, haulm destructors and moss killers’ together make up over 80% of all sales with an approximately even balance between these two groups. See Figure 3(a).

In Spain, the group ‘Fungicides and bactericides’ has the greatest sales in all years with some 40-60 % of total sales. This group is followed by ‘Other PPPs’ and ‘Herbicides, haulm destructors and moss killers’ with a reasonable balance of sales between the two. ‘Insecticides and acaricides’ occupies fourth place in all years. See Figure 3(b).

In Italy, ‘Fungicides and bactericides’ is the dominant group with around 60 % of total sales. It is followed by ‘Other PPPs with around 20 % of the total. See Figure 3(c).

In Germany 'Herbicides, haulm destructors and moss killers', 'Insecticides and acaricides' and 'Fungicides and bactericides' together account for over 90 % of total sales in all years, with an approximate balance between the three groups. See Figure 3(d).

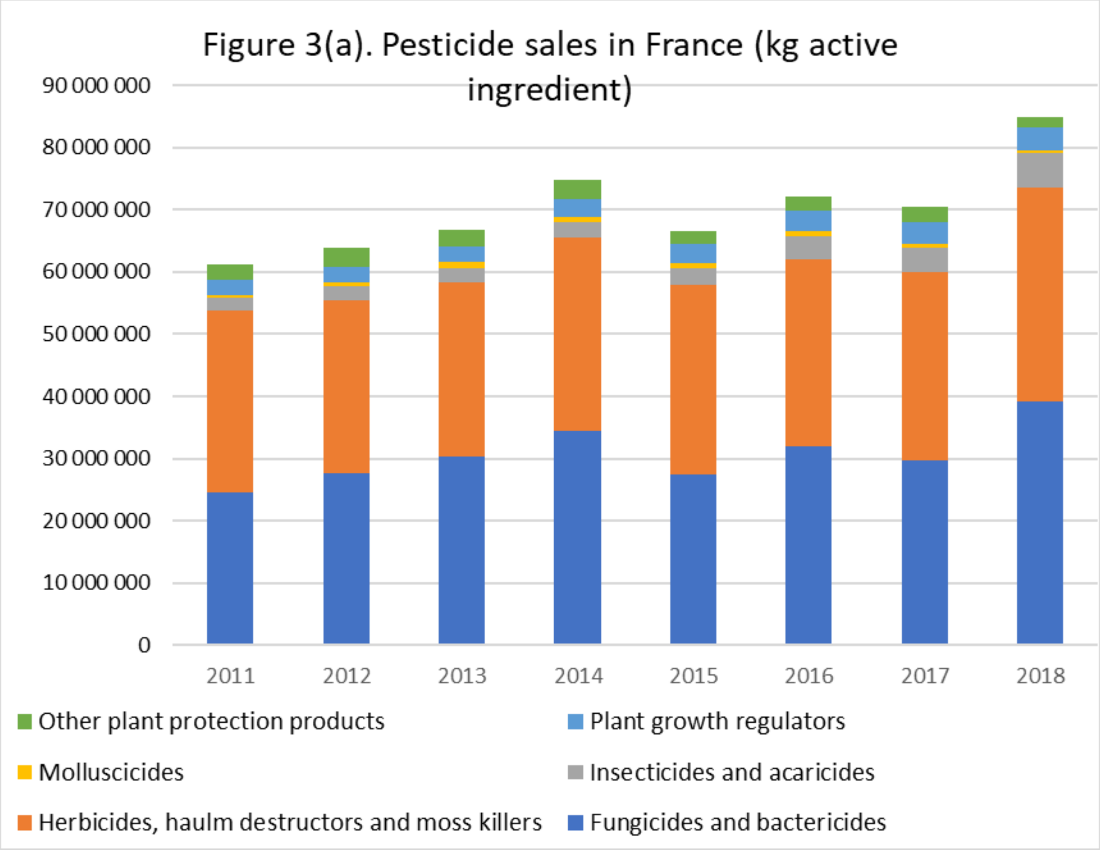


Figure 3. Pesticide sales in (a) France, (b) Spain, (c) Italy and (d) Germany between 2011 and 2018 for different pesticide groups

Source: Eurostat

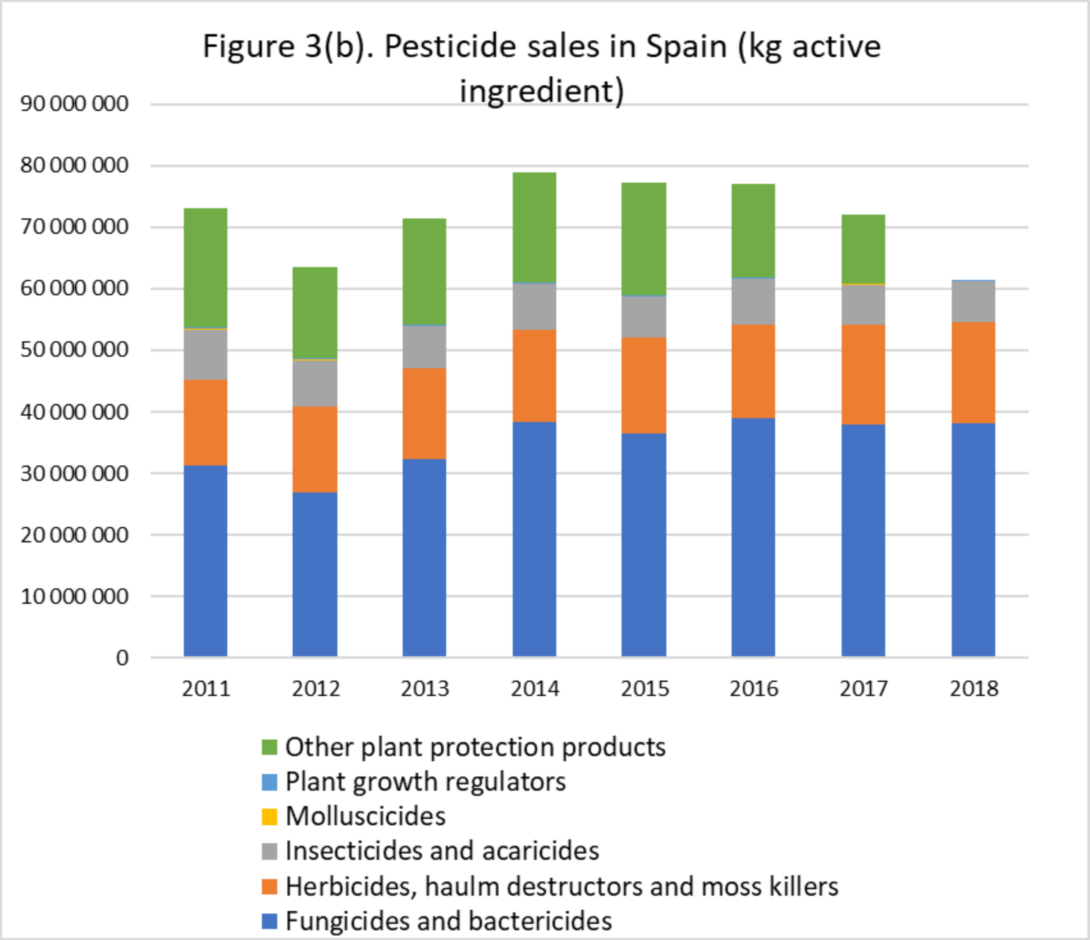


Figure 3(b). Pesticide sales in Spain (kg active ingredient)

Figure 3(c). Pesticide sales in Italy (kg active ingredient)

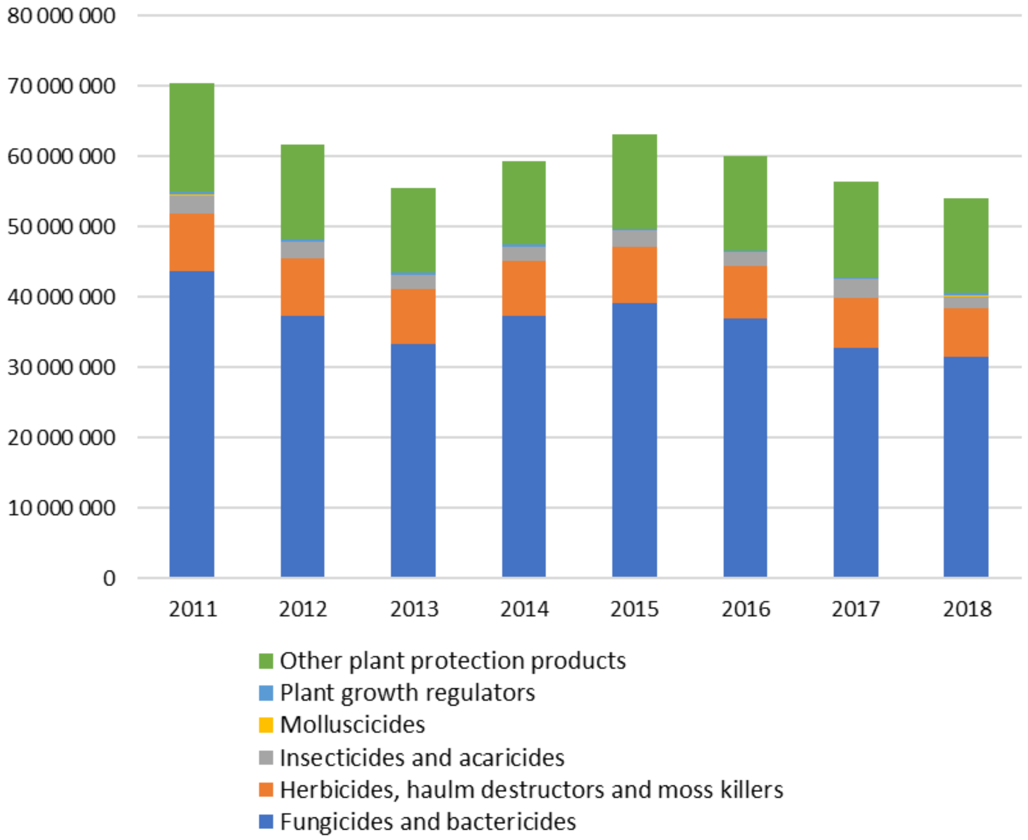
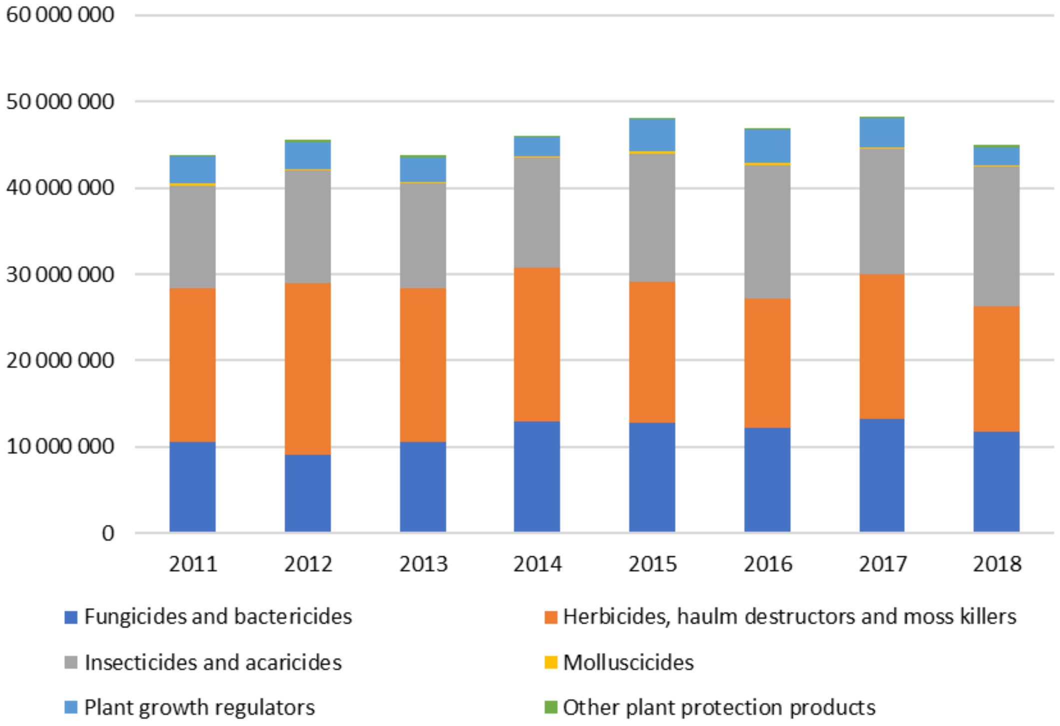


Figure 3(d). Pesticide sales in Germany (kg active ingredient)



While Figure 1 shows a marginal overall decline (below 4 %) in total EU pesticide sales (kg active ingredients) between 2011 and 2018, the EU total does not reflect more significant increases and decreases in individual Member States over the same period.

Figure 4 shows the percentage change from 2011 to 2018 in pesticide sales for some individual Member States (plus Norway), for which there was a complete dataset in Eurostat.

The greatest increase in sales occurred in Cyprus (+94 %), followed by Austria (+53 %), France (+39 %) and Slovakia (+38 %).

The greatest decrease was in Portugal (-43 %), followed by Denmark (-42 %), Ireland (-28 %), Czechia (-27 %), Norway (-25 %), Italy (-23 %) and Sweden (-22 %).

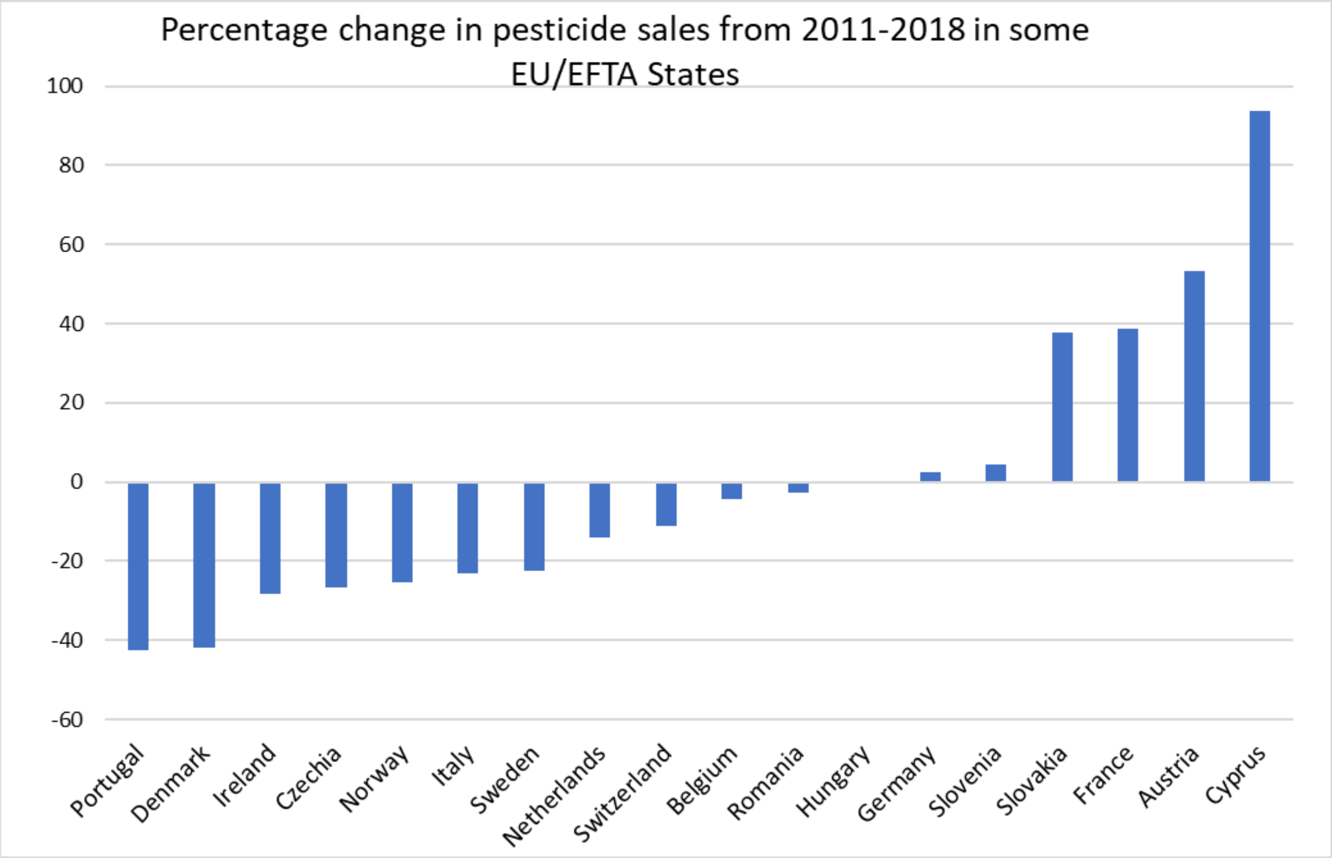


Figure 4. Percentage change in pesticide sales from 2011-2018. Data shown for EU Member States (plus Norway) for which complete datasets were available
Source: Eurostat

2.2.2. Harmonised Risk Indicators

There is a need for better data on pesticide use (expressed as kg active ingredients per ha). However, simply looking at the amount of pesticides used does not take into account the potency of different pesticides. For active ingredients such as microorganisms, measuring the kg of active ingredients used is not appropriate. Instead, it is necessary to agree conversion factors at EU level.

Directive 2009/128/EC (the Sustainable Use Directive, or SUD) established the concept of Harmonised Risk Indicators (HRIs). HRIs enable monitoring of the reduction in risks and adverse impacts of pesticides used for human health and the environment. Two EU HRIs are currently available: HRI 1 and HRI 2.

The European Commission website[6] explains how the two HRIs are calculated:

> *“**Harmonised Risk Indicator 1** is calculated ‘by multiplying the quantities of active substances placed on the market in plant protection products by a weighting factor.*
>
> *For practical purposes, active substances are grouped into four categories in line with Regulation (EC) No 1107/2009. The weightings applied to each category are intended to reflect policy on the use of pesticides and to support the goal of the Sustainable Use Directive to reduce the risk and impact of pesticide use and promote alternative approaches or techniques.*
>
> *A baseline of the average of three years 2011-2013 is used as the starting point against which subsequent values are compared.”*
>
> *Harmonised risk indicator 1 shows a 20 % reduction in the risk to human health and the environment from pesticides in the period 2011-2017.*
>
> *“**Harmonised Risk Indicator 2** is calculated by multiplying the number of emergency authorisations granted by Member States under Article 53 of Regulation (EC) No 1107/2009 by a weighting factor. As with Harmonised Risk Indicator 1, active substances are grouped into four categories, and weightings applied to each category. A baseline of the average of three years 2011-2013 is used as the starting point against which subsequent values are compared.*
>
> *Emergency authorisations are granted for a wide range of reasons, including emerging plant health issues and minor uses, as defined by Article 3(26) of Regulation (EC) No 1107/2009. Up to this point, Member States have not recorded the scale of individual emergency authorisations (for example, the number of hectares treated), or the quantities of PPPs used under these authorisations. Therefore, it has not been possible to establish a more sophisticated indicator to reflect the risks associated with these authorisations. “*

Harmonised Risk Indicator 2 increased by 50 % in the period from 2011 to 2017. This is an unwanted situation for many stakeholders.

It seems possible that the apparent anomaly shown by the different directions of the trends of HRI 1 and HRI 2 may be due to obstacles in implementing Regulations (EC) 1107/2009 and (EC) 396/2005. A Study supporting the REFIT Evaluation of the EU legislation on plant protection products and pesticides residues (Ecorys, 2018) observes that obstacles created by the legislation mean that “MS increasingly resort to emergency authorisations to make products available to farmers.” Commission Staff Working Document COM (2020) 208 Final reports a similar observation. See Section 5.2.1 for more information.

Farmers and PPPs industry have to deal with uncertainty for the market placement of the substances. According to Buckwell et al., 2020 “the public might be reassured by the decline of HRI 1 but be concerned about the potential risk indicated by HRI 2”.

---

[6] https://ec.europa.eu/food/plant/pesticides/sustainable_use_pesticides/harmonised-risk-indicators/trends-hri-eu_en

Figure 5 shows the trends for HR 1 and HR 2 over the period 2011-2017.

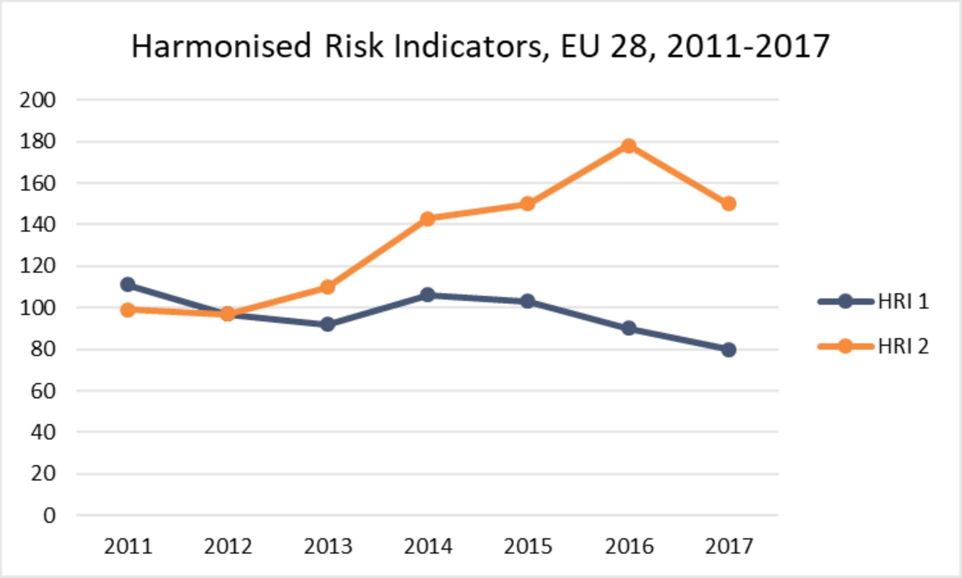
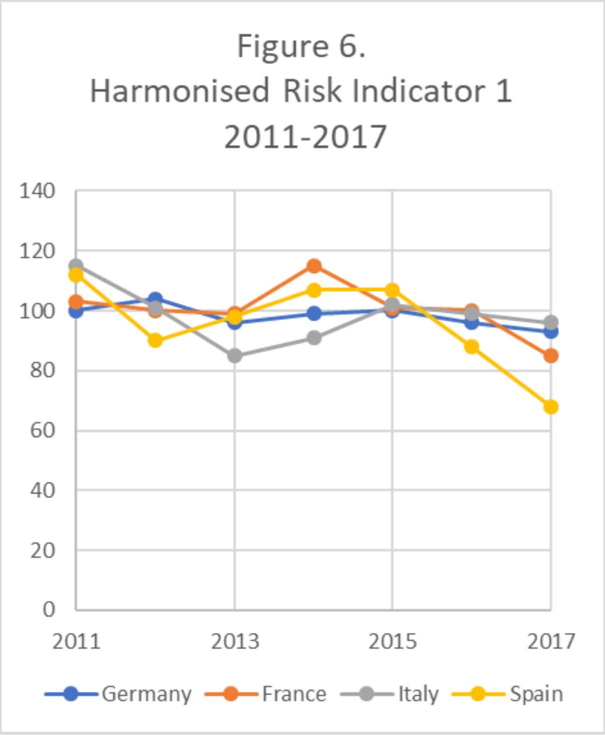
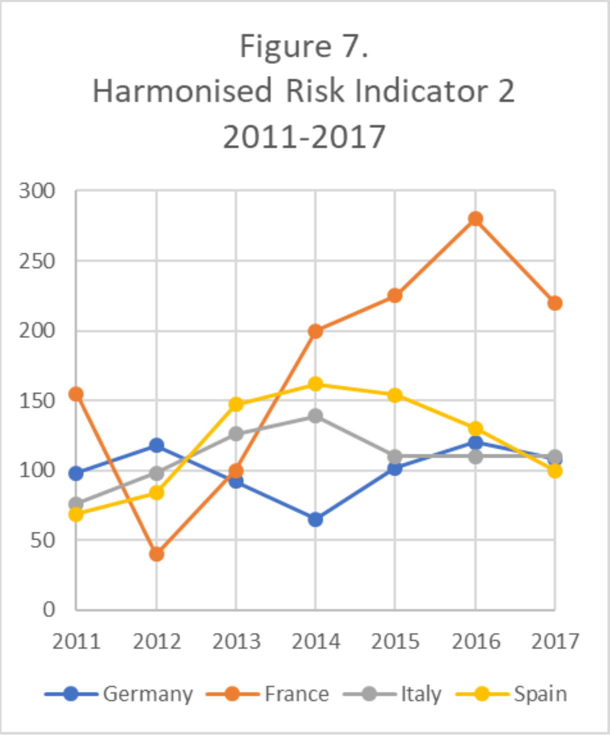


Figure 5. Trends in Harmonised Risk Indicator 1 and Harmonised Risk Indicator 2 for the EU-28 from 2011-2017

Source: https://ec.europa.eu/food/plant/pesticides/sustainable_use_pesticides/harmonised-risk-indicators/trends-hri-eu_en

All countries are obliged to gather data on HRI 1 and HRI 2 and need to make these publicly available. The four countries that account for two-thirds of the pesticide sales in the EU and 51 % of the EU agricultural area (Germany, France, Italy and Spain), have published their HRI 1 and HRI 2 data for the period 2011-2017. The HRI 1 and HRI 2 for these countries are shown in Figures 6 and 7.





Figures 6 and 7. Trend for Harmonised Risk Indicator 1 (Figure 6), and Trend for Harmonised Risk Indicator 2 (Figure 7) for Germany 7, France8, Italy 9 and Spain 10 from 2011 to 2017

2.2.3. Data on the use of PPPs

There is a lack of publicly available information on the extent of the use of PPPs in the European Union. Reliable data on the intensity of use per crop are lacking and harmonised comparable data are needed.

In April 2019, Eurostat published a research paper focused on the statistics on "agricultural use of pesticides in Europe and outlining a potential methodology for harmonisation for data collection"[11]. The paper presented preliminary data on the use of active substances on winter wheat, potatoes, apples, and olives for the period 2010-2014. The data was provided by Member States on a voluntary basis to aid the methodological approach.

The major findings of the research paper are reported in the paragraphs below. These give an indication of the dependency of these crops on the major pesticide groups. The findings are summarised in Table 2.

Common winter wheat and spelt

PPP use for the cultivation of common winter wheat and spelt was surveyed by 16 EU Member States. The number of active substances reported as used in individual MS ranged from 30 to 171. This does not mean that this number was used in one crop.

Use of the major pesticide groups 'Fungicides and bactericides', 'Herbicides, haulm destructors and moss killers', and 'Insecticides and acaricides' were reported from all countries. The reported kg of active substances was the highest for 'Herbicides, haulm destructors and moss killers', closely followed by 'Fungicides and bactericides'. Use of 'Plant growth regulators' was reported from 15 countries.

Potatoes

Twenty-three MS reported the number and kg of active substances used in growing potatoes. The number of active substances ranged from 22 to 128 (again, this does not mean that this number was used in one crop). 'Fungicides and bactericides' was the most used group on potatoes, followed by 'Herbicides, haulm destructors and moss killers', and 'Insecticides and acaricides'. Use of 'Plant growth regulators' was reported from 12 countries.

Apples

PPP use for growing apples was surveyed by 18 MS. The number of active substances reported by individual MS for use in apple cultivation ranged from 9 to 164. Use of the major pesticide groups 'Fungicides and bactericides', 'Herbicides, haulm destructors and moss killers', and 'Insecticides and acaricides' were reported from all MS. Use of 'Plant growth regulators' was reported from 11

---

[7] https://www.bvl.bund.de/DE/Arbeitsbereiche/04_Pflanzenschutzmittel/01_Aufgaben/02_ZulassungPSM/05_HarmonisierteRisikoindikatoren/psm_HRI_node.html

[8] https://agriculture.gouv.fr/reduction-des-pesticides-les-indicateurs-de-risque-harmonises-etablis-au-niveau-europeen

[9] https://indicatori-pan-fitosanitari.isprambiente.it/node/19

[10] https://www.mapa.gob.es/es/agricultura/temas/sanidad-vegetal/productos-fitosanitarios/uso-sostenible-de-productos-fitosanitarios/

[11] https://ec.europa.eu/eurostat/documents/749240/0/Statistics+on+the+agricultural+use+of+pesticides+in+the+EU/fd403698-259e-4027-92d1-a2be4b0acbac

MS. 'Fungicides and bactericides' accounted for the most kg of active substances used on apples, followed by 'Insecticides and acaricides'.

Olives

'Olives' or 'Table olives' were surveyed by 7 countries; 5 reported data on Olives, and 2 on Table olives. The latter is a sub-category of Olives in crop statistics. The number of active substances reportedly used in the countries related to olive cultivation ranged from 8 to 57. Use of the major pesticide groups 'Fungicides and bactericides', 'Herbicides, haulm destructors and moss killers' and 'Insecticides and acaricides' were reported from all countries.

Table 2 Dependency of selected crops on the major pesticide groups

Crops Groups	Cereals	Potatoes	Apples	Olives
Fungicides and bactericides	🟥 High	🟥	🟥	🟥
Herbicides, haulm destructors & moss killers	🟥	🟥	🟧	🟥
Insecticides and acaricides	🟧 Intermediate	🟧	🟥	🟥
Plant Growth regulators	🟧	🟧	🟧	🟩
Molluscicides	🟩 Limited	🟩	🟩	🟩
Other plant protections products	🟩	🟩	🟩	🟩

Source: Eurostat[12]. Eurostat data are preliminary, based on voluntary provision of data by a limited number of Member States. Methodology is under development.
Red = high dependency | Orange = intermediate dependency | Green = limited dependency.

2.3. Alternative cultivars of arable crops

The major arable crops in the EU include cereals, oil seeds, green maize and potatoes. Other major arable crops are beans, peas, sugar beet, lucerne, soya and pulses. The areas of various arable crops grown in the EU North, Central and South zones[13] are shown in Annex 1.

For cereals, oil seeds, maize and potatoes, analyses of possible alternative crops and cultivars that are less vulnerable to pests and diseases are presented in the following sections:

2.3.1. Cereals

Major cereal crops in the EU include wheat and spelt, barley, oats, triticale, grain maize and corn-cob mix, and rye. Figure 1 (Section 2.2) showed that 'Fungicides and bactericides', and 'Herbicides, haulm destructors and moss killers' were the major groups of PPPs (in terms of kg active ingredients) sold in the EU (Figure 1).

---

[12] https://ec.europa.eu/eurostat/documents/749240/0/Statistics+on+the+agricultural+use+of+pesticides+in+the+EU/fd403698-259e-4027-92d1-a2be4b0acbac

[13] See Annex 1 for details of the EU geographic zones used the assessment of main crops and crop protection strategies

The pesticide groups most used on winter wheat and spelt are 'Herbicides, haulm destructors and moss killers', closely followed by 'Fungicides and bactericides'[14]. Although comprehensive harmonised statistical data on the use of pesticides on specific crops is lacking, these findings indicate a dependency of cereal crops on these two pesticide groups.

The genetic resources for cereal crops used across Europe vary to a great extent as very few cultivars are grown in more than one MS (EuroWheat, 2020). All MS have an extensive cultivar testing system, but the way of ranking resistance characteristics is quite different across MS.

Data from cultivar testing has shown that, under high disease pressure, even the most resistant cultivars often give profitable yield responses from fungicide treatment. This indicates that the resistance genes, although they help a lot, rarely cover all potential disease-causing pathogens at the same time, and their effectiveness is often seen to change gradually over time.

With respect to yellow and brown rust, it is well known that resistant cultivars can completely eliminate the risk from these diseases. But this is not seen to the same extent with diseases such as powdery mildew, *Septoria* leaf blotch, tan spot and *Fusarium* head blight, where often only moderate levels of resistance are seen (EuroWheat, 2020).

In terms of yield loss and grain quality, *Septoria* leaf blotch, brown rust, take-all and *Fusarium* head blight are considered the most important diseases in the main wheat growing countries. Yellow rust, powdery mildew, tan spot and eyespot are also important, but their distribution is much more regional (Jørgensen et al., 2008).

Wheat cultivars vary in their crop architecture, which can substantially affect crop/weed interactions (Andrew et al., 2015). Fast growing, or early canopy-forming, cultivars are less susceptible to weed competition (Hansen *et al*., 2008, McDonald et al., 2010), and taller wheat cultivars are more competitive (Christensen, 1995). Unfortunately, the potential yield of these cultivars under weed free environments is lower than of less competitive dwarf wheat cultivars under wheat-free environments.

When herbicides are available and weeds are controlled this is not a problem. However when herbicides are no longer available or less effective due to herbicide resistance, more competitive winter or spring crops need to be developed (Moss, 2017).

An alternative to current wheat varieties is to grow variety mixtures. During the 1980-1990s, research focused on cereal mixtures as a way to reduce the impact of fungal diseases, such as powdery mildew. German research reported a possible fungicide reduction of 80 % as a result of using spring barley mixtures instead of monocultures (Wolfe et al, 1992).

A laboratory-based study by Schoffner and Tooker (2013) showed that genotypic diversity in wheat (*Triticum aestivum* L.) reduced aphid (*Rhopalosiphum padi* L.) population growth. Increasing genotypic diversity, however, does not always outperform monocultures in aphid suppression (Mansion-Vaquié et al. 2019; Grettenberger and Tooker, 2016) and most likely depends on which varieties are combined, as shown in a detailed study by Dahlin et al. (2018).

---

[14] https://ec.europa.eu/eurostat/documents/749240/0/Statistics+on+the+agricultural+use+of+pesticides+in+the+EU/fd403698-259e-4027-92d1-a2be4b0acbac

Grettenberger and Tooker (2016) observed, from laboratory and greenhouse experiments, that control of aphid populations was better in mixtures compared to monocultures, but found that lady beetles were significantly attracted to mixtures compared to monocultures.

Field experiments by Mansion-Vaquié et al. (2019) showed that combining intra and interspecific diversity did not outperform each individual practice in reducing aphid populations. Taken separately, intercropping tended to have lower aphid infestation, while it was intermediate in cultivar mixtures.

A detailed study on the mechanism of aphid response to mixtures of varieties (Dahlin et al., 2018) showed that populations decreased most in a mixture where both cultivars showed a reduced aphid–plant acceptance after reciprocal volatile exposure in the laboratory, and this reduced population growth compared to monocultures in the field.

A meta-analysis by Kiaer et al. (2009) indicated that mixing is beneficial when the mixed varieties show: different grain yields; complementarity in disease resistance; and diversity in weed suppressiveness. In general, the use of cereal mixtures increases disease and weed control and, therefore, yield. Borg et al. (2018) found, in their meta-analysis, a 3.9 % increase in yield from wheat cultivar mixtures compared to single varieties.

2.3.1. Oilseeds

Major oilseed crops in the EU include winter and spring rape seed, sunflower, soya and turnip rape seed.

Insect pests are one of the biggest challenges for growing oilseed rape. No insect-resistant oilseed rape cultivar is currently available on the market. Hervé (2017) reviewed the constraints that make phenotyping for insect resistance particularly challenging with oilseed rape.

Black leg disease (*Phoma* stem canker) caused by the fungus *Leptosphaeria maculans* is a major cause of yield loss in oilseed rape [redacted]ide (Fitt et al., 2006). The interaction between *L. maculans* and rape seed is a typical gene for gene relationship, which means resistance in the plant can easily be overcome by the pathogen. Aubertot et al. (2006) lists disease management strategies that can minimise the risk of resistance being overcome. Rotations with other crops, stubble removal and tillage all decrease incidence of blackleg through reduced exposure to inoculum. Separation of rape seed crops from stubble sources by at least 500 metres is recommended in Australia; beyond that distance the amount of inoculum does not cause enough disease to depress yield significantly (Marcroft et al., 2004).

One of the reasons why rape seed is vulnerable to pests and diseases is because it is grown in the same area year after year. Diversification of oilseed production by replacing rape seed different oilseed species may be a strategy to reduce pest and disease incidence.

The majority of plant-derived oils (approximately 80 %) are used for food products and approximately 14 % are used for industrial products, such as surfactants, plasticisers, chemicals, and fuels (Zanetti et al. 2013).

The functionality of plant-derived oils for industry depends on the type of fatty acids that they contain. In an analysis of the suitability of twenty-four promising oilseed crops in Europe, Zanetti and colleagues (2013) identified Ethiopian mustard (*Brassica carinata* L.), brown mustard (*B.*

juncea L.) and crambe (*Crambe abyssinica* Cranz) as mature oilseed crops for large-scale cultivation and commercialisation in the EU South zone, in view of their considerable drought resistance and low cold tolerance.

Cultivation in more continental areas would be possible only by adopting spring sowing, which seems feasible for the north Mediterranean area.

In view of their remarkable cold tolerance and winter hardiness, it seems likely that camelina *(Camelina sativa* L.) and meadowfoam (*Limnanthes alba* L.) could be grown in continental regions. The north Mediterranean Basin also appears a suitable area for camelina.

For all EU geographic zones, flax (*Linum usitatissimum*) could be an alternative oilseed.

Coriander (*Coriandrum sativum* L.), cardoon (*Cynara cardunculus* L.), safflower *(Carthamus tinctorius* L.), hemp (*Cannabis sativa* L.), and castor bean (*Ricinus communi*s L.), are cultivated worldwide. Re-introducing these crops in Europe would increase the number of oilseed crops cultivated and diversify oilseed crops in Europe (Zanetti et al. 2013). Cardoon and safflower have high potential for (re-) introduction in the South zone.

2.3.2. Maize

In the North zone, maize is mainly grown for silage (green maize can yield 47.1 t/ha), while in the Central and South zones, grain maize is the predominant type (grain maize and corn-cob-mix can yield 8.0 and 8.8 t/ha in the Central and South zones respectively). Other types of maize cropping include seed maize, sweet maize and maize for agro-fuel or gas. Most grain maize is used for animal feed, and the remainder is used for human consumption as oil, starch or flour.

Weeds and insects are the major agents affecting maize. Maize is very susceptible to competition from weeds in its early growth stages (Dewar 2009). Over 50 weed taxa are noted as being important in European maize production. Some species cause problems in all European countries (e.g. *Echinochloa crus-galli*, *Setaria viridis* and *Chenopodium album)* while the majority of species are specific to certain regions (Meissle et al. 2010). According to Meissle et al 2010 weeds are controlled with herbicides on more than 90 % of the maize production area in all EU zones.

The most important arthropod pest of maize in Europe is the European corn borer, *Ostrinia nubilalis*. In infested areas, *O. nubilalis* occurs in most fields – ranging from 20 % in Hungary to 60 % in Spain – and estimated yield losses of 5–30 % are typical in the absence of control measures (Meissle et al. 2010). In France and Spain, the Mediterranean corn borer *Sesamia nonagrioides* causes additional economic damage. Economic losses are caused by these corn boring pests in 2-4 million ha of maize grown in Europe (Brookes 2009).

Wireworms (*Agriotes* spp.) are another major pest in most European countries. A range of other pests have regional significance.

Before the European ban on neonicotinoids, seeds were treated with insecticides in all EU zones. Soil application and on-plant spraying are other practices to control insect pests. The proportion of land where these measures are applied varies between regions (Meissle et al. 2010).

Of the fungal diseases, *Fusarium* spp. causing ear, stalk and root rot are the most economically significant diseases in most European regions (Meissle et al. 2010). The most dominant *Fusarium* species causing both stalk and ear rot is *F. graminearum*, followed by *F. verticillioides*, *F. proliferatum*, and *F. culmorum*, depending on different climatic conditions. One major problem with *Fusarium* spp. is the production of mycotoxins, which contaminate both human food and animal feed.

Other important fungal diseases in Europe are root and stalk rot caused by *Pythium* spp., *Rhizoctonia* spp., and *Acremonium* spp. Some other fungal diseases cause problems in certain regions (Meissle et al. 2010). More than 95 % of maize seeds are treated with fungicides (Meissle et al. 2010). Foliar sprays against fungal diseases are not used, with the exception of seed production in South-west France (Meissle et al. 2010).

Maize hybrids currently grown in Europe are predominantly derived from traditionally bred germplasm, developed to maximize yield according to their suitability to local environmental conditions in each country. Breeding efforts have also been successful in developing high-yielding maize hybrids that are resistant to stalk rot diseases (i.e. *Fusarium* spp.), and producing inbred lines with elevated resistance to European corn borer (*Ostrinia nubilalis*) (Vasileiadis et al., 2011).

There are reports of host plant resistance to insect pests. Crops of mixed maize varieties have been found to have reduced densities of the corn leafhopper (*Dalbulus maidis*) than would be expected from averaging the leafhopper population densities in monocultures of each component variety (Power 1988). Furthermore, the Endure network (which focusses on maize-based cropping systems in Europe) identified that cultivars with increased rooting capacity and consequent reduced yield loss due to damage by Western Corn Rootworm larvae (*Diabrotica virgifera virgifera*) may be considered in future breeding programmes (Vasileiadis et al., 2011).

The cultivation of genetically modified, herbicide-tolerant crops can in theory contribute to the reduction of herbicide use. These crops would make herbicide application at the most susceptible weed growth stage possible and would make additional herbicide treatments in this or other crops redundant. However, adoption of this technology poses a risk for resistance development in weeds when herbicidal modes of actions are not alternated or combined with non- chemical methods. Worldwide, 38 weed species have been reported as having developed resistance to glyphosate (Heap and Duke, 2018).

In Europe, Bt maize (genetically modified maize, producing insecticidal Cry proteins derived from *Bacillus thuringiensis (Bt)*) is available since 1998. Bt maize varieties (expressing the Bt Cry1Ab toxin) was grown in four EU countries in 2016, with the majority sown in Spain (94.7%) (Camargo et al.,2018). Bt maize varieties are grown to withstand the pests *Sesamia nonagrioides* Lefèbvre (Lepidoptera: Noctuidae) and *Ostrinia nubilalis* Hübner (Lepidoptera: Crambidae). In 2010 Meissle reported a that insecticides were no longer needed against these pests due to the high efficacy of the Bt maize. More recently, a meta- analysis on the development of insect resistance to Bt crops indicates that resistance is developing and increasing, although most target pests are still susceptible (Tabashnik et al., 2014). In Spain, a resistance allele has been detected, indicating that it will be a matter of time before resistance of Bt maize will be broken (Camargo et al., 2018).

Sorghum is being considered as an addition to the grass-maize rotation for animal feed. Sorghum is similar to maize in its cultivation, but is less water dependent and more resistant to pests and diseases. Although somewhat inferior in forage yield and quality to maize when growing conditions are optimum, sorghum has potential for areas of low precipitation or limited irrigation water supply (Getachew et al., 2016).

In Europe, sorghum is mainly produced in France, Italy, Hungary, Romania and to a lesser extent in Spain, Bulgaria and Greece. Sorghum needs a higher temperature to start growing than maize and may not perform well in regions with colder temperatures and shorter growing seasons.

There are two types of sorghum: *Sorgum sudanese* and *Sorgum bicolour*. The latter is grown for its seeds, which have a comparable nutrient content as maize but a lower overall yield. *Sorgum sudanese* is grown for its structure and may outperform maize in yield but has a lower nutritional value. The full potential of sorghum for animal feed has not been realised yet and several European and national initiatives are trying to improve this[15].

There is a lack of information on the feeding value of sorghum silage in the diets of high-yielding dairy cows in controlled studies that measure production performance. Until data becomes available, it is difficult to assess the true potential of sorghum silages for high-yielding dairy cows (Getachew et al., 2016).

Pulses and peas may also be considered as alternative crops to maize when human consumption of animal protein is being replaced by plant proteins. The transition towards sustainable legume-based farming systems and agri-feed and food chains in the EU is assessed in the recent LegValue project[16].

2.3.3. Potatoes

The average yields of potatoes are 28.4 t/ha in the EU North zone, 30.3 t/ha in the Central zone and 29.8 t/ha in the South zone. Pesticide sales data show (Section 2.2) that 'Fungicides and bactericides', and 'Herbicides, haulm destructors and moss killers' were the major groups (in terms of kg active ingredients) sold in the EU for all crops (Figure 1, Section 2.2.1).

'Fungicides and bactericides' were reported as the most used major pesticide groups in potatoes; closely followed by 'Herbicides, haulm destructors and moss killers', and 'Insecticides and acaricides'[17].

Although comprehensive harmonised statistical data on the use of PPPs per crop is lacking, these findings indicate a dependency of potato cultivation on 'Fungicides and bactericides', 'Herbicides, haulm destructors and moss killers' and, to lesser extent, 'Insecticides and acaricides'.

The most devastating potato disease in Europe is 'late blight' caused by *Phytophthora infestans*. A range of other diseases, such as common scab (*Streptomyces scabies*) and viruses, may also cause problems. Of the pest insects, the Colorado potato beetle (*Leptinotarsa decemlineata*) and peach-potato aphid (*Myzus persicae*) are the major problems.

Late blight and other fungal diseases are controlled by frequent applications of fungicides. Various *Phytophthora*-resistance genes are present In the potato gene pool. However, breeding potatoes is difficult because of their complex genetic structure (Schaart et al., 2016).

---

[15] https://www.sorghum-id.com/en/sorghum-in-europe/#

[16] http://www.legvalue.eu/

[17] https://ec.europa.eu/eurostat/documents/749240/0/Statistics+on+the+agricultural+use+of+pesticides+in+the+EU/fd403698-259e-4027-92d1-a2be4b0acbac

In the first half of the twentieth century, breeding programmes concentrated on introducing major genes for blight resistance, but this approach was largely abandoned from the 1960s, when it was found that several R-genes were soon overcome individually by blight. Subsequent breeding efforts have produced cultivars with substantial levels of race-nonspecific resistance (also known as horizontal, partial, or field resistance). But the great majority of European potato production comes from susceptible varieties. Choice of variety is dictated by end users, who demand cultivars with specific agronomic characters, and these are difficult to combine with blight resistance (Cooke et al., 2011).

New breeding technologies like TALEN and CRISPR/Cas9 have been employed to generate transgene-free products in a more precise, prompt and effective way (Hameed et al., 2018). These new gene-editing technologies offer a unique opportunity to edit plant susceptibility (S) genes for their use in potato resistance to late blight. Plant S-genes are required by the pathogen for disease establishment and their impairment leads to loss of susceptibility. In potatoes, it has been shown that modifying several S-genes results in complete resistance to different isolates of late blight (Sun et al., 2016).

At Wageningen University & Research, cisgenesis has been applied for the introduction of a combination of three different *Phytophthora* resistance genes originating from three different wild potato relatives into a commercial potato cultivar (Haverkort et al., 2016). Stacking of resistance genes through cisgenesis is the most advanced technique at the moment for achieving *Phytophthora* resistance in potatoes.

Stacking of *R*-genes is a potential strategy to achieve broad-spectrum and durable late blight resistance. A natural example is the potato cultivar Sarpo Mira, which contains a pyramid of at least five different resistance genes for both complete race-specific resistance and partial resistance to late blight (Rietman et al. 2012). Sarpo Mira is one of the few potato cultivars reported to retain resistance in the field for several years (Kim et al. 2012; White and Shaw 2010).

Commercialisation of cisgenic *Phytophthora*-resistant potato lines could be implemented in a timeframe of 5-10 years, but has been halted by uncertainty regarding its regulation in the EU (Schaart et al., 2016).

Stacking different resistance genes and using impaired S-genes in potatoes is being facilitated by the innovative concept of breeding seed-propagated diploid potato cultivars (Lindhout et al. 2011). This concept is based on crossing self-compatible diploid homozygous inbred lines to make a hybrid. In the last few years, increasing numbers of homozygous diploid potato inbred lines have been developed. Initially, the first inbred lines were very weak, but gradually they have improved through consistent breeding, resulting in the first acceptable hybrid cultivars (Lindhout et al. 2016; De Vries et al. 2016).

Through marker-assisted selection, Su et al. (2019) were able to stack two *Phytophthora* resistance genes in a single diploid variety that outperformed diploid plants with only one of the resistance genes. Furthermore, using seed propagated diploid potato cultivars makes it possible to induce mutations in potato S-genes using conventional mutagenesis. Diploid hybrids cannot yet compete with tetraploid varieties in yield but are very close (Stockem et al., 2020). Since breeding of diploid plants can take place at a faster rate than tetraploid plants, it may not be long before they have similar or better performance, especially for disease resistance.

Partial resistance in combination with fungicides can also slow down the development of late blight. Many reports show that partial resistance in the foliage may be used to complement fungicide applications to allow savings of fungicide by reduced application rates or extended intervals between applications (Cooke et al., 2011). In western Europe, resistant cultivars are not grown on a large scale because commercially important characteristics such as quality, yield and earliness are usually not combined in the same cultivar with late blight resistance (Kessel et al., 2018).

Usually, the first part of the growing season is characterised by low levels of blight. Early-maturing cultivars, pre-sprouting the seed, and early planting can all be used to maximise crop growth during the low risk period.

Potato common scab is a widespread disease causing scab-like lesions on the tubers. The disease is caused by pathogenic *Streptomyces* species. There is a wide range in tolerance levels between potato varieties. "Many public research programmes are committed to breeding for scab-tolerant varieties and are evaluating management methods" (Braun et al., 2017).

Virus resistance in potatoes has been engineered through different approaches, ranging from simple plant breeding to advanced genetic engineering. Hameed et al. (2018) reported that "Transgenic approaches to engineer virus resistance in potatoes seem to be more appropriate than conventional breeding".

Insects are a lesser problem in potatoes in Europe but genetic engineering for pest resistance has led to some promising solutions in other parts of the world (Hameed et al. 2018).

2.4. Alternative cultivars of vegetable crops

Vegetable crops make up 1.9 % of the total cultivated area in the EU (Table 1, Section 2.1) although this includes a large variety of different crops. Annex 1 shows the areas of the most important vegetable crops grown in the EU North, Central and South zones.

Major vegetable crops include strawberries, fresh peas, carrots, onions and cabbages. In the Central and South zones, tomatoes and fresh beans are major vegetable crops. In the North zone, beetroot is a major vegetable crop and in Central zone, asparagus is important. In the South, there are many major vegetable crops, but cauliflower and broccoli stand out.

2.4.1. Carrots

Average yields of carrots in Europe are: 42.7 t/ha in the North zone; 45.0 t/ha in the Central zone, and; 40.4 t/ha in the South zone.

Breeding resistant carrots is the obvious way of controlling pest insects without using insecticides. The current approach is to find wild plants that are highly resistant to attack by a specific pest, such as the cabbage root fly (Ellis et al., 1999), and to breed this resistance into cultivated crop plants. This approach has been successful against the carrot fly.

Crosses made between commercial carrot varieties and *Daucus capillifolius*, a resistant wild *Daucus* species, produced highly resistant 'carrot-like' lines at the F_3 and F_4 stage, which were then sold to four seed companies for further development. Prior to this sale, the levels of resistance were being raised at Wellesbourne by about 1 % per year, whereas the seed companies raised the levels from 60 to 75 % in less than 3 years (Finch and Collier, 2000).

2.4.2. Onions

Average yields of onions in Europe are 24.9 t/ha in the North zone; 30.1 t/ha in the Central zone, and; 34.9 t/ha in the South zone.

Major diseases and insect pests attacking onions include Stemphyllium (*Stemphylium vesicarium*), purple blotch *(Alternaria porri*), onion smut (*Urocystis* spp.), downy mildew *(Peronospora destructor*), white rot (*Sclerotium cepivorum*); pink root (*Pyrenochaeta terrestris*); *Fusarium* basal rot (*Fusarium oxysporum* f. sp. *cepae*); thrips (e.g. *Thrips tabaci*) and onion maggot pests.

The main plant parasitic nematodes in onions are *Ditylenchus dipsaci* and *Pratylenchus penetrans*.

Viruses affecting onions are transmitted by Thrips tabaci. The main ones are Iris yellow spot virus (IYSV) – genus Tospovirus, and Onion yellow dwarf virus (OYDV) – genus Potyvirus.

Many of the storage diseases of onions (e.g. neck rot, bacterial rots) are controlled by planting pathogen-free seed, applying chemicals, or properly curing and storing bulbs. When available, genetic resistance is the preferred method of controlling diseases (Havey, 2018).

Onion germplasm has been reported to show resistance to purple blotch, downy mildew, Botrytis neck rot, and white rot. Resistance to pink root is conditioned by a recessive gene (a loss-of-function mutant in an S-gene) and has been incorporated into many commercial cultivars, although variable performance over environments has been reported (Havey, 2018).

Cultivars showing resistance to *Fusarium* basal rot have been developed, conditioned either by a single dominant gene or by a few loci showing dominance. Cultivars that are susceptible or resistant to *Fusarium* basal rot can be differentiated using real-time qPCR (Sasaki et al. 2015).

A major success has been the introgression of downy mildew resistance from *Allium roylei* into bulb onions (Scholten et al. 2007). This is the only example of successful introgression and commercialisation in bulb onions of a disease resistance from a wild Allium (Havey, 2018).

Thrips resistance has been associated with plants with high amounts of leaf waxes and low amounts of hentriacontanone-16, a ketone that is the major component of epicuticular waxes. It should be possible to select onions with these traits (Havey, 2018). So far, there are no cultivars resistant to IYS virus transmitted by *Thrips tabaci*, however some progress in this area is reported by Kamal and Cramer (2018). No sources of resistance to onion maggots have been reported (Havey, 2018).

2.4.3. Cabbages

Average yields of cabbages in Europe are 32.9 t/ha in the North zone; 33.3 t/ha in the Central zone, and; 36.0 t/ha in the South zone).

Cabbages are affected by several fungal, bacterial and virus diseases and pest species. Most problems are dealt with using plant protection products. Turnip mosaic virus (TuMV), however, is a devastating virus threatening many economically important brassica crops, including cabbage. TuMV disease, was first discovered in the United States but is now found worldwide, especially in Europe, Asia and North America.

TuMV results in a yield loss of up to 70 % and has a wide host range, infecting most cruciferous plants, as well as many non-cruciferous species. This virus is also characterised by high pathotype diversity because of its highly variable genome structure, and has been divided into 12 pathotypes. These characteristics, as well as its non-persistent transmission mode by as many as 89 aphid species, mean the disease is difficult to prevent through traditional methods, such as the application of chemicals, prompting researchers to seek host resistance for effective control (Li et al. 2019).

Resistance to fungal and bacterial diseases has been noticed in certain varieties against cabbage yellows (*Fusarium oxysporum f.sp. conglutinans*), black rot (*Xanthomonas campestris*), *Sclerotinia* rot, *Rhizoctonia solani*, downy mildew, black rot and soft rot (*Erwinia carotovora*). Red cabbage is resistant to caterpillars (*Pieris brasssicae*) but susceptible to aphids (*Brevicoryne brassicae*) and vice versa for green and white cabbage. The hybrid KCH-5 is tolerant to both aphids and caterpillars (Dhall, 2015).

2.4.4. Tomatoes

Tomatoes can be produced in open fields or under shelter. The majority of tomatoes produced in the EU are grown in open fields. Most literature about crop protection strategies, however, is focussed on protected cultivation of tomatoes.

Major problems in tomatoes are caused by insect pests, insect-transmitted viruses and fungal diseases. Whiteflies and whitefly-transmitted viruses – causing Tomato yellow leaf curl disease (TYLCD) and Tomato spotted wilt virus (TSWV) – are transmitted by the thrip *Frankliniella occidentalis.* These insect pests, viruses and fungal diseases cause severe damage in European tomato-growing areas (Arnó et al. 2009).

Since its introduction in the Mediterranean Basin in 2006, the tomato leafminer, *Tuta absoluta* (Meyrick) (Lepidoptera: *Gelichiidae*) has become a serious pest. Larvae of *T. absoluta* penetrate leaves, aerial fruits or stems, on which they feed and develop. This creates conspicuous mines which may be invaded later by secondary pathogens, leading to fruit rot (EPPO, 2005), which reduces crop value (Balzan et al. 2012). Tomato powdery mildew (*Pseudoidium neolycopersici* (syn. *Oidium neolycopersici*)) is one of the most devastating fungal diseases of cultivated tomatoes worldwide (Lebeda et al., 2017).

Cultivars are available that provide some level of tolerance to the two virus diseases, TYCLD and TSWV. Most commercial cultivars tolerant to TYLCD have the Ty-1 gene (Verlaan et al. 2013). The best available cultivars and breeding lines show tolerance rather than resistance to the virus (Arnó et al., 2009).

Tomato cultivars resistant to TSWV have been obtained through the use of the single viral resistance gene Sw-5 (Arnó et al., 2009). For *T. absoluta,* no commercially available cultivars are available but the development of resistant cultivars is in progress (Biondi et al., 2018).

For powdery mildew, tomato genes conferring partial and complete resistance have been identified, including the *Ol-1*, *ol-2* (mutant of the *Mlo* S- gene) and *Ol-4* gene (Bai et al., 2005; 2008). These genes have been used in breeding tomato cultivars with partial or complete resistance to *Oidium neolycopersici.*

2.5. Alternative varieties of fruits, berries and nuts

Fruits, berries and nuts make up 3 % of the total cultivated area in the EU (Table 1, Section 2.1). The areas of the various crops grown in the EU North, Central and South zones are shown in Annex 1.

Apples are the most cultivated fruit crop in all EU zones. Other major fruits include: currants, raspberries and pears in the North zone; plums and cherries in the Central zone; and oranges, peaches and cherries in the South zone.

Nuts are grown predominantly in the South zone with the area of almonds far exceeding the total area of all other nuts grown in the EU. Other important nut crops are chestnuts, hazelnuts and walnuts.

2.5.1. Apples

Apples are produced for fresh consumption and for processing. The quality standard for processed apples is lower than for fresh consumption. Indicative Eurostat data (see Section 2.2) shows that the 'Fungicides and bactericides' pesticide group was the most used (in terms of kg of active substance) used on apples, followed by 'Insecticides and acaricides'.

Arthropod pests, several serious diseases and high cosmetic standards for fresh fruit (e.g. no spots) present major challenges for alternative methods of pest control in apples. As a result, most pest management programmes continue to rely heavily on conventional insecticides and fungicides – in most cases, these are the principal pest and disease control methods in fruit orchards (Damos et al. 2015).

Breeding for pest and disease resistance is one means to reduce reliance on pesticides, but despite many efforts, the adoption of resistant varieties is low. For example, scab is a fungal disease caused by *Venturia inaequalis* which results in black spots on apples, making them visually unattractive; controlling scab is a major concern for the apple industry worldwide.

Breeding programmes may succeed in developing apple varieties that are resistant to diseases, but their acceptance by consumers will depend principally on taste and appearance. Consumer rejection is the most likely explanation for the failure of more than 200 scab-resistant cultivars released in recent years to develop satisfactory sales (*Sansavini* et al., 2004).

Developments in molecular techniques for breeding have greatly accelerated breeding programmes (Evans and Peace 2017; Troggio et al., 2012; Sansavini et al., 2004). Markers for specific loci of resistance genes already identify the presence of resistance genes in the seedling stage. Markers to identify resistance genes are available for scab, powdery mildew, fire blight, aphids, Alternaria bloth (Evans and Peace, 2017). Also, induced early flowering techniques (described in Section 3.2) have greatly advanced apple breeding programmes.

2.5.2. Blueberries (*Vaccinium* spp.)

In Europe the main cultivated blueberry species and hybrids belong to the highbush blueberry *Vaccinum corymbosum*. The crop is relatively new in many regions of Europe. It is therefore of interest as specific pests and diseases are often not present, but may become established after several years of cultivation.

A number of major diseases and pests of blueberries have already been introduced into the EU in recent years. Some still have a limited distribution (fewer than three countries) and it may be necessary to consider how to limit their further spread (Suffert et al., 2018). They include: Blueberry red ringspot virus (Caulimoviridae: soymovirus); Blueberry shoestring virus (sobemovirus), *Calonectria colhounii* (Ascomycota); *Ceroplastes cirripediformis* (*Hemiptera*: *Coccidae*); *Colletotrichum karstii* (Ascomycota); *Diaspidiotus ancylus* (Hemiptera: *Diaspididae*); *Epiphyas postvittana* (Lepidoptera: *Tortricidae*); *Gloeosporium minus* (Ascomycota); *Neopestalotiopsis clavispora* (Ascomycota); *Oligonychus ilicis* (Acarida: *Tetranychidae*); *Prodiplosis vaccinii* (Diptera: *Cecidomyiidae*); *Pseudococcus maritimus* (Hemiptera: *Pseudococcidae*), and; *Zaprionus indianus* (Diptera: *Drosophilidae*) (Suffert et al., 2018).

Botrytis cinerea (Botrytis blossom blight) and *Monilinia vaccinii-corymbosi* (Mummy berry disease) are the two most important pathogens affecting highbush blueberry fruits. Outbreaks of botrytis blossom blight occur occasionally, but they can be very destructive. Recently models for predicting ascospore release of *Monilinia vaccinii-corymbosi* have been developed to optimize fungicide use, however, these should be tested and validated for European conditions (Harteveld et al., 2017).

Blueberry anthracnose (caused by *Colletotrichum acutatum*) can affect the post-harvest fruit quality of highbush blueberries. Plants are susceptible to infection not only during the blooming period, but at all stages of fruit development (bloom to ripe berry). Once the pathogen has become established in a new growing area, it can be highly destructive.

Root rot diseases caused by *Armillaria mellea* and *Phytophthora cinnamomi* affect blueberry crops when the fungi are present in the soil, and environmental conditions are favourable for disease development. Avoiding the establishment of pathogen populations in the soil and careful site selection are key factors for the prevention of these diseases. Particular care must be taken if a new crop is planted on ground previously covered by forest, as pathogen species may be present (Prodorutti et al. 2006).

In European regions where highbush blueberry has been recently introduced, there are generally few infestations of insect pests that seriously affect the crop (Prodorutti et al. 2007). Specific examples are otiorhynchid weevils (*Otiorhynchus* spp.) that damage roots, and noctuid moths (e.g. *Operophtera brumata*, *Conistra vaccinii* and *Eupsilia transversa*) which feed on foliage and flower clusters, and some species of scale insects and aphids.

All of these insect pests were introduced into blueberry fields from nearby crops and plants. Advanced biological techniques are currently applied in commercial fields against weevil larvae. Nematodes (*Heterorhabditis* spp.) – which get into crops via irrigation systems – infect and kill otiorhynchid weevils in the soil. At the present time, this is the only effective method available, as chemical control has proven unsuccessful against *Otiorhynchus* weevils in highbush blueberry (Prodorutti et al. 2007).

In general, it seems that disease management in highbush blueberry crops in new cultivation areas should require only limited use of pesticides.

Disease resistance or tolerance is an important aspect in breeding programmes and the development of commercial biocontrol agents can help in areas where diseases are already established.

It is important to mention the spotted wing drosophila (SWD), *Drosophila suzukii*, an invasive pest threatening the European blueberry industry. It causes direct injury to healthy fruit by ovipositing eggs under the fruit skin, where larvae develop. Sustainable control strategies (such as netting of plantations, attract-and-kill) need to be developed.

2.5.3. Black currant (*Ribes nigrum)*

The European black currant is a deciduous shrub native to northern Europe and north and central Asia. Profitability of black currant production has declined in many European countries due to low retail prices.

Black currants can be affected by mildew and leaf spotting diseases common to gooseberries and red currants, but these problems may be largely avoided by suitable choice of cultivar and site, and if the bushes are pruned to encourage good air circulation.

In a number of countries, plant protection problems have increased as a consequence of a decrease in pest management due to low market prices and a lack of non-chemical control methods in organic growing.

Effective acaricides against black currant gall mites (*Cecidophyopsis ribis* and *C. spicata*) and a free-living gall mite (*Anthocoptes ribis*) are not available. Healthy mother plant stocks produced using hot water treatment and strict hygiene are essential to guarantee freedom from gall mites when plants leave the nursery. In organic production fields, enhancement of endemic predatory mites may help control of free living gall mites.

One of the biggest problems encountered in commercial black currant plantations in the majority of European countries is arachnid gall mite (*Cecidophyopsis ribis*). Effective chemical agents, such as endosulfan and amitraz, have been used. However, these products have been withdrawn from use in the EU due to environmental and health risks. Increasing interest is being shown in integrated and organic production systems. Plant protection sprays are now restricted to sulphur sprays.

Powdery mildew is a common foliar problem caused by *Podosphaera mors-uvae*. The fungus overwinters on shoot twigs; and during the spring and summer it infects leaves, shoots tips and fruits. Control of mildew is dependent on the use of chemical sprays, but continued breeding for durable resistance in black currant cultivars could successfully limit the disease.

Septoria leaf spot (*Mycosphaerella ribis*) is an important disease of black currants in Scandinavia and east European countries. The disease causes premature leaf fall, stunted growth in shoots and reduced crop yield. Black currant leaf spot (Anthracnose) (*Drepanopeziza ribis*) occurs throughout Europe, affecting the leaves and leading to premature defoliation in severe cases. The majority of new black currant cultivars have reasonable resistance to anthracnose and screening for resistant germplasm is routine in most breeding programmes.

2.6. Alternative varieties of grape and olive crops

Grapes and olives are mainly cultivated in the Central and South zones. In the North, only 50 ha of grapes are cultivated, which are entirely used to make wine. No olives are cultivated in North Europe.

2.6.1. Grapes

The majority of grape production is destined for wine, table use or raisins. Crop protection for grapevines is mainly targeted against fungal diseases, which may require some 12-15 pesticide applications per year; and insect pests, which require some 1-4 applications per year in wine grapes and 8-10 applications in table grapes (Pertot et al., 2017).

The grapevine diseases that account for the largest number of treatments in vineyards include *Plasmopara viticola* (the causal agent of downy mildew), *Erysiphe necator* (the causal agent of powdery mildew), and *Botrytis cinerea* (the causal agent of grey mould).

Spider mites and scales are among the major insect pests that cause problems in grapevines. The occurrence of new pests is another concern for European viticulturists. In the last 15 years, two leafminers (*Phyllocnistis vitegenella and Antispila oinophylla*) and a leafhopper (*Erasmoneura vulnerata*) have been detected in northern Italy. Recent findings suggest that the impact of some pests will increase with rising temperatures (Reineke and Thiéry, 2016).

Agronomic practices – such as reducing inoculum or improving the microclimate of the plant – to make conditions less favourable to pests and diseases are commonly implemented in most grape growing areas. Resistant/tolerant varieties may provide a solution for reducing fungicide treatments, but planting such hybrids in large areas has led to a decrease in wine quality (Topfer et al., 2011).

A few breeding programmes in Europe cross hybrids with *V. vinifera* varieties to obtain resistant varieties with traditional flavours that are liked by consumers. Breeding techniques have evolved radically over time (Topfer et al., 2011) and the new techniques (e.g. marker-assisted selection, gene mapping, *in vitro* culture, genetic engineering and pyramidising of resistance) have become increasingly important in recent years.

As a result of these efforts, several new resistant varieties are – or will – soon become available[18] (Pertot et al., 2017). Resistance to downy mildew or powdery mildew has been described for different varieties, as well as resistance and susceptibility against *B. cinerea* (Alonso-Villaverde et al., 2008). Some varieties have been found to have an acceptable level of resistance against *P. ampelicida*. Disease resistant wine grape varieties in Europe are listed in the supplementary material of Pertot et al. (2017).

The current approach in resistance breeding is to pyramidise resistance genes of different origin (e.g. from *Vitis rotundifolia* and *V. amurensis*) into a single genotype (Topfer et al., 2011) and to cross them with *V. vinifera.* The aim is to obtain highly resistant genotypes as well as varieties suitable for quality wine production. Resistant genes against *B. cinerea* are not yet known; however the choice of less susceptible varieties or clones (hard skin, loose bunch, early bearing, etc.) quite often represents the easiest and most effective solution against grey mould (Pertot et al., 2017).

2.6.2. Olives

A preliminary study by Eurostat (Section 2.2) indicates a strong dependency of olive cultivation on the major pesticide groups 'Fungicides and bactericides', 'Herbicides, haulm destructors and moss killers' and 'Insecticides and acaricides'.

---

[18] www.bundessortenamt.de

There are three main key olive pests: the olive fly (*Bactrocera oleae*); the olive moth (*Prays oleae*), and; black scale (*Saissetia oleae*) (Homoptera: Coccidae).

The olive fly is probably the main damaging olive pest in the Mediterranean region. Infestation can be severe enough to induce 100 % fruit drop in years of low yield.

The olive moth is also widespread through the entire Mediterranean region and may cause severe damage.

Black scale causes damage due to the secretion of very large amounts of honeydew, which is colonised by sooty mould fungi, covering fruits and leaves by a thick black mass. As a result leaves drop, fruit may be reduced in quality, and twigs dry up.

Other secondary pests that may become key pests are: the oleander scale, *Aspidiotus nerii*; the two olive scolytids, *Hylesinus oleiperda* and *Phloeotribus scarabaeoides* (Coleoptera: Scolytidae), and; the olive pyralid moth, *Euzophera pinguis* (EIP-AGRI Focus Group, 2020b).

Diseases that may cause serious economic losses include the quarantine bacterium *Xylella fastidiosa*, *Verticillium* wilt, and a complex of fungal leaf and fruit diseases – mainly scab or peacock spot caused by *Fusicladium oleagineum*, anthracnose due to *Colletotrichum* spp., and cercosporiose due to *Pseudocercospora cladosporioides*.

Xylella fastidiosa has emerged as a global threat for olive production and has been associated with a novel and severe disease in olives called Olive Quick Decline Syndrome, which is spreading and killing many olives in Apulia, southern Italy.

Verticillium wilt is the main soil borne fungal disease of olive that is caused by the vascular fungus *Verticillium dahlia*. This is considered the most serious fungal disease and the main challenge for olive growing in the Mediterranean region (EIP-AGRI Focus Group, 2020b).

Most olive selection programmes rely on clonal selection; very few cultivars have emerged from formal breeding programmes (Doveri and Baldoni, 2007). Crossbreeding in olives was only initiated in the second half of the twentieth century and currently represents the most promising strategy to provide farmers with new cultivars (Rallo et al., 2018). A successful example is the cultivar Maalot, which is resistant to *Spilocea oleagina* (Doveri and Baldoni, 2007).

A difficulty in olive breeding is that the genetic diversity is not yet well organised according to the gene pool concept. In addition, despite recent significant efforts, the knowledge on single-locus traits and Quantitative trait loci (QTL) remains limited (Rugini and De Pace, 2016).

2.7. Potential impact of alternative crops and cultivars

One possible technical solution to reduce the environmental impact of crop production would be to grow crops that are resistant or less susceptible to pests, diseases and weeds, thus allowing a reduction in the current dependency on PPPs. The potential of alternative crops and cultivars depends on two critical issues, which are discussed below.

The first critical issue is food security at EU and global levels. The EU has a relatively low population growth[19] and a widespread over-consumption of carbohydrates, fats and protein. This is accompanied by a level of food waste along the food chain of at least 20 %[20]. Potentially, the EU may be able to feed itself on a lower overall level of agricultural production.

Questions on matters such as the responsibility of the EU towards global food security; the impact of EU policies on improving technology (such as new breeding techniques), and; the displacement of the environmental impacts of agricultural production from the EU to other parts of the world need to be addressed when considering this issue.

The EU is a significant exporter of agri-food products. EU agri-food imports include a high proportion of fruits and vegetables that are more difficult to grow under European climatic conditions. One option may be to change the EU food production system to one that is driven by the need for the EU to feed itself. This could have "a large impact on poverty, hunger and malnutrition, and deforestation in other parts of the world, depending on the level of import substitution that could be achieved" (Buckwell et al., 2020).

The second critical issue concerns possible changes to the dietary habits of EU citizens. The typical current diet for many EU citizens is associated with illnesses such as diabetes and heart disease. The EAT-Lancet report (EAT-Lancet Commission, 2018) states that "*transformation of healthy diets by 2050 will require substantial dietary shifts. A diet rich in plant-based foods and with fewer animal source foods confers both improved health and environmental benefits*".

Current production patterns cannot be maintained (Poux & Aubert, 2018; IPES-Food, 2016). There is a need to increase plant production and reduce the amount of land dedicated to animal production systems. This should be realised through the development of new circular systems, based on efficient varieties and sustainable crop protection. However, this also requires a major paradigm shift in society.

The implication at the global level is that consumption of food such as fruits, vegetables, nuts, seeds and whole grains would need to double; and the intake of foods such as sugar and red meat would need to reduce by 50 %. Over-consumption mainly takes place in wealthy places, such as the EU (Willet et al. 2019).

At present, half of the total cultivated area in the EU is used for livestock production. This includes 50 % of the cereal area (European Commission, (2020)[21]), plus all the grassland and grazing (Section 2, Table 1). Adoption of the new dietary patterns proposed by Willet et al. (2019), and embracement of the concept of the EU feeding itself, would have huge implications for agricultural land use and the crops grown.

A shift towards more vegetable, fruit and grain consumption could be expected. The production of fruits, vegetables and nuts would need to increase wherever possible to meet dietary requirements and reduce the need for imports.

---

[19] Eurostat https://ec.europa.eu/eurostat/statistics-explained/index.php?title=The_EU_in_the_world_-_population

[20] FAO, 2011. Global food losses and food waste – Extent, causes and prevention. FAO, Rome, 37 p., http://www.fao.org/3/a-i2697e.pdf

[21] https://ec.europa.eu/info/food-farming-fisheries/farming/facts-and-figures/markets/overviews/market-observatories/crops_en

Providing the required range and volume of products with the necessary quality to meet the demands of processors, retailers and consumers would be a challenge. "Currently, food crops are grown in operations that aim to ensure reliable harvests and the consistent supply of uniform, disease and blemish-free produce. There is little tolerance for unreliable delivery or product quality" (Buckwell et al., 2020). The use of PPPs currently provides the whole chain with an efficient tool for delivering quality produce to consumers.

Undoubtedly new cultivars would play an important role in moving to a more sustainable system of vegetables and fruits production.

There is a good prospect that breeding programmes will succeed in developing vegetable and fruit varieties that are resistant to diseases and pests, which would and reduce the need for PPPs. A good example is the presence of resistance genes to fungal diseases in cabbage. For other pest-crop combinations (e.g. IYS virus transmitted by *Thrips tabaci* in onion) no resistant cultivars could be developed or no source of resistance has been identified (onion maggot). There will be nevertheless, prospect for the reduction of the dependence on agro chemicals when plant breeding programs will (continue to) focus on the development of the major pests and diseases in the major vegetable crops.

As reported in Section 2.5.1., developments in molecular techniques have accelerated breeding programmes in fruit crops. In addition, induced early flowering techniques (described in Section 3.2) have greatly advanced apple breeding programmes.

One factor that may slow the development of new crop varieties is the desire to integrate a number of traits into one variety. Consumer preferences have an influence in this respect as breeders must integrate resistance traits with others responsible for look, feel and taste. This applies particularly to fruit crops and can constrain the development of new varieties. In addition, supply chain operators look for uniform products.

The potential of new crop varieties is therefore influenced by the demands of retailers, processors and consumers, as well as by the needs for sustainable production methods and food security.

Crop protection in both grapevines and apples is mainly targeted against fungal diseases and insect pests. Resistant/tolerant varieties may represent a solution to reduce fungicide treatments, but planting of such varieties in large areas in the past has led to a decrease in wine quality and difficulties in marketing apples. At the moment, the choice of less susceptible grape varieties or clones (hard skin, loose bunch, early bearing, etc.) quite often represents the easiest and most effective solution against grey mould. Resistance breeding aims at pyramidizing resistance genes into a single genotype and cross them with *V. vinifera* in order to obtain both highly resistant genotypes and varieties for quality wine production.

The occurrence of new pests is another concern for European growers. Increasing temperatures may cause new pests, diseases and weeds to appear. One example is the detection of two leafminers and a leafhopper in grapevines in northern Italy within the last 15 years. A high level of care must be taken to avoid the introduction or establishment of new diseases. Strict phytosanitary measures should be applied to plant material coming from infected areas, and disease-free planting stocks should be used. The development of commercial biocontrol agents (see Section 3.3) can help in areas where diseases are already established.

Most long-standing olive selection programmes have relied on clonal selection, and very few cultivars have emerged from formal breeding programmes. Crossbreeding in olives was only initiated in the second half of the twentieth century; it now represents the most promising strategy for providing growers with new cultivars. A difficulty in olive breeding is that the available genetic diversity is not yet well organised according to the gene pool concept.

Production costs for farmers will, in general, not significantly increase when they grow new cultivars. However, many fruit crops and nuts are perennials, and these require high investment to replace plantations of older cultivars with new ones.

Vegetables such as tomatoes, salads, herbs and some fruits are increasingly grown in in protected production systems, such as glass houses, poly tunnels or in vertical farming systems (using LED lighting). In these systems, climate can be controlled, water losses and nutrient losses limited, and biocontrol agents can be highly successful in reducing the dependence of growers on agrochemical pesticides. The downsides of these systems are the high investment costs for farmers, and the limited contribution to biodiversity and ecosystem functioning.

However, arable crops such as cereals and potatoes will continue to be grown in soil in field systems. These crops occupy a high proportion of agricultural land in the EU, and show a relatively high dependency on PPPs (Section 2). Plant breeding projects show potential for the development of resistance cultivars and varieties for these arable crops.

The challenge for crop breeders is the slow speed at which developments can take place and the integration of resistance to multiple organisms in one variety. Additionally, the need for climate-withstanding varieties demands the integration of traits such as resilience to drought or salinity.

It is important to develop cultivars that fit into systems that are resilient to abiotic (non-living) stressors caused by climate change (drought, extreme precipitation, increased temperature), and biotic (living) stressors such as pests, diseases and weeds. Potentially, these varieties grown in such systems could achieve sustainable levels of production and contribute to biodiversity.

2.8. Conclusions on PPP use and alternative crops and cultivars

Pesticide use (expressed as sales of active ingredients) in the EU has not decreased significantly in the period 2011-2018. In 2018, over 350 million kg active ingredients (i.e. 350 000 tonnes) were sold in the EU. Four Member States account for two thirds of annual sales in the EU; France, Spain, Italy, and Germany (Section 2.2.1., Figure 2). However, the pattern of sales of the various pesticide groups varies significantly between these MS (Section 2.2.1., Figure 3).

Sale of active ingredients of PPPs is not itself a direct indicator of the scale of negative impacts of plant protection products. This is because potency varies and individual PPPs may differ significantly in their impact on the environment.

The EU has developed two new indicators for monitoring the risks and adverse impacts of PPPs. These are the Harmonised Risk Indicators HRI 1 and HRI 2.

Harmonised Risk Indicator 1 shows a 20 % reduction in the risk to human health and the environment from pesticide use in the period 2011-2017.

In contrast, Harmonised Risk Indicator 2 shows a 50 % increase in the period 2011-2017, indicating that the number of emergency authorisations of pesticides on the market went up.

The HRI data shows that EU agriculture is still strongly dependent on pesticides for crop protection. However, harmonised data on pesticide use by crop area is lacking and cannot provide comprehensive information on the dependency of individual crops on pesticides.

Nevertheless, the combination of data on the major pesticide groups sold in EU Member States; the share of land area per crop in the EU; and information from literature on major pests and diseases in these crops, gives an indication of the dependency of EU crop production on pesticides.

Dependency on 'Fungicides and bactericides', 'Herbicides, haulm destructors and moss killers', and 'Insecticides and acaricides' is high. Cereal crops such as wheat, root crops such as potatoes, and perennial fruit and vegetable crops such as apples and olives have a high dependency on pesticides in many Member States (Section 2.2., Table 2).

The application of Integrated Pest Management (IPM) strategies in pest and disease management has contributed to a reduction in the use of PPPs for specific diseases, pests and weeds in vineyards (Mailly et al., 2017), arable crops (Kessel et al., 2018), Burger et al., 2012), and fruit crops (Caffi et al. 2017). Many examples show the role of IPM in disease control, together with the resulting reduction in pesticide use.

The potential for growing alternative crops in the EU is influenced by deliberations regarding sustainable land use. These deliberations need to take into account future EU and global food security, as well as possible changes to the dietary habits of European citizens.

A shift in EU dietary patterns towards more plant-based diets with lower consumption of animal products would mean a reduction in the area of land needed to feed animals (i.e. the arable crop land and grassland used for animal production); while the area of food crops grown for direct human consumption would increase. Disease and pest resistant varieties of food crops would be needed to meet future demand while reducing the current level of dependency on pesticides.

Current breeding programmes focusing on disease and pest resistance exist, but the development process is time-consuming and many new varieties fail to meet the quality demands of the supply chain and consumers. These are constraints to rapid progress. For the major arable crops (wheat and root crops such as potatoes) resistant varieties are vital for reducing dependence on pesticides. The new varieties should be grown in resilient production systems that contribute to improvement of ecosystems (biodiversity) while maintaining or improving production levels.

3. Assessment of existing and emerging crop protection practices

This chapter provides an assessment of current and emerging crop protection practices, and their impact on future crop production in Europe. The practices are not specific to regions and are described here under the following categories:

- Mechanical techniques;
- Plant breeding;
- Biocontrol;
- Induced resistance;
- Applying ecological principles;
- Precision agriculture (PA);
- Plant protection products.

Each paragraph includes text boxes that show existing techniques (applied in practice for at least 10 years); emerging techniques (available for implementation in practice); and future techniques (undergoing research and development). Each section ends with a summary of the potential impact of the emerging crop protection practices.

3.1. Mechanical techniques

3.1.1. Existing practices

Mechanical techniques are mainly used to control weeds. Weed management tools can be distinguished by their scale of operation: full field, inter-row, intra-row; and their mode of action: mechanical weeders, electro-weeders, thermal weeders.

Full field weeders cover entire fields or crops. Examples are the cultivator, harrow, hoe, comb cut, rod weeder and broad cast knife. Important aspects are the timing and the intensity of application, which determine the degree of selectivity (Kurstjens, 2007).

Mechanical techniques

Existing practices

- Full field weeders
  - Cultivator
  - Harrow
  - Comb cut
  - Rod weeder
  - Broad cast knife
  - Hoe
- Inter-row weeders
  - Inter-row cultivators
  - Brush weeders
  - Rotary cultivators
  - Rolling cultivators
  - Basket weeders
  - Rolling harrows
- Intra-row weeders
  - Torsion weeders
  - Finger weeders
  - Flame weeders
  - Air pressure weeders
  - High-power electric discharges (Zasso),
  - Electricity to boil weeds inside out from the root upwards (Rootwave)

Emerging practices

- Inter-row weeders using guidance systems.
- Intra-row weeders using cameras and computer vision and real time kinetic global positioning systems (RTK GPS)
- Weed seed harvesters, preventing weed seed return

Practices under development

- Autonomous robotic weeders with non-chemical actuation
  - Robovator (Denmark)
  - Robocrop InRow weeder
  - Steketee IC weeder
  - Agrorobotti (AgroIntelli)

Source : EIP-AGRI Focus Group (2020a)

Inter-row weeders operate between the crop rows and include inter-row cultivators, discs, brush weeders, rotary cultivators, rolling cultivators, basket weeders and rolling harrows. An overview of non-chemical weed management strategies in crops such are vegetables and fruits is given in Pannacci et al. (2017).

The most important innovation for inter-row weeders is guidance systems that take over the role of the driver. They enable larger areas to be covered and higher driving speeds.

Physical guidance systems that follow the crop row are widely available and cheap. Their downside is that the crop needs to be firmly rooted to guide the machine. However, automated guidance systems based on global positioning systems (GPS) or row/plant recognition have now been developed.

3.1.2. Emerging practices and practices under development

Intra-row weeding is the most challenging cultivation since the risk of crop damage is highest when removing weeds growing close to the crop. Available tools are torsion weeders, finger weeders, flame weeders, and air-pressure weeders. Air-pressure weeders have potential for insect control as well; they can be adjusted in such a way that they blow insects into a container (Khelifi et al., 2001)

Over the last two decades, two developments have led to major innovations in intra-row weeding: the combined use of cameras and computer vision; and the development of real-time kinetic global positioning systems (RTK GPS). Computer vision technologies are able to recognise the crop row based on shape, colour and location; they steer the weeding device in the crop row to cut, uproot, burn or bury the weeds. The latest step is the development of autonomous robotic weeders with non-chemical actuation.

Commercial intra-row weeders include the Robovator intra-row cultivator from Denmark, which is equipped with two flat-blade tines per crop row that undercut weeds at 1- 2 cm below the soil surface. The tines are positioned in the intra-row area until they approach a crop plant, at which point the computer system opens the tines to safely pass by the crop, then closes them again on the following side (Melander et al. 2015). Other examples of commercially available automated intra-row weeders are the Robocrop InRow weeder[22] Steketee IC weeder[23], and Agrorobotti[24].

Equipment targeting the weed seed bank is also under development. In the USA, a weed seed destructor, 'The Seed Terminator' is under development. This device consists of dual hammer mills that pulverise plants, including weed seeds, after the harvesting and threshing process[25].

3.1.3. Potential impact of emerging mechanical techniques

This section describes the potential impact of emerging mechanical techniques for weed control on future crop production.

Seven studies report on the side effects of mechanical weeding on soil-dwelling insects compared to the side effects of other forms of weed control such as herbicide application or mulching (Bartram & Perkins, 2003; Holland & Luff, 2000; Kromp, 1989; Kromp, 1999; Lorenz, Ulber, & Poehling, 1994; Thorbek & Bilde, 2004; Yardim & Edwards, 2002).

---

[22] **www.garford.com**, accessed 15 April 2020

[23] **www.steketee.com**, accessed 15 april 2020

[24] http://www.agrointelli.com, accessed 25 June 2020

[25] https://www.dtnpf.com/agriculture/web/ag/crops/article/2020/04/16/research-indicates-seed-terminator, accessed 9 October 2020

Side effects were described for the following weed control techniques: brush weeding, hoeing, mowing and harrowing. The affected organisms were *Staphylinidae*, *Coleoptera: Carabidae (*beetles*)*, F*ormicidae (*ants*), and Araneae (*spiders*)*.

Weed control using mechanical techniques generally requires multiple passes to achieve the same degree of control as herbicides. The impact on biodiversity varies with the type of organism – the impact on fauna increases with the number of passes.

The side effects of mechanical weeding on soil dwelling insects are often indirect. The more efficient the weed management practice, the lower the amount of remaining biomass; the lower the biomass, the lower the population of beetles and spiders.

Due to the developments in precision agriculture, mechanical weeding will become more precise in future, which will reduce the remaining biomass. The expectation is that both the direct and indirect negative effects of mechanical weeding on beetles and spiders will increase.

Current full-field mechanical weed control techniques have a destructive effect on the eggs of farmland birds. To reduce the negative effect on birds and their nests, it is necessary to detect and protect the nests during weeding. Vision-based detection systems are under development (Steen, Therkildsen, Green, & Karstoft, 2015). These techniques will minimise the negative side effects of mechanical weeding on bird nests and farmland birds in future.

Existing mechanical techniques used for weed control inflict damage to the crop; individual plants are uprooted and killed or damaged. With increasing precision, the damage will reduce significantly, perhaps to the same level as that caused by herbicides. Herbicide damage (phytotoxicity) can set back crop growth. It is foreseen that the impact of improved mechanical techniques on crop yield will be similar to the impact of existing herbicides.

Developments in mechanical weeding are mainly driven by the developments in precision agriculture (see Section 3.6 for a description, including potential impacts).

3.2. Plant breeding

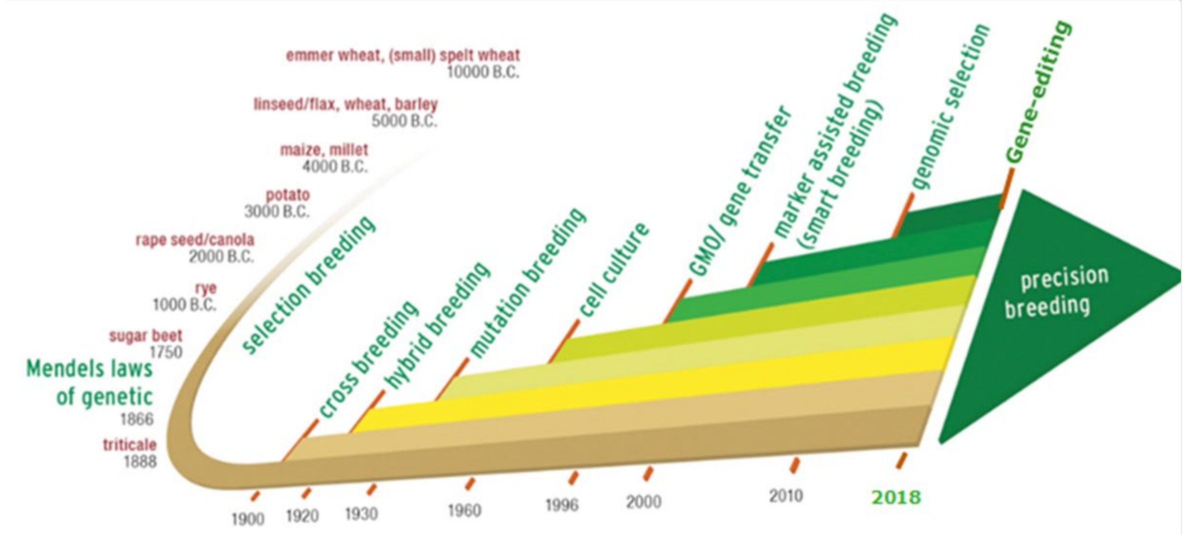
Plant breeders use a variety of methods to create new cultivars. The simplest method is to select the best plants in a crop. Greater progress can be made by including plants from all over the world in the selection process to make optimal use of naturally-occurring genetic variation. A further step is the crossbreeding of different plants to combine their characteristics. There is a long history of selection breeding, crossbreeding and hybrid breeding.

The technique of mutation breeding (or mutagenesis) was added during the 20th century. Random (or conventional) mutagenesis involves artificially changing a trait through chemical treatment or radiation to create a mutation.

Further developments in plant breeding since the 1990s include genetically modified organisms (GMOs) and gene transfer techniques.

In recent years a range of new plant breeding techniques (NPBTs) have been developed to provide a more efficient and precise adjustment of the genetic make-up of crops (Figure 8). These techniques include genome editing (or directed mutagenesis), which has made major progress since the introduction of CRISPR-Cas in 2012 (Cong et al. 2013). These new techniques will support plant breeders in improving important crop traits that have been difficult to improve by crossbreeding.

NPBTs include a diverse set of technologies for improving the efficiency and precision of plant breeding. They can shorten breeding programmes considerably – sometimes from decades to years – depending on the crop and the plant traits being targeted. Genetic modification is frequently used in these techniques, but only as a tool during the breeding process. No DNA from non-crossed species is present in the end product.



Source : Adapted from Europeanseed.com

Figure 8: Milestones in plant breeding

Genome editing (sequence-specific nuclease (SSN) technology) or directed mutagenesis allows DNA to be changed at precisely specified points in the plant genome. This allows the adjustment of plant traits in an accurate and efficient way. Using SSN technology, any gene of interest can be eliminated, mutated, or replaced with a stable result. Mutations produced with SSN can be also obtained using conventional mutagenesis.

The benefit of SSN technology over conventional mutagenesis is that it only produces a mutation at the desired location. In conventional mutagenesis, thousands of mutations are produced in many plants, which makes it difficult and time-consuming to find the desired mutation. CRISPR-Cas, TALENs and ZFNs are different examples of SSN. CRISPR/Cas9 is a rapidly evolving technology and its application in virus and bacterial disease resistance – and recently its potentiality in fungal disease management – is growing year by year (Pal et al., 2019).

Cisgenesis and intragenesis refer to the production of plants by genetic modification using only genes from the species itself, or from a species that can be crossed with this species using traditional methods.

In cisgenesis, genes used are added as an extra copy and are natural variants with improved characteristics, for example providing disease resistance. In transgenesis, the genes inserted are from species outside the species' gene pool.

A cisgenic plant can, in principle, also be produced through traditional breeding, but this would require a much longer period of time. The DuRPh programme (Haverkort et al. 2016) has shown as proof of principle that cisgenesis can be used to produce potato varieties with durable resistance to the disease late blight. This is achieved by incorporating disease resistance genes from wild potato species. For other examples see Mujjassim et al. (2019).

Intragenesis is different from cisgenesis in that the genes are introduced as a new combination of functional elements of different genes. Making such new combinations creates new possibilities, for example regarding when and where in the plant a gene is activated. The results of intragenesis cannot be achieved through normal breeding as the new combinations are unlikely to arise in the breeding process.

Plant Breeding

Existing practices

- Traditional breeding
    - Selection breeding
    - Crossbreeding
    - Hybrid breeding
- Mutagenesis
- Marker-assisted selection
- Cisgenesis
- Intragenesis

Emerging practices and Practices under development

- Genomic selection
- Genome editing techniques
    - Sequence-Specific Nuclease (SSN)
        - CRISPR-Cas
        - TALENs
        - ZFNs
- Reverse breeding
- Induced early flowering

Reverse breeding is a method designed to create homozygous parental lines from offspring of a heterozygous plant. This approach allows the rapid fixation of chromosome substitutions resulting from the heterozygous plant, which will facilitate breeding at an individual chromosome level.

A GM step to suppress recombination of chromosomes, and specific tissue culture steps are used to create these parental plants.

In the final reverse-breeding steps the genes used for the genetic modification are crossed out, resulting in end-products that are free of GM-related DNA sequences.

Reverse breeding has been demonstrated experimentally in the plant *Arabidopsis thaliana* (thale cress) but the technique is still far from being applied in commercial crops.

Induced early flowering is a technique where a transgene induces fruit tree seedlings to flower years before they normally would. This enables fruit tree breeders to cross plants every year, allowing for the fast introduction and combination of desirable traits, after which the transgene is eliminated. The technique accelerates introgression of disease resistance genes from wild species into new varieties through crossing (Schaart et al. 2015).

3.2.1. Potential impact of emerging plant breeding techniques

The objective of breeding – through either conventional or new breeding techniques – is to provide varieties with good characteristics. With regard to crop protection, this means developing

crop varieties that are resistant against specific pests and diseases, or tolerant or suppressive to weeds, which reduces the need to control those pests and diseases by other means.
Compared to chemical pesticides, the introduction of resistant varieties contributes to safeguarding biodiversity and the protection of human health. Furthermore, it contributes to farmers' incomes by saving the costs of pesticide application.

The question of whether new breeding techniques will contribute to the competitiveness of EU farming largely depends on the legal situation on the use of the new techniques – both within the EU and elsewhere. The EU has, to date, been reluctant to allow the use of new breeding techniques, which could create a competitive disadvantage for EU farmers.

3.3. Biocontrol

Plants are constantly under attack from a wide range of pathogens and pests that cause crop damage. The organisms that cause the damage have natural enemies (or antagonists). These enemies exist naturally in any agricultural system. However, their numbers or effectiveness are often too low to contribute to crop protection.

Different types of natural enemies can be identified: microorganisms such as bacteria, viruses and fungi; and macro organisms such as insects and nematodes. "Biocontrol entails all methods, tools, measures and agents of plant protection that rely on the use of beneficial organisms, as well as their natural mechanisms and interactions which steer the relationship between biological species in the natural environment. Biocontrol includes augmentative control, conservation biocontrol, and the use of biopesticides, semiochemicals and plant defence stimulators" (Lamichhane et al., 2017).

Depending on the context, the term biopesticides is used for a variety of products and agents. In this report, the term is used only to refer to the use of arthropods, microorganisms, nematodes, viruses and products derived from these organisms for crop protection. Plant defence stimulators are discussed in the next section (on induced resistance). Nanoparticle-based micronutrient formulations that enhance plant defence mechanisms are discussed in Section 3.7 on PPPs.

During the last decade, the rate of introduction of new biological products has exceeded that of conventional plant protection products worldwide[26]. "Despite the recent rapid growth of the biocontrol market, less than 5 % of plant protection products currently sold worldwide are biocontrol agents" (Buckwell, 2020).

Lamichhane et al. (2017) prioritised 13 pests and diseases that cause most problems in arable crops in the EU. They also indicated the possible biocontrol solutions that are available, or under development, to control these priority pests and diseases. The authors conclude that, in arable cropping systems, a limited number of biocontrol options are available to control the major pests, diseases and weeds. However, the use of bacteria, fungi and viruses for weed control has received increasing attention in the literature over the last three decades (Stubbs and Kennedy, 2012; Harding and Raizada, 2015).

---

[26] https://croplife.org/wp-content/uploads/2018/11/Phillips-McDougall-Evolution-of-the-Crop-Protection-Industry-since-1960-FINAL.pdf

Biocontrol

Existing practices

Insect control

- Release of antagonists (insects, mites, nematodes, fungi, virus)
- Pest behaviour manipulation
- Sterile insect technique

Nematode control

- Inoculation of soil with antagonists (bacteria, fungi, nematodes)

Disease control

- Spraying with antagonists (fungi, bacteria)
- Inoculation of soil with antagonists against soil fungi

Weed control

- Antagonists (fungi) for control of *Cirsium* spp. (New Zealand)

Emerging practices

Weed control

- Antagonists (insects, bacteria) for control of *Cirsium* spp.
- Rust for control of all weeds
- Seed-eating beetles for control of all weeds

Most biological weed control products are sold in countries outside the EU, although there is no widely used commercial biological herbicide (Buckwell, 2020). The EU pesticide database contains a small number of biological weed control products based on acids (acetic acid, lauric acid, oleic acid).

Achieving consistent suppression of weeds in field conditions is a common difficulty with biocontrol methods. This is because the efficacy of bioherbicides is, generally, more sensitive to environmental variation than conventional herbicides. One commonly reported problem is the need for continuous moisture availability during the period in which the biocontrol agent infects the plant (Boyette and Hoagland, 2015).

Nanoformulations have the potential for controlled release of active phytotoxins, which could be achieved using variations of nanoparticles and other nanoformulation technology. The potential of improved formulation systems to help resolve current weed management problems suggests that commercial products will emerge. These will combine the benefits of bioherbicides with nanotechnology in formulations that are less detrimental to the wider environment. However, even with all the benefits, the use of nanotechnology, especially in agricultural production, should be thoroughly studied to avoid or limit further damage to the environment and human health (Kremer, 2019).

Lamichhane et al. (2017) listed 12 of the most common pests for vegetable production in the EU. More options for biocontrol are available for vegetables than for arable crops.

A good example is control of *Tuta absoluta* in tomatoes. Despite *T. absoluta* behaving as an invasive pest, positive results have been achieved using augmentative and/or conservation biological control based on indigenous natural enemies.

The basis of current strategies entails pest control with either biological or selective insecticides until the population of predators is high enough to control the pest by themselves (Urbaneja et al. 2012). For tomatoes grown in open fields, which include the majority of the tomato production area, this is not a common practice.

A case study by Balzan and Moonen (2012) in Tuscany (Italy) shows that current management strategies aimed at the control of *T. absoluta* and other pests of tomatoes in open-field cultivations have so far relied on calendar-based application of a wide range of pesticides. Hardly any pest monitoring techniques are used in these areas to adjust pesticide applications.

The ecological disturbances caused by the calendar-based pesticide applications are likely to compromise biological control services and make agroecosystems less resistant to invasions, such as those currently recorded for *T. absoluta*.

Lamichhane et al. (2017) prioritised 12 pests and diseases that are the most common problems for EU Member States in perennial crops such as apples, pears and grapes. The researchers identified the possible biocontrol solutions that are either available or under development for the control of these high priority pests and diseases.

An important bacterial pathogen used as a biological control agent is *Bacillus thuringiensis* (Bt), which is a gram-positive bacterium that is pathogenic to Lepidoptera larvae. Because of its high selectivity, Bt is often used in apple IPM programmes for the management of various moth species, such as leafrollers (Damos et al., 2015). Other promising techniques for biocontrol of pest insects in fruit trees are mating disruption and sterile insect technology (Chouinard and Cormier, 2016).

The most promising virus agent for controlling apple arthropod pests is a granulovirus (family Baculoviridae) (Damos et al., 2015). Granulovirus of codling moth (CpGV) is an insect-specific granulovirus that offers new means of highly selective control of the codling moth *Cydia pomonella* L in fruit orchards. The commercial products that are utilised in IPM programmes contain the virus in an aqueous suspension and are sprayed during the egg hatch. Commercial products of CpGV are registered and available in Europe and North America and are used by orchard growers worldwide (Damos et al., 2015).

A novel technique to enhance larval mortality is the combined use of granulovirus, yeast-based attractants and feeding stimulants or the smell of pears (Knight and Witzgall, 2013).

3.3.1. Potential impact of biocontrol methods

"It is generally presumed that biocontrol methods are inherently less risky for both human health and the environment as these products have originated and evolved in nature. There should be less concern about persistence, bioaccumulation and residues as they are generally quickly broken down and recycled. They should pose less harm to operators" (Buckwell, 2020).

However, these properties do not automatically apply, so such general claims must be scrutinised. The International Biocontrol Manufacturers Association (IBMA) argues that Regulation (EU) 1107/2009, which was designed to address synthetic active substances and products, is not appropriate for the approval and authorisation of biological plant protection products. The data needed to assess a microorganism will be very different from that needed for a chemical substance. The European Commission is currently working to update the data requirements and assessment methodologies for microorganisms.

For farmers, the effectiveness of biocontrol agents compared to agrochemicals is the main consideration. Farmers are risk adverse and these products should have at least a reliable and adequate level of control if they are to substitute for synthetic products. Furthermore, it is important that schemes are developed in which these products can be used in combination with synthetic PPPs.

As shown in the tables above, the number of biocontrol tools developed for field crops is still limited and the combined use of biocontrol products with synthetic PPPs can be expected. Today, biocontrol products are seen by farmers as less efficient and reliable than synthetic products. Farmers need to gain experience with these types of products to build trust and acquire knowledge.

Biocontrol agents generally have a narrower spectrum of application of crop/pest combinations than chemical products. The use of several products in one crop can therefore be expected. This may be costlier to farmers than the use of conventional pesticides. Potentially, their costs of production may increase as a result.

The International Organisation for Biological Control (IOBC) has identified four main limitations to the uptake of biocontrol worldwide (Barrat et al., 2018). These are:

- risk averse and unwieldy regulatory processes;
- increasingly bureaucratic barriers to access biocontrol agents;
- insufficient engagement and communication with the public, stakeholders, growers and politicians of the considerable economic benefits of biocontrol;
- fragmentation of biocontrol sub-disciplines.

3.4. Induced resistance

The defence mechanisms of plants can be induced by a variety of biotic and abiotic agents. There have been a number of studies in recent years aimed at understanding how best to use induced resistance in practical crop protection.

Walter et al. (2013) provide a review of the current advances in this area. Applying induced resistance for crop protection is an emerging field of research (Borges et al., 2015.

Induced resistance tends to be broad-spectrum and can be long-lasting, but is rarely completely effective. Most inducing agents reducing disease by 20-85 % (Walter et al., 2013).

In contrast to breeding for resistance, the genome of the plant is not altered by induced resistance. An example is amending soil with biochar, which induces systemic-resistance to grey mould (*Botrytis cinerea*) on pepper; powdery mildew (*Leveillula taurica*) on tomatoes; and the broad mite pest (*Polyphagotarsonemus latus*) on pepper (Elad et al. 2010).

Induced Resistance

Emerging practices and practices under development

- Soil amendments
- Seed treatments
- Elicitors as foliar sprays
- Elicitors as root drench

The addition of biochar to soil causes a cascade of effects on plant-soil-microbe interactions in addition to changes to physical and chemical properties of the soil. These effects are not yet well understood (Zhu et al., 2017).

Biochar does not always elicit induced resistance. The variability in the amount and types of biochar volatile organic compounds that can act as microbial inhibitors may be the reason for this uncertainty in biochar-triggered pathogen resistance (Zhu et al., 2017).

In most cases, elicitors are applied to plants as either foliar sprays or a root drench. A convenient way of applying crop protection treatments involves treating the seed. Seed treatments can be particularly useful, since they can provide protection to young plants during a vulnerable stage in their development (Walter et al., 2013).

Work by Worrall et al. (2012) demonstrated that treating tomato seeds with jasmonic acid (JA) and or β-Aminobutyric acid (BABA) primed plants for enhanced defence against pests and pathogens. "Plants grown from JA-treated seed exhibited increased resistance against attack by spider mites, caterpillars and aphids, as well as against the necrotrophic fungal pathogen *B. cinerea*. Seed treatment with BABA-primed plants enhanced resistance against powdery mildew caused by *Oidium neolycopersici*".

What was particularly interesting about this work was the finding that protection was long-lasting, with enhanced resistance sustained for up to 8 weeks (Walter et al., 2013). Active compounds produced by *Trametes versicolor* can restrict the growth of mycotoxigenic fungi and the biosynthesis of their secondary metabolites (e.g., mycotoxins) in wheat. Tramesan is a 23 kDa α-heteropolysaccharide secreted by *T. versicolor* that acts as a pro-antioxidant molecule in animal cells, fungi, and plants. Foliar-spray of Tramesan (3.3 µM) on durum wheat cultivars susceptible to Septoria Leaf Blotch Complex, before inoculation of causal agents of Stagonospora Nodorum Blotch and Septoria Tritici Blotch, significantly decreased disease incidence (Scala et al., 2020).

3.4.1. Potential impact of induced resistance

Priming of induced resistance by treating seeds could be of great value in agriculture and horticulture, especially for crops that are likely to face pest and pathogen attack early in the growing season. If the priming effect is long-lasting, the need for further crop protection treatments (elicitors or pesticides) would be reduced. This can benefit biodiversity, reduce environmental impact, and reduce production and labour costs.

Pinto et al. (2012) examined the use and economic viability of resistance elicitors (Agro-Mos and potassium phosphite) in the management of grapevine downy mildew, caused by *P. viticola*. They found that, although both elicitors reduced infection, potassium phosphite – which induced resistance in this system – was an economically viable option for management of grapevine downy mildew. It worked either on its own or in combination with a fungicide.

3.5. Applying ecological principles: diversified systems

An emerging strategy to reduce damage from pests is to apply ecological principles to increase plant diversity in and around cropping fields. Biodiversity is critical for the functioning of natural ecosystems and is also a prerequisite for developing agro-ecological farming systems (Barot et al., 2017; Beilloun et al., 2019; Malézieux, 2012).

Biodiversity at the field level can be considered in three domains: temporal, spatial and genetic (see text box).

Temporal diversity includes crop rotation, which may be enhanced by including cover crops to provide green manure (i.e. organic material) to the soil. Including legume crops in a rotation also enhances soil fertility.

Spatial diversity includes extending and improving semi-natural habitats (e.g. hedgerows, flower strips) around field crops.

Genetic diversity includes various ways of mixing crops, including agroforestry.

While the impact of improving biodiversity on pest reduction may vary from year to year, or from field to field, there is a consensus that increased biodiversity in and around crops has positive effects (Martin et al., 2019).

On the other hand, enhancing plant biodiversity often comes at a cost. Land taken up by non-crop vegetation reduces the overall cropping area. Also, yields per hectare from the productive area of biodiverse systems have tended to be lower than from conventional systems (Letourneau et al. 2011).

Applying ecological principles to increase biodiversity

Existing practices

- Temporal diversity
    - Widening of the crop rotation
    - Use of green manures
    - Under sowing of clover
    - Extended mowing
    - Minimal tillage
- Use of service crops (e.g. Tagetes)
- Living mulches and roller crimper

Emerging practices

- Spatial diversity
    - Use of flower strips
    - Use of hedgerows, beetle banks and riperian buffers
    - Wildlife friendly mowing (from the inside to the outside)
    - Mulching
- Genetic diversity
    - Variety mixtures
    - Mixed cropping of legumes and cereals
    - Mixed farming
    - Agroforestry
    - Novelty crops
    - Agri-environmental schemes
- Cut and carry fertilizer instead of manure

Practices under development

- Agroforestry
- Pixel cropping
- Strip cropping
- Nature inclusive agriculture

It can be expected that the effects of diversity actions will differ both within and between the three domains, as described in the following paragraphs.

Temporal diversity can be achieved by sowing a crop in rotation with other crops (Bennett et al. 2012). However, a crop rotation comprising crops with similar timing of cultivations (e.g. a rotation of winter cereals) will have a lower effect on weed reduction than crops with different management and timing of cultivations (e.g. a rotation including winter cereals and spring-sown tubers) (Weisberger 2019).

Therefore, diverse rotations typically include crops with different planting and harvest dates – which provide contrasting growth habits and competitive characteristics – and with dissimilar tillage and weed management practices. Consequently, weeds can be challenged with a wide range of stressors, which checks their growth and reproduction (Isbell et al., 2017). A review of studies conducted with a range of crop species found that rotation resulted in lower weed densities in 21 cases, higher in one case and equivalent in five cases, when compared to monoculture systems (Liebman & Dyck 1993).

Temporal diversification can also be achieved by using cover crops, which may be grown before or after 'main crop' production. Cover cropping can suppress weeds by: altering environmental factors that affect weed germination and establishment; competing for growth resources, and; releasing phytotoxins[27], thereby reducing the number of weed seeds and vegetative propagules available to infest succeeding crops (Isbell et al., 2017; Teasdale et al. 2007).

Osipitan et al., (2019) showed in a meta-analysis of 53 studies on the impact of cover crop management on weed management, that weed biomass and density were negatively related to cover crop biomass. The meta-analysis showed that cover crops suppress weeds to an extent that depends on management decisions such as:

- choice of cover crop species;
- cover crop sowing season (autumn or spring);
- sowing dates within seasons;
- seeding rate;
- cover crop termination date;
- delay in main crop planting after cover crop termination;
- tillage system under which the cover crop was produced, and;
- integrating the cover crop with other weed control inputs.

Pest insects can use cover crops as a survival shelter. To avoid exposure to severe cold and or fluctuating temperature, many insects overwinter under plant debris or burrow into the soil. As air temperature changes, the temperature under the cover rises and falls slowly (especially when insulated by snow cover), giving insects, pests – and predators – a far more stable environment[28].

As cover crops can increase insect pests and disease populations, a better understanding of the interaction between them and their cover crop hosts will help in the design of crop management plans to minimise the risks to the main crop.

Regarding **spatial diversity**, Martin et al (2019) showed in a study covering 1 515 landscapes across Europe that landscapes with narrow fields (i.e. many boundaries relative to area) had 44 % more natural enemies and pest control increased 1.4-fold while maintaining high yields.

---

[27] https://www.scipress.com/ILNS.56.25, accessed 8 October 2020

[28] https://www.canr.msu.edu/news/how_insects_survive_cold_the_potential_effect_of_a_mild_winter, accessed October 8th 2020.

Skelsey et al. (2010) found that narrow strips of potatoes have a better disease suppression than wider strips.

Regarding **genetic diversity**, the use of variety mixtures in cereals (see Section 2.3.1) can be expected to have a lower effect on pest reduction than mixed cropping such as wheat and peas (Iverson 2014).

Mixed cropping involves the combination of two or more crops, which together improve plant health or reduce pest, disease or weed incidence (Boudreau 2013). In temperate regions, substantial research has been done on cereal-legume combinations.

A meta-analysis conducted to quantify the disease suppressive effect of intercropping cereals with legumes at different levels of nitrogen fertilisation showed that intercropping reduced disease incidence by 45 % on average (Zhang et al., 2019). While this reduction was significant for four out of six studied pathogens, it also showed that intercropping was sufficient to provide complete disease control and is therefore best used as a component in an integrated approach for managing plant diseases (Zhang et al., 2019).

Promising results in reduction of *P. infestans* in potatoes have been seen when cultivated in combination with other crops (Bouws & Finckh 2008).

Cover crops should be mixed to achieve high competition and biochemical suppression of weed growth (Varnholt et al., 2016). Further research is needed to evaluate and minimise the negative allelopathic impacts of cover crops on the main crop (Koehler et al., 2020), while realising their benefits for weed management (Shekoofa et al., 2020).

Another example of plant diversity contributing to pest suppression is 'push-pull' planting: insect-repellent plants are added to fields of crops to 'push out' pests; and insect-attracting plants are planted at the edges of the fields to 'pull out' pests and disrupt their life cycles (Midega et al. 2015).

When crops lack critical resources to support pest predators and parasitoids, mixed plantings and non-crop borders can provide nectar, pollen, alternate prey and refugia, thus increasing numbers and richness of these natural enemies of pests (Isbell et al., 2017). The diversity of vegetation across the surrounding landscape tends to be positively associated with the in-field abundance, richness and parasitism/predation rates of natural enemies. The diversity of vegetation is also associated with the diversity of insect herbivore pests, though not necessarily with pest abundance (Dainese et al. 2019; Holland et al. 2016; Chaplin-Kramer et al. 2011; Letourneua et al., 2009).

However some studies relating the richness of natural enemies to arthropod biological control have shown negative and neutral effects (Letourneau et al., 2009).

The mechanisms underlying the effects of increased biodiversity on pest reduction are not well understood. Further research is needed to explore beyond richness effects and develop sophisticated approaches for isolating mechanisms underlying biodiversity effects (Crowder and Jabbour, 2014).

Furthermore, to understand the mechanisms underlying biodiversity effects, it is important to include the socio-economic factors involved in creating and maintaining biodiversity-mediated ecosystem services such as pest control (Kremen et al., 2012). The essence of systems based on ecological principles is to restore soil and above-ground biodiversity in order to maximise natural and circular processes for plant nutrition and in-built health, pest and disease resistance, thereby creating a resilient production system (RISE, 2020).

3.5.1. Potential impact of applying ecological principles

The potential impacts of ecological functions in agriculture can be both positive and negative. Farming systems based on ecological principles potentially require lower levels of nutrient and PPP inputs and will therefore have a reduced impact on wider biodiversity, human health and environment.

There is a risk of lower yields when lower amounts of nutrients and PPPs are applied. Meta studies of organic farming show yield penalties compared to conventional farming of between 5 % and 45 %, depending on the crop (Ponisio et al. 2015; Seufert et al. 2012). Unless the farmed area is expanded proportionately, food output would fall if most or all EU land was converted to organic systems. However, expanding the agricultural area could be highly damaging to habitats and biodiversity.

New systems that combine the best of conventional and more sustainable practices are needed. A recent meta-analysis (Bellouin et al. 2019) summarising 3 736 primary studies on crop diversification showed that all diversification strategies benefit biodiversity. The majority of the studies indicate a positive impact of diversification on soil quality and also on productivity (Figure 9).

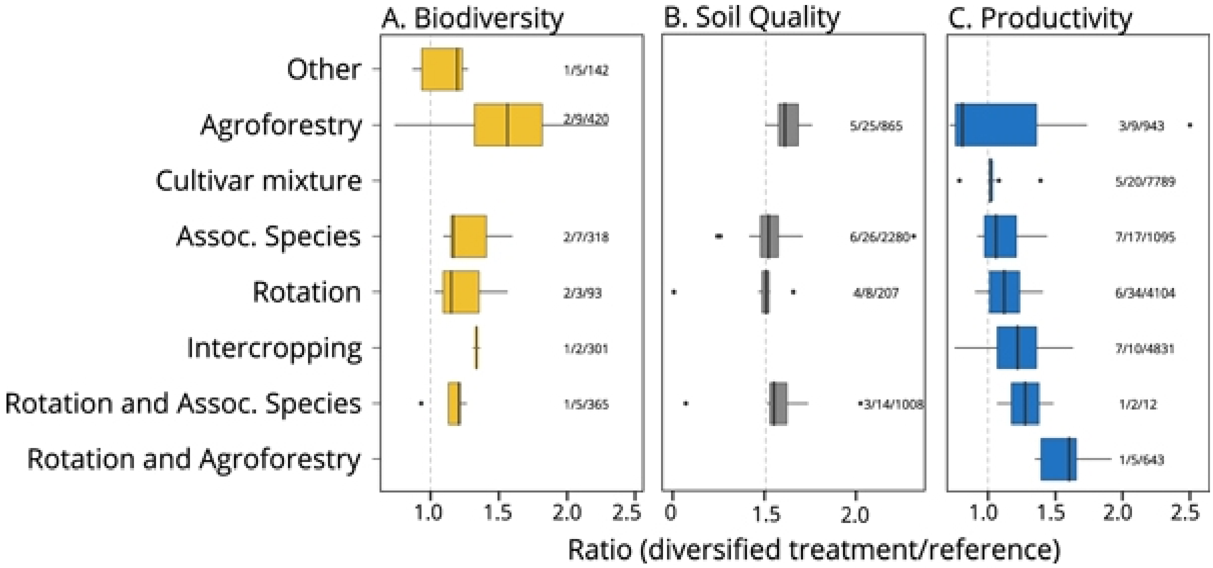


Figure 9. Impacts of crop diversification on biodiversity (yellow), soil quality (grey) and productivity levels (blue)

Source: Bellouin et al. 2019

The impacts are quantified with effect sizes (i.e. the ratios of a measurement in a diversified cropping system to its corresponding value in a less diversified cropping system).

The number of meta-analyses/effect sizes/individual studies included in each pair-strategy outcome are indicated at the right of the boxplots. When the ratio is greater than 1, the diversified system outperforms the less diversified one for the considered outcome.[29]

The meta-analysis by Beillouin et al. (2019) shows that diversified systems can contribute to sustainability and production goals. Although diversified farming practices have the potential to lead to higher and more stable yields, increase profitability and reduce risks in the long-term, the ecological benefits for the farmer do not outweigh the economic costs in the short term (Rosa-Schleich et al., 2019).

Combined practices deliver the greatest ecological and economic benefits at the farm level. Financial instruments are needed to increase the implementation of combined practices by adequately rewarding farmers for investing in the ecological benefits.

The challenge is to combine diversified and conventional practices into a sustainable system that secures food production, preserves biodiversity and supports farm incomes.

Key outstanding questions regarding the application of ecological principles are:

- how to restore and sustain natural resources (soil, water and biodiversity)?
- how to respond and adapt to the effects of climate change, including drought, rising temperatures and unpredictable rainfall patterns?
- how to control pests, diseases and weeds with a lower dependency on pesticides? and;
- how to maintain the incomes of farmers operating such a system?

On 25 June 2020, Wageningen University and Research launched the 'Farm of the Future'[30] to address these questions and experiment with diversified systems at a practical level (Figure 10). More fundamental questions are addressed by the H2020 project, including Diverimpacts[31] and Remix[32].

---

[29] Source: Evidence map of crop diversification strategies at the global scale, Damien Beillouin et al., 2019 Environ. Res. Lett. 14 123001 doi:10.1088/1748-9326/ab4449.

[30] www.farmofthefuture.nl

[31] https://www.diverimpacts.net

[32] https://www.remix-intercrops.eu/

Figure 10. Farm of the Future based on diversification at Wageningen University and Research[18]

3.6. Precision agriculture and DSS

Two trends in EU agriculture are relevant for the development of precision agriculture: 1) the number of people working on farms in the EU is decreasing, and; 2) the average holding size in the EU is increasing (STOA, 2016[33]).

These trends favour the introduction of precision farming technologies, provided that finances and skills are not limiting.

Precision agriculture, or precision farming, is a modern farming management concept using digital techniques to monitor and optimise agricultural production processes.

The development and implementation of PA is enabled by various technologies: object identification, sensors, Global Navigation Satellite Systems (GNSS), connectivity and other information and communication technology, robotics, and autonomous navigation. A detailed description of the development of these techniques is given by STOA (2016).

Precision agriculture

Existing practices

- Controlled traffic farming
- Decision support systems
- Variable rate technology
- Task maps

Emerging practices

- Precision spraying

Practices under development

- Sensor-based methods for detection, identification and quantification of diseases
- Remote sensing for weed control

In the following paragraphs, the PA techniques relevant to crop protection are discussed.

---

[33] STOA has previously commissioned a Scientific Foresight project 'Precision Agriculture and the future of farming in Europe', which provides relevant information for this section: https://www.europarl.europa.eu/thinktank/en/document.html?reference=EPRS_STU(2016)581892

Controlled traffic farming was one of the first PA applications in arable farming. Since 2004, farmers have been able to use GNSS on farm machinery in order to define precise routes ('tram lines') in the field. This prevents overlap or gaps in application, thus saving energy, water and agrochemicals. Typical savings are in the order of 5-10 %. Adoption rates for GNSS can be as high as 80 % on modern farms in specific regions of the EU (STOA, 2016). Farmers follow the tram lines for subsequent cultivations.

Farmers started using **decision support systems** (DSS) to optimize crop management in the 1980s. However, the first applications of geo-data in DSS for crop management are only 15 years old.

The use of crop, weather and soil sensors enables the collection of real-time data on crop and environmental conditions. Connection of that information to the location of pests, diseases or weeds, together with the population dynamics of the target crop, will increase the efficacy of control measures.

Decision support applications, such as Akkerweb[34], collate this data and present it as management information for the farmer – an example would be a task map for spraying (Evert, van et al., 2018).

Currently, about 30 applications are available on Akkerweb. The Potato Haulm Killing application, for example, gives a recommendation for desiccant use to terminate a potato crop, and may lead to an average reduction in herbicide use of 38 % (Evert, van et al., 2018).

The late blight application makes recommendations on the application of fungicide to control *Phytophthora infestans*. The application advises on when to spray, depending on climatic conditions and growth development of the fungus; and indicates the amount of fungicide to apply, based on the amount of above-ground leaves and stems measured by crop reflection sensors (Cooke et al. 2011). The application has resulted in reductions of fungicide use of 20-30 % (Evert, van et al., 2018).

Recent developments in viticulture have been described by Pertot et al. (2017). Scheduling fungicide application against downy mildew, based on new forecasting models of infection rate, allowed a reduction of 50-66 % in pesticide applications (Caffi et al., 2010). This model is integrated into a DSS named vite.net® (Rossi et al., 2014).

About ten years ago **variable rate technology** (VRT) for plant protection products was first applied (Kempenaar et al., 2014 b, 2014c).

The ability to vary the dosage rate can be linked to soil organic matter content to control herbicide application. For plant growth regulators, the application rate can be based on the biomass present. For leaf desiccants, the rate can be based on the chlorophyll detected. Considerable work is underway for weed identification to allow selective spraying of contact herbicides.

A good example is variable rate potato haulm killing (Kempenaar et al., 2014b), where the herbicide dose is varied based on the conditions of the potato canopy conditions measured by sensors. Kempenaar et al. (2017) made an overview of potential variable rate applications (VRAs) in potato crop management in The Netherlands and identified 13 potential VRAs in potato. These

---

[34] www.akkerweb.eu

ranged from soil tillage, to planting, to crop care, to selective harvest. Soil herbicide weed control, late blight control, and haulm killing were among the most promising applications of VRA, for which a cost-benefit assessment was made. Savings on pesticide use and N-fertiliser use with the VRAs were on average about 25 %. Savings in pesticides will increase with higher precision.

Precision spraying is another development for optimising the application of PPPs through improved application technology. Modern crop sprayers are able to vary application rates based on (near) real time data.

Further developments in spraying include a range of automated sprayer functions: automatic tank filling to avoid spillage; automatic dilution and sprayer cleaning; automatic boom height adjustment to enable lower nozzle height and reduce spray drift; automatic GPS nozzle-control to eliminate overlaps, and; individual nozzle control for high-precision dose rates.

As an example of nozzle control, Machado et al. (2019) were able to reduce application rates of insecticides in wheat by 50 % through a combination of a twin flat fan-tip nozzle and use of the adjuvant sodium lauryl ether sulphate.

Electrostatic spraying to reduce drifting of pesticides away from the target crop and improve spray efficiency is another area of spray research, evaluated by Urkan et al. (2016). The evaluation found that electrostatic spraying achieves better coverage than conventional spraying and uses up to 10 times less water, but also has disadvantages.

Appah et al. (2019) looked at the characteristics of pesticide spray droplets and ways of improving spray efficiency by including surface-active agents, or adjuvants, to lower the surface tension of the spray solution and improve the spreading of droplets on crop surfaces. The reviewers proposed an optimum combination of electrostatic parameters to improve spray efficiency.

Sensor-based methods are under development for the detection, identification and quantification of plant diseases (Mahlein, 2016; Hillnhütter et al. 2010; Mahlein et al. 2012; Sankaran et al. 2010).

Sensor-based methods for disease detection include: early detection of head blight (Fusarium graminearum) in wheat (Bauriegel et al. 2011, Bravo et al. 2003); early detection of fire blight (Erwinia amylovora) in pear trees (Bagheri et al. 2020); and detection and discrimination of Cercospora leaf spot from other fungal diseases in sugar beet using a smartphone (Hallau et al. 2018).

A potential use-case of a sensor-based method is being investigated in the Dutch project 'Precisielandbouw 2.0 project Smart Ziekzoeken'[35]. Using hyperspectral cameras, fungus-infected potato plants are observed in the field for subtle changes in light reflection in the first phase after plant infection. In combination with 3D cameras that measure the volume and change in leaf structure, infected plants can be detected. These techniques enable much shorter time intervals between crop surveys (also called scouting), which can be decisive for robust disease detection.

---

[35] https://library.wur.nl/WebQuery/wurpubs/fulltext/385490

In the IOF2020 project[36], an arable trial investigates use cases to examine how Internet of Things (IoT) technology enables precision farming. The use cases are used to "link existing sensor networks, earth observations systems, crop growth models and yield gap analysis tools to a variety of databases. This combination of information creates effective, standardized actuation protocols ('task maps') for machines and robots. Focusing on the cultivation of three main crops (wheat, soybeans and potatoes), in different European regions and climate zones, the trial includes activities along the cropping cycle. With the help of IoT technologies, data on key variables such as the soil, climate conditions, growth of plants and weed, disease or pest prevalence can be combined in a meaningful way."

Attention should be given to the spatial and temporal dynamics of pest and disease development, and how the use of continuously updated models can offer support in decision making for effective and reduced PPP use. A spatial network of continuous sensing of climatic conditions, together with disease and pest observations, can be an early warning tool for intervention. The network should also include observations on predator developments so as to assess the damage risk for the crop. This is also a tool for reducing the risk of new invasive pests and diseases.

Remote sensing may be used to detect and control weeds. Most studies focus on detecting weeds between rows, which means detecting the rows and then the vegetation in-between. The detection is based on the geometric structure of the rows and the spectral contrast between vegetation and soil (Weiss et al. 2020).

The problem becomes harder when weeds and crops are mixed together within the same image and have a similar spectral behaviour, although these weeds can be removed using mechanical intra-row weeders (see Section 3.1).

Methods of weed control are constantly developing with new inventions emerging. These include micro-spray techniques, hot-water sprays, and laser systems.

3.6.1. Potential impact of precision agriculture

The Scientific Foresight Study "Precision agriculture and the future of farming in Europe" (STOA, 2016) draws the following conclusions on the potential impact of precision agriculture:

- PA can make a significant contribution to food security and safety:
- PA offers technology solutions to produce more with less inputs;
- PA will enhance food safety and plant health;
- PA can promote sustainable farming:
- PA technologies are already in use with positive impacts on the environment;
- PA will generate sustainable productivity gains;
- PA will trigger wider societal changes:
- PA will influence work practices and life conditions on farmland;
- New farming business models are under development;
- Precision agriculture requires the learning of new technological, environmental and managerial skills.

---

[36] www.iof2020.eu

The STOA study found that *"At the moment, a lot of progress has been made in PA development, and the PA market is fully embraced by the sector and investors, but the full potential of PA has not yet been harnessed."*

The study had four main conclusions:

- PA can actively contribute to food security and food safety;
- PA supports sustainable farming;
- PA will trigger societal changes along with its uptake rate;
- PA requires new skills to be learned.

Plant protection products

Existing practices

- Alternate mode of action
- Spray nozzles
- Dose reduction (LDS)
- Precision spraying

Emerging practices & practices under development

- Micronutrient formulations

An additional point concerns the interoperability of farming equipment, which needs to be improved. Exchanging data between field machinery and farm management information systems is key for a further growth of PA technologies and smart farming methods in Europe[37]. There is active collaboration within the industry to make the different technologies compatible through ISOBUS, an international communication protocol that sets the standard for agriculture[38]

These techniques will require a certain investment by farmers. The need for large investments may lead to an increase in farm size and a reduction in the number of small family farms. However, contractors currently carry out about 60 % of farm work in Europe according to CEETTAR (The European Confederation of Agricultural, Rural and Forestry Contractors)[39] and can provide farmers with technical equipment and qualified personnel, thus reducing investment costs for farmers.

Despite the investment costs, precision farming has the potential in increase farm incomes by producing 'more with less'. Furthermore, PA may be easier for some (mostly large-scale) farmers to incorporate into their existing farming practices than some other emerging crop protection practices, such as the application of ecological principles (Lefevre et al., 2020).

3.7. Plant protection products

The discovery and introduction of plant protection products was one of the major enablers of intensification of agriculture in the 20th century.

Intensification has led to increased yields per hectare, which has been a critical development for food security at both the EU and global levels. Without intensification, more land would be needed for food production, which would have negative environmental impacts.

In the other hand, the intensification of food production has had undesirable side effects, including declines in biodiversity, soil and water quality, as well as concerns for human health.

As a result, it is necessary to regulate the use of PPPs at national and European levels. EU regulation is based on the use of hazard-based risk criteria and risk assessments. This approach has

---

[37] www.IOF2020.eu

[38] https://www.agleader.com/blog/what-is-isobus-2

[39] https://www.ceettar.eu/news.php?item=12

led to the removal of a number of PPPs (products and active ingredients) from the European market. Most PPPs are agrochemicals and new products are released continuously. The introduction of new working mechanisms in products is one of the means to prevent resistance development in target organisms. However, most new products today are reformulations using existing active substances. The discovery of new active substances is currently at a relatively low level.

An overview of the use of PPPs is provided in Section 2.2. Biopesticides are discussed in Section 3.3 on biocontrol. Possible reductions in the use of PPPs through precision agriculture and spray application technologies are described in Section 3.6. This section focuses on the health and environmental impacts of PPPs, and farmer behaviour and economics with respect to PPPs.

3.7.1. Health impacts of PPPs

Pesticide use in the EU is governed by Regulation (EC) No 1107/2009 (the PPP Regulation), and Regulation (EC) No 396/2005 (the Maximum Residue Level (MRL) Regulation).

Both these Regulations have been extensively evaluated (as explained in Section 5.2.1.) and one of the conclusions was that Regulation (EC) 1107/2009 contributes to the protection of both human health and the environment. Societal concerns are likely to result in stricter environmental and health criteria.

Another important consideration regarding the use of PPPs is the risk of human pathogens becoming resistant to human medicines that are of the same class of chemicals as those used in PPPs. Resistance that develops in one sector can be transferred across sectors and species.

Through processes of co-selection and cross-resistance, resistance to one antibiotic may render an organism resistant to various unrelated drugs and chemicals[40]. An example is resistance of the fungus Aspergillus sp. to azole drugs. This fungus can cause lung conditions in humans that can be life-threatening for people with an underlying condition. Pathogen resistance to chemical treatments is therefore a growing concern.

3.7.2. Environmental impact of PPPs

There has been a substantial decline in biodiversity – both above and below the ground – in agricultural ecosystems, as reflected in declining populations of farmland birds and insects in parts of the EU. As a result, the ecosystem functions that these organisms provide – including natural pest control – are endangered or lost as well.

Among other factors, pesticide use has been identified as an important cause of environmental impacts. Pesticides contribute to the pollution of ground and surface waters, and there are strong indications that long-term exposure to PPPs can have a negative impact on biodiversity (Topping et al., 2020).

Other factors affecting the environment include industrial chemicals, medicines, fertilisers, and mechanisation. Other threats include climate change and the introduction of alien invasive species.

---

[40] http://www.fao.org/3/BU657en/bu657en.pdf

There is a multitude of factors – both within and outside agriculture – that can have affect the environment. It is therefore difficult to isolate and assess the specific impact of PPPs. The complexity of interactions: between species; over (trophic) levels along food chains; above and below ground, makes distinguishing cause and effect very hard. Reduction in one species may interfere with habitat or food requirements of another species in another trophic level.

"The impacts and potential risks of PPPs on terrestrial above-ground and water organisms are relatively well documented. Tighter restrictions and withdrawal of active substances with negative impacts on pollinators have contributed to a higher level of environmental protection" (Buckwell, 2020).

Insects (particularly pollinators) and birds are the two most studied groups. The European Environmental Agency (EEA) monitors changes in farmland biodiversity using two main indicators: the farmland bird index and the grassland butterflies index. Both indices show similar decreases between 1990 and 2017: a 33 % reduction in common farmland bird numbers and 39 % reduction in grassland butterfly populations[41].

Several studies have linked the use of PPPs to insect decline. Geiger et al. (2010) identified 13 components of agricultural intensification and found pesticides had the greatest consistent negative impact on the species diversity of plants, carabid beetles and farmland birds.

There can be little doubt that agricultural intensification has contributed to declines in farmland birds across the EU. Loss of habitat is a direct effect of intensification. Indirect effects through changes in food availability as a result of PPP use, and sub-lethal effects on birds, have also been found (Mackenzie, 2009).

The impact on below-ground soil organisms is even more complicated. Soil scientists have just begun to unravel the complex food webs of micro and macro-organisms in soil. Communities of microorganisms in the soil can affect plant growth and interactions with above-ground herbivores.

The soil biome (or biological community) is highly complex and influenced by climatic conditions and plant coverage (Mommer et al., 2018). There is growing interest in utilising soil microbiomes to improve crop performance, for example as a means of pest control. Plant responses to microbiomes are species-specific and emphasise the need to characterise the responses of taxonomically diverse plant species to different microbiomes (Howard et al., 2020).

The beneficial effects of a microbiome inoculant for one plant species may not be predictive of its capacity to improve the performance of another. The evidence on the potential impact of PPPs on soil functions and soil ecosystems is not consistent (FAO and ITPS, 2017) and more insight and data on soil ecosystem functioning is needed.

EEA monitoring data regarding the chemical status of European waters (EEA, 2018[42]) shows that pesticides and their metabolites cause 6.5 % of groundwater bodies (by area) to fail in achieving the 'good status' objective set in the Water Framework Directive. The monitoring data show a reduction in pesticide contamination in surface water over recent years, although only a limited number of substances were monitored.

---

[41] http://www.eea.europa.eu/data-and-maps/indicators

[42] https://www.eea.europa.eu/publications/state-of-water

More monitoring data would help to verify whether the model predictions during the risk assessment are correct and/or risk mitigation measures are effective (Ecorys, 2018).

Further research is necessary. Better assessment methods are needed to understand the cumulative risks from pesticides for populations; for diversity within and between species, and; for relationships between species and ecosystem services.

3.7.3. PPPs and farmer behaviour and economics

Farmer behaviour

Although alternative methods have been developed, farmers continue to use plant protection products. Lee et al. (2019) carried out a literature review of policy instruments for reducing pesticide use in Europe. The review assessed the issues and discussed ways in which farmers might be encouraged to alter their practices. The following paragraphs are quoted from the review:

"The review determined that no specific instrument is guaranteed to reduce pesticide use. Instead, characteristics comprising an instrument were confirmed to be beneficial to reducing pesticide use. In particular, mixes of instruments, with varying degrees of authoritative force, applied at multiple scales with stakeholder collaboration were identified as beneficial to reducing farmer pesticide use."

"Despite the development and promotion of alternative methods, barriers to reducing conventional pesticide use persist, including a lack of knowledge of alternative methods, a lack of funds, labour, time and tools and concerns over crop yield productivity and profitability (Van Eerdt et al., 2014; Lefebvre et al., 2015; Birch et al., 2016; Lamichhane et al., 2016b; Doonan, 2017). As a consequence, pesticide use reduction will not emerge spontaneously."

"According to Runhaar et al. (2017), behavioural change by farmers depends on the extent to which farmers are (i) enabled, (ii) legitimised, (iii) demanded and (iv) motivated to change their behaviour towards the desired policy goals". "The presence or absence of these four, interrelated, factors partly is a given, and partly can be provided by instruments"

"The first factor relates to ability, such as time, skills, information or resources farmers should possess to reduce their pesticide use aided by information or economic instruments (Timprasert et al., 2014; Tey et al., 2014; Wyckhuys et al., 2018; Runhaar et al., 2017). Employing alternative crop protection methods is more time, labour, information and knowledge intensive than conventional farming systems (Beckmann and Wesseler, 2003; Lefebvre et al., 2015)."

"The second factor relates to whether or not using or reducing pesticide use and its consequences is legitimised, supported or accepted by legal or social norms (Feola and Binder, 2010; Hall et al., 2015; Runhaar et al., 2017). Legitimacy can be enhanced by instruments such as covenants or interactive governance arrangements (Bouwma et al., 2015)."

"The third factor is whether or not farmers are directly or indirectly requested to reduce pesticide use. This can be in a negative way (e.g. NGO campaigns) or in a positive way (e.g. a consumer demand for pesticide-free food."
"…demand can be influenced by formal requirements and regulations, consumer awareness and market pressure (Runhaar et al., 2017)."

"The fourth factor is willingness to change pesticide use and adopt alternative farming practices, which can originate from an intrinsic motivation or an extrinsic one (commercial opportunities for instance)."

"The four factors are interrelated. For example, the presence of ability can often enhance farmer motivation to reduce their pesticide use as seen in an example of types of land tenures (Runhaar et al., 2017)."

"The coupling of social, environmental and economic aims within an instrument mix is viewed to be beneficial to reducing pesticide use (e.g. Falconer and Hodge, 2001; Archer and Shogren, 2001; Barzman and Dachbrodt-Saaydeh, 2011). A multiple aim may appropriately consider the varying reasons why farmers do not desire to alter their practices (e.g. Jacquet et al., 2011; Peshin et al., 2009; Van Kasteren, 2012)."

"However, other literature has shown that farmers' ability to adopt more sustainable farming practices (including but not limited to pesticide use reduction) is substantially limited by outside factors and actors, including requirements set, and prices paid by, other companies in agri-food industry (Schoonhoven and Runhaar, 2018). This underlines that reducing pesticide use is not always a free choice and that multiple instruments, by public and private actors, will often be needed for effective steering towards pesticide use reductions."

"In conclusion, four instrument mixes were reported from the review as beneficial to reducing pesticide use; covenants and subsides; prescriptions and subsidies; prescriptions and advisory services; prescriptions, monitoring, taxes, training and advisory services. Ineffective reports were frequently identified regarding the sole use of regulatory based instruments, namely bans and prescriptions."

Economics

Few case studies of the economic loss of individual active substances have been published.

Noleppa et al., (2017) performed an *ex ante* study after the ban of neonicotinoids to investigate the economic impact on oilseed rape production in six European countries[43]. They found that European oilseed rape farmers would have generated an additional 400 million Euro market revenue without the banning of neonicotinoids.

An average arable European farmer has lost an income equivalent to one week of work. The oilseed rape sector's income has decreased by 513 million Euro. These results were found in the years immediately after the ban and do not include the long-term effects.

Following the ban, farmers switched to pyrethroid use instead of seed treatments with neonicotinoids. However, actions such as introducing new crops and changing crop rotations were not included in the study. In future, the costs of the withdrawal of active substances should take into account crop rotation effects as well, in order to assess the economic impact on overall farm income rather than just an individual crop.

In contrast, a study at the farm level from France shows that low pesticide use rarely decreases productivity and profitability in arable farms (Lechenet et al. 2017).

---

[43] https://www.ecpa.eu/sites/default/files/documents/HFFA_Research_Paper_neonics_internet_protection.pdf

The study analysed the potential conflicts between pesticide use and productivity or profitability. Data from 946 conventional (non-organic) commercial arable farms showed contrasting levels of pesticide use covering a wide range of production situations in France.

In 77 % of the farms, no conflict between low pesticide use and both high productivity and high profitability was detected. In 59 % of the farms, total pesticide use could be reduced by 42 % without any negative effects on both productivity and profitability.

An important qualifying remark made by the study is that the potential reduction in pesticide use without significant productivity loss holds for farms with a relatively high pesticide usage.

3.8. Summary of the potential impacts of new and emerging crop protection practices

Sections 3.1 to 3.7 of this chapter assess seven categories of new and emerging crop protection practices. Table 3 rates the potential impacts of these seven practices on a range of key sustainability factors for the future of crop protection in Europe.

Each category is rated on its potential to have a positive, neutral or negative impact on the various sustainability factors.

The table is based on the information found in (peer-reviewed) literature as described in Sections 3.1 to 3.7, together with expert judgement. The weighting of the impacts should be seen as indicative.

Table 3 Potential impacts of new and emerging crop protection practices

Practice / Impact factor	Mechanical techniques	Plant Breeding	Biocontrol*	Induced resistance*	Ecological principles*	Precision agriculture	PPPs
Crop yield	=	+ +	+ +	+	+ +	+ +	=
Farmer income	=	+	=	=	=	+	=
Biodiversity and pollinators	=	=	+ +	=	+ +	+	-
Climate change	-	+	=	=	+	+	=
Public health	+	+	+	=	=	+	=
Food safety	+	+	+	=	+	+	=
Food security	=	+	=	+	=	+	=
Competitiveness of EU farming	=	+ +	+	+	=	+ +	=

*The impact assessment is indicative, i.e. the available data and information is insufficient or inconclusive.
The impacts are rated as Positive (+ or + +), Neutral/Unknown (=) or Negative (-)

Table 3 shows that Precision agriculture has positive impacts on all factors, with high impacts on Crop Yield and Competitiveness. A particularly important aspect of PA, which is not evident from

Table 3, is that its various practices have complementary effects on the other categories of practices.

Plant breeding is positive on all factors except Biodiversity, which is neutral.

All impacts of Biocontrol, Induced resistance and Ecological Principles are positive or neutral; with Biocontrol and Ecological principles having high impacts on Biodiversity and Cropyield, although their impacts on Farmer income are neutral.

Improved Mechanical techniques have small positive impacts on Public health and Food safety. However, there is a negative impact on Climate change due to increased greenhouse gas emission from the soil and increased use of fuels. The impact of mechanical techniques is likely to improve in future when they are combined with precision agriculture practices.

Complementary interactions of PPPs with other new practices, particularly Precision agriculture and improved sprayer technology, can be expected to improve application efficiency and therefore reduce the amounts of PPPs that are applied. Furthermore, the combined interactions of all the other new practices can be expected to reduce the overall need for PPPs in the future and reduce the negative impact on biodiversity and pollinators.

Table 4 rates the potential impact of the new and emerging crop protection practices on the control of weeds, diseases and insects. These ratings aim to give an indication of how well weeds, diseases and insects can be controlled when the use of PPPs is reduced or eliminated.

The table is based on the information found in peer-reviewed literature as described in Sections 3.1 to 3.7, together with expert judgement. The weighting of the impacts should be seen as indicative.

Table 4. Potential impact* of new and emerging crop protection practices on the control of weeds, diseases and insects

Pests Practices	Weeds	Diseases	Insects
Mechanical techniques	●●●	○	●
Plant breeding	●●	●●●	●●
Biocontrol	●	●	●●
Induced resistance	○	●●	●
Ecological principles	●●●	●●●	●●●
Precision agriculture	●●●	●●●	●●●

*The weighting of the impact should be seen as indicative.
●●● high potential impact, ●● intermediate potential impact, ● low potential impact, ○ [illegible]
impact.

It can be seen from Table 4 that Precision agriculture and Ecological principles have high potential impacts on all three pest groups. Plant breeding follows with a high potential impacts on diseases, and intermediate potential impacts on weeds and insects.

Mechanical techniques have a high potential impact on Weeds, but otherwise they have no or a very low potential impact on diseases and insects. Biocontrol and Induced resistance have intermediate, low or no potential impacts on weeds, but are seen as potential practices for disease and insect control.

Table 4 indicates that a combined approach employing most of these categories of practices is required to provide effective control of weeds, diseases and pests with reduced use of PPPs. The most critical categories are Mechanical techniques, Plant breeding, Ecological principles and Precision agriculture. Biocontrol and Induced resistance may become increasingly effective over time.

3.9. Conclusion on crop protection practices

The widespread adoption of alternative crop protection practices requires changes in farming systems. Current intensive systems are 'high input – high output' whereas the aim of sustainable farming would be to produce 'more with less'.

Despite progress in the development of alternative practices, farmers continue to have a high dependency on crop protection products. Reduction in pesticide use will not take place spontaneously; farmers are most likely to be motivated by a mixture of social, environmental and economic aims within policy instruments (Lee et al., 2019).

New and emerging crop protection practices include mechanical techniques, plant breeding, biocontrol, induced resistance, applying ecological principles, precision agriculture, and plant protection products. All of these can contribute to the development of sustainable farming systems; and the greatest impact will be seen when they are used together in the most suitable combinations.

MacRae et al (1990) suggested three stages in the transition to sustainability: efficiency, substitution and redesign (the ESR paradigm). Regarding crop protection practices into an ESR context, the conclusion is that until recently focus has mainly been on increasing efficiency of PPPs and substituting PPPs. Redesign has so far received less attention. Further steps in the transition to sustainability will require an increased focus on systems redesign.

Section 3.5 on ecological principles concluded that combinations of diversified and conventional practices are likely to deliver the greatest ecological and economic benefits at farm level. These systems are diverse, and have a natural resilience towards pests, diseases and weeds. The need for control will be reduced and as a result, the need for external inputs as well. However, pests, weeds and diseases will always be attracted to crops and some form of management will be necessary. Erisman et al. (2016) describe a "better balance benefits both" approach to agriculture and biodiversity, which "provides opportunities to create a resilient system in which both food production and nature can thrive". An example of how a combined approach could work at farm level is the Farm of the Future[44] (Section 3.5.1. Figure 10). However, there are considerable challenges for developing and implementing such an approach.

Monitoring agricultural processes, including crop protection, is important for optimising production, including risk assessment and management. Precision agriculture enables monitoring

---

[44] www.farmofthefuture.nl

through the use of sophisticated digital techniques, although further research is needed to improve understanding of cumulative and combined effects (Section 3.6).

Precision agriculture benefits all sustainability factors. Its use continues to increase in conventional farming because of the efficiency savings that it brings. It therefore seems almost inevitable that its uptake will continue, almost regardless of the rate of uptake of alternative practices. PA may be easier for some (mostly large-scale) farmers to incorporate into their existing farming systems than some other crop protection practices.

A can be seen in Tables 3 and 4, plant breeding is a highly positive factor for improving crop yield and the competitiveness of EU farming. However, the contribution to competitiveness will depend on the relevant legal permissions to use new breeding techniques inside and outside the EU. Greater restrictions within the EU could put EU producers at a competitive disadvantage compared to producers elsewhere.

Biocontrol (along with ecological principles and precision agriculture) is one of just three practices showing the potential to make a positive contribution to biodiversity. It also shows a high potential for improving crop yields and shows positive impacts for public health and food safety. However, it may be costlier to use than conventional pesticides and there are currently a number of barriers limiting uptake worldwide.

The challenge is to integrate the new varieties, mechanisation, and biocontrol tools in new cropping systems that are enabled by precision agriculture technologies, such as autonomous robots, sensing devices and decision support tools. Breeding programs take at least 10 to 15 years, the development of a biocontrol agent takes 5-10 years, and designing diversified cropping systems including addressing underlying research questions, will all take significant time. Continuous development of all crop protection practices is needed to better disrupt the life cycle of pests, diseases and weeds, and to improve non-chemical control methods and application of chemical control using intelligent application technologies adapted to local circumstances, including the knowledge and skills of operators.

As explained in Section 3.7.3, farmers face a number of barriers to reducing their use of conventional pesticides; they will not give them up spontaneously. Behavioural change by farmers depends on addressing a number of inter-related internal and external factors. Chapter 4 discusses ways to initiate and facilitate such change.

4. Drivers and enablers for implementing alternative crop protection practices

This chapter describes drivers and enablers for implementation of alternative crop protection practices – drivers trigger change, enablers facilitate change.

The main aim for implementing alternative crop protection practices is to enable European farmers to work in a sustainable manner while securing overall food production, preserving biodiversity and supporting their incomes.

As it is farmers who implement crop protection practices, this chapter focuses mainly on actions to encourage them to adopt alternatives. Section 3.7.3 explains how behavioural change depends on farmers being sufficiently enabled, legitimised, demanded and motivated. When choosing the most suitable actions, or combinations of actions, it is necessary to consider these factors, as well as the social, environmental and economic characteristics of the farmers being targeted.

A list of actions grouped under the social, environmental and economic contexts is presented below. The actions may be drivers or enablers. Note that some actions may address more than one context:

Social context

Social drivers

- **Social events** help to foster relationships and co-operation between farmers. Farmers learn from their peers. Discussion groups, overseen by a facilitator have proven to be a satisfactory method. Demonstration farms and focus farmers have a key role in this process. Participatory budgeting could be a strategy to foster co-operation.
- **Farmers' associations** can be very influential. Trade journals published by farmers' associations are a good information source for farmers. Other ways of informing farmers may include the local mayor's office, rural fairs and agricultural shows.
- **Engagement of young farmers** (including at school or university) is important. In order to enable young farmers to adopt new crop protection techniques, they should be integrated into both the practice and theory of their studies at an early stage. Young people are often more flexible and open to new ideas than their elders.

Social enablers

- Support from **training and advisory services**, such as those planned in the SUD (Sustainable Use Directive) – Directive 2009/128/EC.
- **Multi-stakeholder action** involves government, farmers, researchers and markets – with interactivity between public and private sector views (Lee et al., 2019). This type of approach takes into account: the multi-faceted nature of the challenge (i.e. the social, environmental and economic contexts); the effects of geography and time-scale on stakeholder decisions; and the different and often contrasting interests and objectives of the various stakeholders.
- A valid 'innovation broker' (often a team of trained experts) is crucial for the implementation of **multi-farmer participatory approaches**. Although innovation in crop protection has significant policy relevance, innovation brokerage (i.e. **extension services**),

has been delegated by governments to the private sector in most European countries. There are arguments for restoring the link between public policies and on-farm practices. The future EU Common Agricultural Policy (CAP) gives Member States more opportunities to strengthen the role of AKIS (Agricultural Knowledge and Innovation Systems)[45] to link public policies and on-farm practices.

- The use of mobile phones and social media for fast and widespread **dissemination of information** is an increasingly important way for farmers to keep up-to-date on developments in alternative crop protection practices.

Environmental context

Environmental drivers

- An analysis of potential **conflicts with EU regulations** concerning the introduction of new crop protection measures is required to remove any unsubstantiated barriers to their use. One issue concerns the regulation of **new plant breeding techniques**. There are also some **pesticide regulations** (e.g. safe dosage levels) that may need to be updated to take into account the more accurate applications that can be achieved with new precision agriculture techniques.

- An analysis and possible review of **risk assessment** for crop production may be required to take into account advances in crop production and crop protection. There is a need for analysis of the effects of policy and regulatory changes following from:
  - The European Green Deal[46] and the Farm to Fork Strategy[47]
  - The future CAP
  - Financial support conditions
  - Revision of EU legislation

- **Activation of existing local farmer networks** to test ways of enhancing diversity in field crops for protecting and enhancing biodiversity in arable systems. This involves assessing the functional diversity (i.e. those components of the ecosystem that have most influence on biodiversity). Such projects could list and communicate locally adapted good practices to maintain or increase biodiversity in arable crops.

- **An analysis of potential risks of biocontrol** tools and techniques for product handling is needed to assess and remove potential barriers. Biocontrol agents are regarded as natural and, in general, are regarded as less harmful for the environment and human health. However, they may be harmful, and they need to be subject to careful review. There is a need for risk assessment schemes that aid and speed up the review process for biocontrol products.

Environmental enablers

- **Involving local farmers in testing new technologies** for precise weed, pest and disease control. Involving farmers in testing new machinery allows them to try out relatively expensive machines under their own conditions. The farmers are then able to share their experiences with other farmers in the area. Similarly, farmers would benefit from being involved in testing new biocontrol techniques. However, as biocontrol testing may take

---

[45] www.proakis.eu.

[46] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

[47] https://ec.europa.eu/food/farm2fork_en

several years and may result in lower yields, it would be reasonable to expect that farmers would receive financial compensation for any losses they incur compared to their conventional techniques.

- **Participatory projects** enable farmers to become involved in the introduction of new crop varieties, mixtures and cultivation techniques with the help of experts, for example:
    - Developing local strategies for cover cropping. This would involve farmers and experts identifying the most promising species (and mixtures), along with the most suitable cultivation methods and programmes for the locality.
    - Developing local strategies for intercropping. In this case, farmers would work with experts to identify the most promising crop/intercrop combinations and cultivation methods for the local conditions, taking into account market demands.

Economic context

Economic drivers

- Possible **dietary changes** by European citizens (see Section 2.7) would have major impacts on the demand for various foods and stimulate changes in agricultural systems and supply chains.
- **Informing farmers** on the limitations of existing technology and machinery on farms, and the benefits of new technologies. Considerations would include assessing the degree of obsolescence of current technologies and machinery, and comparing with the investment costs and the returns from upgrading. The assessment would take into account both immediate gains and long-term impacts.
- Analyses of the **profitability** of alternative crop protection strategies compared to the use of agrochemicals – at both micro-economic (farm level) and macro-economic (regional, national and European levels) – are needed to give useful information for guiding future actions.

Economic enablers

- **Training** and qualification of farmers and contractors to improve their skills.
- Education of farmers on the sustainability benefits and incentives of **EU initiatives** including:
    - The European Green Deal[48] and the Farm to Fork Strategy[49]
    - The future CAP
    - Financial support conditions
    - Revision of EU legislation

- **Co-design groups** provide a participatory approach involving farmers, researchers, industry, advisers and other stakeholders in the design of alternative farming systems. A participatory approach allows farmers to discuss and learn from peers and other stakeholders under expert guidance. The new designs can be implemented on local farms to suit local conditions and market demands. This is a way of enhancing regional agroecological support which, together with support from an expansion of public

---

[48] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

[49] https://ec.europa.eu/food/farm2fork_en

advisory services, would help to mitigate the financial risks taken by farmers embarking on such major changes.

- The use of **certification schemes** concerning the traceability of farm products and registration of crop protection measures, which cater to consumer expectations and are enforced by retailers or traders. Product Marketing Organisations will be stimulated under the new CAP and may have a role in supporting farmers with such registrations.
- Enable the **insurance for financial losses** in case of yield losses stemming from reduced/alternative crop protection applied by of contractors
- Adopting alternative farming practices to improve biodiversity may make it useful for farmers to keep records of their field activities in a **field passport**. It could be helpful to have a history of biodiverse practices when buying or selling land.

5. Key legislation relevant to current and possible alternative crop protection practices

5.1. Introduction

The European Parliament has requested to provide them with policy options which can support farmers in developing their future crop protection strategy. We look forward to 2050 and take all existing and emerging techniques in crop protection into account. The extent to which the crop protection techniques are desired is a political issue and will therefore be ignored by us.
When putting policy options into practice, we have to deal with EU legislation. Therefore, we review relevant directives and other EU legislation with consequences for crop protection on social and economic impacts of existing and emerging crop protection practices. We will consider the emerging crop protection techniques as elaborated in the section 3.1 to 3.7 of this report. With respect to the impact assessment, we put the farmer and the grower in the centre of our analysis and assess what the consequences are of the existing legislation for the crop protection measures he can apply, and what the consequential impact on costs, yield and farm income is.

Section 5.2. describes the legislation. Section 5.3. analyses the legislative consequences for the alternative crop protection practices outlined in Sections 3.1–3.7 of this report. Section 5.4 briefly summarises the regulatory issues arising from alternative crop protection practices.

5.2. EU legislation with relevance for crop protection

5.2.1. Regulation (EC) 1107/2009 and Regulation (EC) 396/2005

Regulation (EC) 1107/2009 (the PPP Regulation) “lays down rules for the authorisation of plant protection products in commercial form and for their placing on the market, use and control within the Community”.

“The purpose of this Regulation is to ensure a high level of protection of both human and animal health and the environment and to improve the functioning of the internal market through the harmonisation of the rules on the placing on the market of plant protection products, while improving agricultural production.”

Regulation (EC) 396/2005 (the MRL Regulation) establishes “in particular the need to ensure a high level of consumer protection and harmonised Community provisions relating to maximum levels of pesticide residues in or on food and feed of plant and animal origin”.

Both regulations cover chemical and non-chemical PPPs.

Both regulations have been extensively evaluated in 2018 (Ecorys, 2018) as part of the EU Regulatory Fitness and Performance programme (REFIT)[50]. With respect to the impacts, this evaluation draws important conclusions:

1. Regulation (EC) 1107/2009 contributes to the protection of both human health and the environment.

---

[50] https://ec.europa.eu/food/plant/pesticides/refit_en

2. Regulation (EC) 396/2005 ensures a high level of consumer protection and facilitates the functioning of the internal market.
3. However, several provisions of the two Regulations have yet to be implemented or fully enforced. Delays in the assessment of active substances mean they are often not evaluated satisfactorily in the light of the latest scientific and technical knowledge (see below).
4. Several stakeholders complain that the competitiveness of EU agriculture is negatively affected by the legislation (especially Regulation (EC) 1107/2009) due to a reduced availability of PPPs. However, this claim is not supported by the quantitative evidence. The complaints can be explained by concerns relating to foreseen negative effects of the non-approval of several substances currently in use.
5. Setting MRLs can create non-tariff trade barriers if the MRLs in the EU are more stringent than in countries that export to the EU. Despite concerns of importers, there is no evidence that MRLs in the EU are more stringent than in other countries.

There are, however, important issues regarding the two Regulations that affect the regulatory system. As the Ecorys (2018) report comments:

> "Several provisions of the two Regulations have yet to be implemented, and several others cannot be fully enforced. This creates obstacles to ensuring a high level of protection for human and animal health and the environment. Active substances and PPPs are not assessed in a timely manner and, therefore, are often not evaluated satisfactorily in light of the latest scientific and technical knowledge. Delays lead to uncertainty and unpredictability. This hinders innovation and affects the capacity of the sector, particularly SMEs, to replace hazardous substances with either other substances or alternative methods. The lack of innovative solutions may have a negative effect on the objectives of improving agricultural production and safeguarding the competitiveness of the European agriculture."

Commission Staff Working Document COM (2020) 208 Final points out that the number of emergency authorisations for PPPs (see Section 2.2.2) has increased since the PPP Regulation entered into force (in 2009). It seems that emergency authorisations are often misused by Member States to overcome procedural delays in the regular authorisation process and increase PPP availability. The Working Document states:

> "The main issues that contributed to the increase have been identified as follows:
>
> - emerging new pests for which the submission and evaluation of applications for regular authorisations takes some time;
> - the loss of a number of pesticides with widespread use which have to be replaced by several PPPs containing different active substances;
> - lack of applications for authorisations of PPPs for minor uses or small markets, such as the northern zone;
> - procedural delays in granting zonal or national authorisations or in the mutual recognition of authorisations."

5.2.2. Directive 2009/128/ EC

Directive 2009/128/EC (the Sustainable Use Directive or SUD):

> "establishes a framework to achieve a sustainable use of pesticides by reducing the risks and impacts of pesticide use on human health and the environment and promoting the use of integrated pest management and of alternative approaches or techniques such as non-chemical alternatives to pesticides."

It is not likely that implementation of the SUD has resulted, nor will result, in significant impact on yield, costs, farmer income or competitiveness, for the following reasons:

Firstly, the SUD contains requirements for Member States and not for individual farmers.

Secondly, the IPM principles are framed within economic guidelines, since they allow the use of pesticides as a last resort to prevent unacceptable losses.

It could be that banning the use of specific pesticides in vulnerable areas would cause differences in competitiveness between farms within and between Member States. However, this has not been reported in an evaluation study conducted by the European Parliamentary Research Service (EPRS), (Remáč, 2018).

5.2.3. Directive 2001/18/EC

Directive 2001/18/EC (The GMO Directive) concerns the deliberate release into the environment (including placing on the market) of genetically modified organisms.

The Directive "provides that GMOs must be authorised following an assessment of the risks which they present for human health and the environment and also makes them subject to traceability, labelling and monitoring obligations" (European Court of Justice, 2018b).

New techniques in plant breeding, particularly directed mutagenesis (see Section 3.2) have called into question whether the GMO Directive should be updated to reflect the new technologies.

In July 2018, the Court of Justice of the European Union decided that all organisms obtained by mutagenesis (including new mutagenesis techniques) are genetically modified organisms within the meaning of Directive 2001/18/EC, and they are therefore subject to the obligations laid down by the Directive.

However, the Court observed that "recital 17 states that 'this Directive should not apply to organisms obtained through certain techniques of genetic modification which have conventionally been used in a number of applications and have a long safety record'".

The scientific perspective has been presented in a statement from the European Commission Group of Chief Scientific Advisors (European Commission, 2018)[51], which concludes that "the GMO Directive should be revised to reflect current knowledge and scientific evidence, and as part of a broad dialogue with relevant stakeholders and the public at large."

The Scientific Advisors point out that new gene-edited techniques are potentially safer than random (conventional) mutagenesis, as unintended effects will occur less frequently in gene-edited products.

---

[51] https://ec.europa.eu/info/news/commissions-chief-scientific-advisors-publish-statement-regulation-gene-editing-2018-nov-13_en

In legal terms, the products of gene editing can be authorised in the EU according to the GMO Directive. However, this can be a costly and time-consuming process, which may diminish incentives for investment and limit their commercialisation.

Taking into account the situation and the potential of gene-edited crops, the Advisors made the recommendation to revise the GMO Directive. Acknowledging the strongly held views on the regulation of GMOs, they also urged a dialogue with relevant stakeholders and the general public.

5.2.4. Directive 2000/60/EC and Council Directive 98/83/EC

The Directive 2000/60/EC (the Water Framework Directive or WFD) contributes to the provision of the sufficient supply of good quality surface water and groundwater, and a significant reduction in pollution of groundwater (among other things).

Council Directive 98/83/EC (the Drinking Water Directive or DWD) sets the essential quality standards for water intended for human consumption. The Directive obliges Member States to monitor the quality of water for human consumption. The DWD also sets maximum concentration levels for pesticides found in drinking water.

The DWD was evaluated in 2016. The evaluation reported that the DWD has not been effective in reducing pollution of drinking water with pesticides (Klaassens et al., 2016). However, the report contains no information on the costs of measures taken by farmers and/or imposed by Member States to reduce pesticide contamination of drinking water sources. Therefore, there is no indication whether the DWD leads to additional costs for farmers.

5.2.5. Regulation (EC) No 1272/2008

Regulation (EC) No 1272/2008 concerns the classification, labelling and packaging of substances and mixtures. No relevant information has been found regarding the impacts of this Regulation on costs, yield and farmer income.

5.2.6. Regulation (EC) No 1185/2009

This regulation contains requirements for Statistics on Pesticides. No relevant information has been found regarding the impacts of this Regulation on costs, yield and farmer income.

5.2.7. Directive No 2009/127/EC

Directive 2009/127/EC amends Directive 2006/42/EC with regard to machinery for pesticide application. It specifies requirements for the use of machines applying pesticides against pests, diseases and weeds. The requirements are designed to protect both human health (applicants and bystanders) and the environment.

No relevant information has been found with respect to impacts on costs, yield or farmer income.

5.2.8. Commission Implementing Regulation (EU) 2016/673 amending Regulation (EC) No 889/2008

Commission Implementing Regulation (EU) 2016/673 amending Regulation (EC) No 889/2008 lays down detailed rules for the implementation of Council Regulation (EC) No 834/2007 on organic production and labelling of organic products.

The Regulation lays down detailed production rules for seaweed. No relevant information has been found with respect to impacts on costs, yield or farmer income.

5.3. Regulation of possible alternative crop protection practices

This section discusses the regulation of possible alternative crop production practices (as described in Sections 3.2 to 3.7).

5.3.1. Mechanical techniques

In section 3.2 it is argued that the shift from the use of herbicides to mechanical weeding can have impacts on soil dwelling insects and on nests of birds. There is no specific EU legislation that protects soil and soil life from mechanical techniques.

Directive 92/43/EEC protects natural habitats; but most farmland is not considered as natural habitat and is therefore out of scope of the Directive.

Directive 2009/147/EC requires Members States to take measures regarding the conservation of wild birds, including the birds, their eggs, nests and habitats. It can be anticipated that precision technology can make a positive contribution to bird conservation.

5.3.2. New plant breeding techniques

The legal situation concerning Directive 2001/18/EC and the need to update it is explained in Section 5.2.3.

Currently, no gene edited crops are ready for commercialisation in the EU. However, economists calculate that the costs of refraining from the use of gene editing can be considerable.

For example, China approved Bt rice in 2009 but has not yet cultivated it; this delay was estimated to have cost USD 12 billion (Jin et al., 2019).

A report for the Netherlands Commission on Genetic Modification (COGEM) commented on the current situation in the EU: "There are indications that this loss of perspective may lead to reduced possibilities for research funding. It may also lead to loss of practical interest amongst plant breeders and ultimately to loss of the technical know-how in the EU"[52].

Farmers need robust and resilient crop varieties to cope with future challenges – including climate change, and new and emerging pests and diseases – and to reduce their dependency on pesticides.

Advances in plant breeding therefore remain central to the future of crop production, regardless of the techniques used. Integration of different crop traits such as drought or heat resistance, carbon sequestration, and pest and disease resistance is needed to meet future demands.

However, realising the potential of new techniques within the EU depends on EU legislative decisions. In other parts of the world, these innovations will be applied in agriculture (Buckwell, 2020).

---

[52] https://cogem.net/app/uploads/2020/03/CGM-2020-03-ECGE-Eindrapport-uitspraak-europees-Hof.pdf

In a Briefing for the European Parliament, the European Parliamentary Research Service (EPRS) (Laaninen, 2019[53]) summarised the EU debate on regulating the new techniques:

> " Those who take the view that the new techniques should be exempt from GMO legislation generally argue that the end product is very similar to products generated using conventional breeding techniques, or that similar changes could also occur naturally. Those who consider that the new techniques should fall within the scope of GMO legislation contend that the processes used mean that plants bred using the new techniques are in fact genetically modified."

Regarding this debate, the European Commission Group of Chief Scientific Advisors (European Commission, 2018) pointed out that "The GMO Directive refers to both the process used in genetic engineering and the product resulting from the use of such techniques (Abbott, 2015)".

When determining the safety of a GMO product, the Advisors argue that its risks:

> "should be assessed in the same way independently of whether they are produced by conventional breeding techniques, random or directed mutagenesis, or by ETGM"[54].

The Advisors go on to conclude from this that:

> "the regulatory framework for GMOs should put much more emphasis on the features of the end product, rather than on the production technique."

The level of competitive disadvantage that would result from a European reluctance to apply new breeding techniques would depend on the willingness to create non-tariff trade barriers on imported plant products which result from breeding techniques not permitted in the EU.

5.3.3. Biocontrol agents

The registration of microbial biocontrol agents is subject to criteria laid down in Regulation (EC) 1107/2009.

Registration of invertebrate biocontrol agents is subject to the national law of Member States (Buckwell et al, 2020).

There is a risk that non-indigenous biocontrol agents imported into the EU may become invasive alien species threatening plant health and/or biodiversity. Such biocontrol agents are subject to risk assessment under Regulation (EU) 1143/2014 on the prevention and management of the introduction and spread of invasive alien species, or under Regulation (EU) 2016/2031 on protective measures against pests of plants.

Among the limitations to the uptake of biocontrol agents, Barrett et al. (2018) report "risk averse and unwieldy regulatory processes; increasingly bureaucratic barriers to access to biocontrol agents". This subject was debated in a workshop organised by EPPO and COST (European

---

[53] https://www.europarl.europa.eu/RegData/etudes/BRIE/2019/642235/EPRS_BRI(2019)642235_EN.pdf.

[54] ETGM: established techniques of genetic modification

Cooperation in Science and Technology[55]. A harmonised, and consistent legal approach is recommended to enhance the adoption and application of biocontrol agents.

5.3.4. Induced resistance

This review did not find any negative impacts from the use of substances to induce resistance (see Table 3 in Section 3.8), and there are no regulatory requirements specifically concerning induced resistance.

5.3.5. Applying ecological principles to increase plant diversity

There are no regulatory requirements specifically concerning the application of ecological principles to increase plant diversity.

5.3.6. Precision Agriculture

A Scientific Foresight Unit (STOA) study (Kritikos, 2017) analysed the suitability of the EU legal and policy framework to deal with the legal, social and ethical considerations raised by the development of precision agriculture. Relevant points raised by the study are described below:

The main challenge is to develop a framework that can cope with the potential threats to the privacy and autonomy of individual farmers in a pragmatic, inclusive and dynamic manner.

The study noted that the uptake of precision agriculture techniques can lead to a significant change in the power division in the agricultural sector:

> "Due to the scale, technical complexity, and infrastructural requirements of precision farming, uptake of precision agriculture might lead to a reliance of the vast majority of farmers on off-farm service support, to a rapidly growing digital division between small and big farmers, and significant power shifts. These can in turn lead to potential abuses of data by agricultural commodity markets or manipulation by major multinationals because small farmers might lack the investment capital or knowledge to acquire precision agriculture technologies, which in effect may signal an unprecedented power shift in the industrial farming process."

Farmers need support in understanding their position in the digital environment, in accordance with the CAP objectives: to ensure a fair income to farmers, and; to rebalance the power in the food chain.

Farmers need to have access to the benefits of sharing the data they generate. The administrative burden can be reduced by the development and implementation of better information systems, enhancing the use of data interchange standards, and clear management systems.

If implemented well, data exchange and analysis can contribute to the transition to sustainable agricultural practices. The study points out the benefit of applying plant protection products under IPM to optimise cost-efficient production.

---

[55] https://www.eppo.int/media/uploaded_images/MEETINGS/Meetings_2015/budapest/05_Ward.pdf

5.3.7. PPPs

PPPs will continue to be needed for crop protection for the foreseeable future. The necessity for their regulation will mean continuous updating of EU legislation.

Regulation (EC) 1107/2009, Regulation (EC) 396/2005 and Directive 2009/128/EC will remain at the core of the legal framework regarding PPPs.

Increased application of biocontrol agents and natural enemies will need investment in training of farm managers, advisory services and also in data-based decision support methods.

However, there will still be pests, weeds and insects that cannot be treated with alternative methods. There will therefore continue to be a need for synthetic PPPs, which will ideally be very specific so as to minimise disturbance to the ecological balance of the diversified systems.

5.4. Summary of regulatory issues

Adoption of the alternative crop protection practices described in this chapter raise regulatory issues, mainly with regard to:

- new plant breeding techniques (revision of Directive 2001/18/EC);
- the registration of microbial biocontrol agents (Regulation (EC) 1107/2009, Regulation (EU) 1143/2014, Regulation (EU) 2016/2031);
- privacy and autonomy issues regarding precision agriculture, which are covered by a number of regulations (see Kritikos, 2017);
- continuous updating of EU legislation regarding plant protection products (Regulation (EC) 1107/2009, Regulation (EC) 396/2005 and Directive 2009/128/EC).

6. References

Abbott, A. (2015). Europe's genetically edited plants stuck in legal limbo. *Nature*. https://doi.org/10.1038/528319a

Ahnström, J., Höckert, J., Bergeå, H. L., Francis, C. A., Skelton, P., & Hallgren, L. (2009). Farmers and nature conservation: What is known about attitudes, context factors and actions affecting conservation? In *Renewable Agriculture and Food Systems* (Vol. 24, Issue 1, pp. 38–47). Cambridge University Press. https://doi.org/10.1017/S1742170508002391

Alonso-Villaverde, V., Susana Boso, José Luis Santiago, Pilar Gago & María-Carmen Martínez (2008) Relationship Between Susceptibility to Botrytis Bunch Rot and Grape Cluster Morphology in the Vitis vinifera L. Cultivar Albariño, International Journal of Fruit Science, 8:4, 251-265, DOI: 10.1080/15538360802597481

Andrew, I. K. S., Storkey, J., & Sparkes, D. L. (2015). A review of the potential for competitive cereal cultivars as a tool in integrated weed management. *Weed Research*, *55*(3), 239–248. https://doi.org/10.1111/wre.12137

Appah, S., Wang, P., Ou, M. X., Gong, C., & Jia, W. D. (2019). Review of electrostatic system parameters, charged droplets characteristics and substrate impact behavior from pesticides spraying. *International Journal of Agricultural and Biological Engineering*, *12*(2), 1–9. https://doi.org/10.25165/j.ijabe.20191202.4673

Arnó, J., Gabarra, R., Estopà, M., Gorman, K., Peterschmitt, M., Bonato, O., Vosman, B., Hommes, M., & Albajes Garcia, R. (2009). *Implementation of IPM programs on European greenhouse tomato production areas: tools and constraints*. http://repositori.udl.cat/handle/10459.1/49254

Aubertot, J. N., West, J. S., Bousset-Vaslin, L., Salam, M. U., Barbetti, M. J., & Diggle, A. J. (2006). Improved resistance management for durable disease control: A case study of phoma stem canker of oilseed rape (Brassica napus). *European Journal of Plant Pathology*, *114*(1), 91–106. https://doi.org/10.1007/s10658-005-3628-z

Bai, Y., Pavan, S., Zheng, Z., Zappel, N. F., Reinstädler, A., Lotti, C., De Giovanni, C., Ricciardi, L., Lindhout, P., Visser, R., Theres, K., & Panstruga, R. (2008). Naturally occurring broad-spectrum powdery mildew resistance in a Central American tomato accession is caused by loss of Mlo function. *Molecular Plant-Microbe Interactions*, *21*(1), 30–39. https://doi.org/10.1094/MPMI-21-1-0030

Bai, Y., Van Der Hulst, R., Bonnema, G., Marcel, T. C., Meijer-Dekens, F., Niks, R. E., & Lindhout, P. (2005). Tomato defense to Oidium neolycopersici: Dominant Ol genes confer isolate-dependent resistance via a different mechanism than recessive ol-2. *Molecular Plant-Microbe Interactions*, *18*(5), 508.

Bagheri, N. (2020). Application of aerial remote sensing technology for detection of fire blight infected pear trees, Computers and Electronics in Agriculture, Volume 168, 105147, ISSN 0168-1699, https://doi.org/10.1016/j.compag.2019.105147.

Balzan, M. V., & Moonen, A. C. (2012). Management strategies for the control of Tuta absoluta (Lepidoptera: Gelechiidae) damage in open-field cultivations of processing tomato in Tuscany (Italy). *EPPO Bulletin*, *42*(2), 217–225. https://doi.org/10.1111/epp.2558

Barot, S., Allard, V., Cantarel, A., Enjalbert, J., Gauffreteau, A., Goldringer, I., Lata, J. C., Le Roux, X., Niboyet, A., & Porcher, E. (2017). Designing mixtures of varieties for multifunctional agriculture with the help of ecology. A review. In *Agronomy for Sustainable Development* (Vol. 37, Issue 2, pp. 1–20). Springer-Verlag France. https://doi.org/10.1007/s13593-017-0418-x

Barratt, B. I. P., Moran, V. C., Bigler, F., & van Lenteren, J. C. (2018). The status of biological control and recommendations for improving uptake for the future. *BioControl*, *63*(1), 155–167. https://doi.org/10.1007/s10526-017-9831-y

Bartram, H., & Perkins, A. (2003). The biodiversity benefits of organic farming. In *Organic agriculture sustainability, markets and policies*. CABI Publishing and CAB International.

Bauriegel, E., Giebel, A., Geyer, M., Schmidt, U., & Herppich, W. B. (2011). Early detection of Fusarium infection in wheat using hyper-spectral imaging. *Computers and Electronics in Agriculture*, *75*, 304–312. https://doi.org/10.1016/j.compag.2010.12.006

Beckmann, V., & Wesseler, J. (2003). How labour organization may affect technology adoption: An analytical framework analysing the case of integrated pest management. *Environment and Development Economics*, *8*(3), 437–450. https://doi.org/10.1017/S1355770X0300238

Beillouin, D., Ben-Ari, T., & Makowski, D. (2019). A dataset of meta-analyses on crop diversification at the global scale. *Data in Brief*, *24*, 103898. https://doi.org/10.1016/j.dib.2019.103898

Biondi, A., Narciso, R., Guedes, C., Wan, F.-H., & Desneux, N. (2018). Ecology, Worldwide Spread, and Management of the Invasive South American Tomato Pinworm, Tuta absoluta: Past, Present, and Future. *Annu. Rev. Entomol*, *63*, 239–258. https://doi.org/10.1146/annurev-ento-031616

Borg, J., Kiaer, L. P., Lecarpentier, C., Goldringer, I., Gauffreteau, A., Saint-Jean, S., Barot, S., & Enjalbert, J. (2018). *Unfolding the potential of wheat cultivar mixtures: A meta-analysis perspective and identification of knowledge gaps*. https://doi.org/10.1016/j.fcr.2017.09.006

Borges, A.A. & Sandalio, L.M. (2015) "Induced resistance for plant defense," Front Plant Sci, vol. 6, doi: 10.3389/fpls.2015.00109.

Bouwma, I. M., Gerritsen, A. L., Kamphorst, D. A., & Kistenkas, F. H. (2015). Policy instruments and modes of governance in environmental policies of the European Union; Past, present and future. *WOt Technical Report*, 46

Boudreau, M.A. (2013) Diseases in Intercropping Systems, Annual Review of Phytopathology 51:1, 499-519.

Bouws, H. and Finckh, M.R. (2008), Effects of strip intercropping of potatoes with non-hosts on late blight severity and tuber yield in organic production. Plant Pathology, 57: 916-927. doi:10.1111/j.1365-3059.2008.01860.x

Boyette, C. D., & Hoagland, R. E. (2015). Bioherbicidal potential of Xanthomonas campestris for controlling Conyza canadensis. Biocontrol Sci. Technol. 25, 229–237. doi: 10.1080/09583157.2014.966650

Braun, S., Gevens, A., Charkowski, A., Allen, C., & Jansky, S. (2017). Potato Common Scab: a Review of the Causal Pathogens, Management Practices, Varietal Resistance Screening Methods, and Host Resistance. *American Journal of Potato Research*, *94*(4), 283–296. https://doi.org/10.1007/s12230-017-9575-3

Bravo, C., Moshou, D., West, J., McCartney, A., & Ramon, H. (2003). Early disease detection in wheat fields using spectral reflectance. *Biosystems Engineering*, *84*(2), 137–145. https://doi.org/10.1016/S1537-5110(02)00269-6

Brodt, S., Klonsky, K., & Tourte, L. (2006). Farmer goals and management styles: Implications for advancing biologically based agriculture. *Agricultural Systems*, *89*(1), 90–105. https://doi.org/10.1016/j.agsy.2005.08.005

Buckwell, A., De Wachter, E., Nadeu, E., & Williams, A. (2020). *Crop Protection & the EU Food System: Where* *are they going?* https://www.risefoundation.eu/images/files/2020/RISE_CP_EU_final.pdf

Bürger, J., Günther, A., De Mol, F., & Gerowitt, B. (2012). Analysing the influence of crop management on pesticide use intensity while controlling for external sources of variability with Linear Mixed Effects Models, Agricultural Systems, Volume 111,pages 13-22, https://doi.org/10.1016/j.agsy.2012.05.002.

Caffi, T., Helsen, H.H.M., Rossi, V., Holb, I.J., Strassemeyer, J., Buurma, J.S., Capowiez, Y., Simon, S., Alaphilippe, A. (2017). Multicriteria evaluation of innovative IPM systems in pome fruit in Europe, Crop Pr

Camargo, A.M., Andow, D.A., Castañera, P. et al. First detection of a Sesamia nonagrioides resistance allele to Bt maize in Europe. Sci Rep 8, 3977 (2018). https://doi.org/10.1038/s41598-018-21943-4

Chaplin-Kramer, R., O'Rourke, M.E., Blitzer, E.J. and Kremen, C. (2011), A meta-analysis of crop pest and natural enemy response to landscape complexity. Ecology Letters, 14: 922-932. doi:10.1111/j.1461-0248.2011.01642.xotection, Volume 97,Pages 101-108, https://doi.org/10.1016/j.cropro.2016.12.009.

Christensen, S. (1995). Weed suppression ability of spring barley varieties. *Weed Research*, *35*(4), 241–247. https://doi.org/10.1111/j.1365-3180.1995.tb01786.x

Chouinard, C., A. Firlej, D. Cormier, (2016). Going beyond sprays and killing agents: Exclusion, sterilization and disruption for insect pest control in pome and stone fruit orchards, Scientia Horticulturae, Volume 208, Pages 13-27, ISSN 0304-4238, https://doi.org/10.1016/j.scienta.2016.03.014.

COMMISSION STAFF WORKING DOCUMENT Accompanying the document REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL Evaluation of Regulation (EC) No 1107/2009 on the placing of plant protection products on the market and of Regulation (EC) No 396/2005 on maximum residue levels of pesticides. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020SC0087

Cong, L., Ran, F. A., Cox, D., Lin, S., Barretto, R., Habib, N., Hsu, P. D., Wu, X., Jiang, W., Marraffini, L. A., & Zhang, F. (2013). Multiplex genome engineering using CRISPR/Cas systems. *Science*, *339*(6121), 819–823. https://doi.org/10.1126/science.1231143

Cooke L.R., Schepers H.T.A.M., Hermansen A., Bain R.A., Bradshaw, N.J., Ritchie F., Shaw D.S., Evenhuis A., Kessel G.J.T., Wander, J.G.N., Andersson B., Hansen, J.G., Hannukkala A., Nærstad, R. & Nielsen, B.J. (2011). Epidemiology and Integrated Control of Potato Late Blight in Europe, Potato Research (2011) 54:183–222, DOI 10.1007/s11540-011-9187-0

Crowder, D. W., & Jabbour, R. (2014). Relationships between biodiversity and biological control in agroecosystems: Current status and future challenges. *Biological Control*, *75*, 8–17. https://doi.org/10.1016/j.biocontrol.2013.10.010

Dahlin, I., Rubene, D., Glinwood, R., & Ninkovic, V. (2018). *Pest suppression in cultivar mixtures is influenced by neighbor-specific plant-plant communication*.

Dainese, M., Martin, E. A., Aizen, M. A., Albrecht, M., Bartomeus, I., Bommarco, R., Carvalheiro, L. G., Chaplin-Kramer, R., Gagic, V., Garibaldi, L. A., Ghazoul, J., Grab, H., Jonsson, M., Karp, D. S., Kennedy, C. M., Kleijn, D., Kremen, C., Landis, D. A., Letourneau, D. K., … Steffan-Dewenter, I. (2019). A global synthesis reveals biodiversity-mediated benefits for crop production. *Science Advances*, *5*(10), eaax0121. https://doi.org/10.1126/sciadv.aax0121

Damos, P., Colomar, L. A. E., & Ioriatti, C. (2015). Integrated fruit production and pest management in europe: The apple case study and how far we are from the original concept? *Insects*, *6*(3), 626–657.

https://doi.org/10.3390/insects6030626

De Vries, M., Ter Maat, M., & Lindhout, P. (2016). The potential of hybrid potato for East-Africa. *Open Agriculture*, *1*(1), 151–156. https://doi.org/10.1515/opag-2016-0020

Dewar, A. M. (2009). Weed control in glyphosate-tolerant maize in Europe. *Pest Management Science*, *65*(10), 1047–1058. https://doi.org/10.1002/ps.1806

Dhall, R. K. (2015). Breeding for Biotic Stresses Resistance in Vegetable Crops : A Review Breeding for Biotic Stresses Resistance in Vegetable Crops : A Review. *STM Journals*, *4*(January), 13–27.

Douglas, A. E. (2018). Strategies for Enhanced Crop Resistance to Insect Pests. *Annual Review of Plant Biology*, *69*(1), 637–660. https://doi.org/10.1146/annurev-arplant-042817-040248

Doveri, S., & Baldoni, L. (2007). Olive. In C. Kole (Ed.), *Genome mapping and molecular breeding in plants*.

EAT-Lancet Commission. (2018). Food Planet Health. Healthy Diets From Sustainable Food Systems. Summary Report. *EAT-Lancet*. https://eatforum.org/content/uploads/2019/07/EAT-Lancet_Commission_Summary_Report.pdf

Ecorys. (2018). *Study supporting the REFIT Evaluation of the EU legislation on plant protection products and pesticides residues (Regulation (EC) No 1107/2009 and Regulation (EC) No 396/2005)*.

Edward Law, S. (2001). Agricultural electrostatic spray application: A review of significant research and development during the 20th century. *Journal of Electrostatics*, *51–52*(1–4), 25–42. https://doi.org/10.1016/S0304-3886(01)00040-7

EEA. (2018) *European Waters, Assessment of status and pressures 2018,* EEA Report No 7/2018

EIP-AGRI Focus Group. (2020a). *Non-chemical weed management in arable cropping systems*.

EIP-AGRI Focus Group. (2020b). *Pest and diseases of the olive tree*.

Ellis, P. R., Pink, D. A. C., Barber, N. E., & Mead, A. (1999). Identification of high levels of resistance to cabbage root fly, Delia radicum, in wild Brassica species. *Euphytica*, *110*(3), 207–214. https://doi.org/10.1023/A:1003752801143

Elad, Y. Dalia Rav David, Yael Meller Harel, Menahem Borenshtein, Hananel Ben Kalifa, Avner Silber, & Ellen R. Graber (2010). Induction of Systemic Resistance in Plants by Biochar, a Soil-Applied Carbon Sequestering Agent Phytopathology 2010 100:9, 913-921, https://apsjournals.apsnet.org/doi/abs/10.1094/PHYTO-100-9-0913

EPPO. (2005). European and Mediterranean Plant Protection Organization. Tuta absoluta. Data sheets on quarantine pests. *EPPO Bulletin*, *35*, 434–435.

Erisman, J. W., van Eekeren, N., de Wit, J., Koopmans, C., Cuijpers, W., Oerlemans, N., & Koks, B. J. (2016). Agriculture and biodiversity: A better balance benefits both. *AIMS Agriculture and Food*, *1*(2), 157–174. https://doi.org/10.3934/agrfood.2016.2.157

European Commission. (2018) A Scientific Perspective on the regulatory status of products derived from gene editing and the implications for the GMO Directive, Statement by the Group of Chief Scientific Advisors, 13 November 2018 https://ec.europa.eu/info/news/commissions-chief-scientific-advisors-publish-statement-regulation-gene-editing-2018-nov-13_en

European Commission, (2020) Cereals market situation, Committee for the Common Organisation of Agricultural Markets, 29 October 2020. Committee for the Common Organisation of Agricultural Markets. https://ec.europa.eu/info/food-farming-fisheries/farming/facts-and-figures/markets/overviews/market-observatories/crops_en

European Court of Justice. (2018a) Case C-528/16, 25 July 2018 http://curia.europa.eu/juris/document/document.jsf?text=&docid=198532&pageIndex=0&doclang=en&mode=req&dir=&occ=first&part=1&cid=11243857

European Court of Justice. (2018b) Press Release No 111/18 of 25 July 2018

EuroWheat. (2020). https://agro.au.dk/forskning/internationale-platforme/eurowheat/. Date Accessed: 2020-05-15

Evans, K., & Peace, C. (2017). *Advances in marker-assisted breeding of apples*. 165–192. https://doi.org/10.19103/as.2016.0017.09

Evert, V., Been, T., Booij, A. J., Kempenaar, C., Kessel, J. G., & Molendijk, P. L. (2018). *Akkerweb: a platform for precision farming data, science, and practice A paper from the Proceedings of the 14 th International Conference on Precision Agriculture*. https://www.cropvision.nl/

FAO and ITPS, 2017. *Global assessment of the impact of plant protection products on soil functions and soil ecosystems*, Rome, FAO. 40 pp

Finch, S., & Collier, R. H. (2000). Integrated pest management in field vegetable crops in northern Europe - With focus on two key pests. *Crop Protection*, *19*(8–10), 817–824. https://doi.org/10.1016/S0261-2194(00)00109-5

Fitt, B. D. L., Brun, H., Barbetti, M. J., & Rimmer, S. R. (2006). World-wide importance of phoma stem canker (Leptosphaeria maculans and L. biglobosa) on oilseed rape (Brassica napus). In *Sustainable strategies for managing Brassica napus (oilseed rape) resistance to Leptosphaeria maculans (phoma stem canker)* (pp. 3–15). Springer-Verlag. https://doi.org/10.1007/1-4020-4525-5_1

Geiger, F., Bengtsson, J., Berendse, F., Weisser, W. W., Emmerson, M., Morales, M. B., Ceryngier, P., Liira, J., Tscharntke, T., Winqvist, C., Eggers, S., Bommarco, R., Pärt, T., Bretagnolle, V., Plantegenest, M., Clement, L. W., Dennis, C., Palmer, C., Oñate, J. J., … Inchausti, P. (2010). Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland. *Basic and Applied Ecology*, *11*(2), 97–105. https://doi.org/10.1016/j.baae.2009.12.001

Getachew, G., Putnam, D. H., De Ben, C. M., & De Peters, E. J. (2016). Potential of Sorghum as an Alternative to Corn Forage. *American Journal of Plant Sciences*, *07*(07), 1106–1121. https://doi.org/10.4236/ajps.2016.77106

Giomi, T., Runhaar, P., & Runhaar, H. (2018). Reducing agrochemical use for nature conservation by Italian olive farmers: an evaluation of public and private governance strategies. *International Journal of Agricultural Sustainability*, *16*(1), 94–105. https://doi.org/10.1080/14735903.2018.1424066

Grettenberger, I. M., & Tooker, J. F. (2017). Variety mixtures of wheat influence aphid populations and attract an aphid predator. *Arthropod-Plant Interactions*, *11*(2), 133–146. https://doi.org/10.1007/s11829-016-9477-1

Hallau, L., Neumann, M., Klatt, B., Kleinhenz, B., Klein, T., Kuhn, C., Röhrig, M., Bauckhage, C., Kersting, K., Mahlein, A. K., Steiner, U., & Oerke, E. C. (2018). Automated identification of sugar beet diseases using smartphones. *Plant Pathology*, *67*(2), 399–410. https://doi.org/10.1111/ppa.12741

Hansen, P. K., Kristensen, K., & Willas, J. (2008). A weed suppressive index for spring barley (Hordeum vulgare) varieties. *Weed Research*, *48*(3), 225–236. https://doi.org/10.1111/j.1365-3180.2008.00620.x

Harding, D.P. & Raizada, M.N. (2015) "Controlling weeds with fungi, bacteria and viruses: a review," *Front Plant Sci*, vol. 6, doi: 10.3389/fpls.2015.00659

Harteveld, D. O. C., Grant, M. R., Pscheidt, J. W., & Peever, T. L. (2017). Predicting Ascospore Release of *Monilinia vaccinii-corymbosi* of Blueberry with Machine Learning. *Phytopathology*, *107*(11), 1364–1371. https://doi.org/10.1094/PHYTO-04-17-0162-R

Haverkort, A. J., Boonekamp, P. M., Hutten, R., Jacobsen, E., Lotz, L. A. P., Kessel, G. J. T., Vossen, J. H., & Visser, R. G. F. (2016). Durable Late Blight Resistance in Potato Through Dynamic Varieties Obtained by Cisgenesis: Scientific and Societal Advances in the DuRPh Project. *Potato Research*, *59*(1), 35–66. https://doi.org/10.1007/s11540-015-9312-6

Havey, M. J. (2018). Onion Breeding. In *Plant Breeding Reviews* (pp. 39–85). Wiley. https://doi.org/10.1002/9781119521358.ch2

Heap, I., & Duke, S. O. (2018). Overview of glyphosate-resistant weeds worldwide. *Pest Management Science*, *74*(5), 1040–1049. https://doi.org/10.1002/ps.4760

Herve, M.R. (2017). Breeding for insect resistance in oilseed rape: Challenges, current knowledge and perspectives, Plant Breeding 137 (1), p27-34, https://doi.org/10.1111/pbr.12552

Hillnhütter, C., Schweizer, A., Kühnhold, V., & Sikora, R. A. (2010). Remote sensing for the detection of soil-borne plant parasitic nematodes and fungal pathogens. In *Precision Crop Protection - The Challenge and Use of Heterogeneity* (pp. 151–165). Springer Netherlands. https://doi.org/10.1007/978-90-481-9277-9_10

Holland, J. M., & Luff, M. L. (2000). The effects of agricultural practices on Carabidae in temperate agroecosystems. In *Integrated Pest Management Reviews* (Vol. 5, Issue 2, pp. 109–129). Kluwer Academic Publishers. https://doi.org/10.1023/A:1009619309424

Holland, John M., Bianchi, F. J., Entling, M. H., Moonen, A. C., Smith, B. M., & Jeanneret, P. (2016). Structure, function and management of semi-natural habitats for conservation biological control: a review of European studies. *Pest Management Science*, *72*(9), 1638–1651. https://doi.org/10.1002/ps.4318

Howard, M.M., Muñoz, C.A., Kao-Kniffin, J. & Kessler, A. (2020) “Soil Microbiomes From Fallow Fields Have Species-Specific Effects on Crop Growth and Pest Resistance,” *Front. Plant Sci.*, vol. 11, doi: 10.3389/fpls.2020.01171.

IPES-Food. (2016). From Uniformity to Diversity - A paradigm shift from industrial agriculture to diversified agroecological systems. *International Panel of Experts on Sustainable Food Systems*, *2*, 1–15. https://doi.org/IPES-Food.

Isbell, F., Adler, P. R., Eisenhauer, N., Fornara, D., Kimmel, K., Kremen, C., Letourneau, D. K., Liebman, M., Polley, H. W., Quijas, S., & Scherer-Lorenzen, M. (2017). Benefits of increasing plant diversity in sustainable agroecosystems. *Journal of Ecology*, *105*(4), 871–879. https://doi.org/10.1111/1365-2745.12789

Jin, Y., Drabik, D., Heerink, N., & Wesseler, J. (2019). The Cost of Postponement of Bt Rice Commercialization in China. *Frontiers in Plant Science*, *10*, 1226. https://doi.org/10.3389/fpls.2019.01226

Jørgensen, L. N., Clark, B., Jahn, M., Antichi, D., Góral, T., Schepers, H., Lucas, P., Rolland, B., Gouache, D., & Hornok, L. (2008). *Using Cultivar Resistance to Reduce Fungicide Input in Wheat*. www.endure-network.eu

Kamal, N., & Cramer, C. S. (2018). Selection progress for resistance to iris yellow spot in onions. *HortScience*, *53*(8), 1088–1094. https://doi.org/10.21273/HORTSCI13041-18

Khelifi, M. Laguë, C. & Lacasse,B. (2001). “Pneumatic Control of Insects in Plant Protection,” in *Physical Control Methods in Plant Protection*, C. Vincent, B. Panneton, and F. Fleurat-Lessard, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 261–269

Kiær, L.P., Skovgaard, Ib.M., Østergård, H. (2009) Grain yield increase in cereal variety mixtures: A meta-analysis of field trials, Field Crops Research, Volume 114, Issue 3,Pages 361-373,

Kempenaar, C., Been, T., Booij, J. et al. Advances in Variable Rate Technology Application in Potato in The Netherlands. Potato Res. 60, 295–305 (2017). https://doi.org/10.1007/s11540-018-9357-4 https://doi.org/10.1016/j.fcr.2009.09.006.

Kempenaar, C., Heiting, S., & Michielsen, J. M. (2014). Perspectives for site specific application of soil herbicides in arable farming. *Proceedings of ICPA Conference*.

Kempenaar, C., van Evert, F. K., & Been, T. (2014). Use of vegetation indices in variable rate application of potato haulm killing herbicides. *Proceedings of ICPA Conference*.

Kessel, GJT, Mullins,W., Evenhuis, A., Stellingwerf, J., Ortiz Cortes, V., Phelan, S., Van den Bosch, T., Förch, M.G., Goedhart, P., Van der Voet, G., Lotz, L.A.p. (2018). Development and validation of IPM strategies for the cultivation of cisgenically modified late blight resistant potato, European Journal of Agronomy, Volume 96, Pages 146-155, https://doi.org/10.1016/j.eja.2018.01.012.

Kim, H. J., Lee, H. R., Jo, K. R., Mortazavian, S. M. M., Huigen, D. J., Evenhuis, B., Kessel, G., Visser, R. G. F., Jacobsen, E., & Vossen, J. H. (2012). Broad spectrum late blight resistance in potato differential set plants MaR8 and MaR9 is conferred by multiple stacked R genes. *Theoretical and Applied Genetics*, *124*(5), 923–935. https://doi.org/10.1007/s00122-011-1757-7

Klaassens, E. (2016). *Study supporting the revision of the EU Drinking Water Directive*. https://doi.org/10.1523/jneurosci.2343-09.2010

Knight, A. L., & Witzgall, P. (2013). Combining Mutualistic Yeast and Pathogenic Virus - A Novel Method for Codling Moth Control. *Journal of Chemical Ecology*, *39*(7), 1019–1026. https://doi.org/10.1007/s10886

Koehler-Cole K. (2020) "Is allelopathy from winter cover crops affecting row crops?," Agricultural & Environmental Letters, vol. 5, no. 1, p. e20015, 2020, doi: 10.1002/ael2.20015013-0322-z

Kremen, C., & Miles, A. (2012). Ecosystem Services in Biologically Diversified versus Conventional Farming Systems: Benefits, Externalities, and Trade-Offs. Ecology and Society, 17(4). Retrieved October 9, 2020, from http://www.jstor.org/stable/26269237

Kremer, R.J. (2019). "Chapter 15 - Bioherbicides and nanotechnology: Current status and future trends," in Nano-Biopesticides Today and Future Perspectives, O. Koul, Ed. Academic Press, pp. 353–366).

Kritikos, M. (2017). Precision agriculture in Europe: Legal, social and ethical considerations. *Scientific Foresight Unit (STOA)*.

Kromp, B. (1989). Carabid beetle communities (Carabidae, coleoptera) in biologically and conventionally farmed agroecosystems. *Agriculture, Ecosystems and Environment*, *27*(1–4), 241–251. https://doi.org/10.1016/0167-8809(89)90089-3

Kromp, B. (1999). Carabid beetles in sustainable agriculture: A review on pest control efficacy, cultivation impacts and enhancement. *Agriculture, Ecosystems and Environment*, *74*(1–3), 187–228. https://doi.org/10.1016/S0167-8809(99)00037-7

Laaninen, T. (2019). New plant-breeding techniques; Applicability of EU GMO rules. *European Parliamentary Research Service*.

Lamichhane, J. R., Aubertot, J. N., Begg, G., Birch, A. N. E., Boonekamp, P., Dachbrodt-Saaydeh, S., Hansen, J. G., Hovmøller, M. S., Jensen, J. E., Jørgensen, L. N., Kiss, J., Kudsk, P., Moonen, A. C., Rasplus, J. Y., Sattin, M., Streito, J. C., & Messéan, A. (2016). Networking of integrated pest management: A powerful approach to address common challenges in agriculture. In *Crop Protection* (Vol. 89, pp. 139–151). Elsevier Ltd. https://doi.org/10.1016/j.cropro.2016.07.011

Lamichhane, J. R., Bischoff-Schaefer, M., Bluemel, S., Dachbrodt-Saaydeh, S., Dreux, L., Jansen, J. P., Kiss, J., Köhl, J., Kudsk, P., Malausa, T., Messéan, A., Nicot, P. C., Ricci, P., Thibierge, J., & Villeneuve, F. (2017). Identifying obstacles and ranking common biological control research priorities for Europe to manage most economically important pests in arable, vegetable and perennial crops. *Pest Management Science*, *73*(1), 14–21. https://doi.org/10.1002/ps.4423

Lebeda, A., Mieslerová, B., Petřivalský, M., Luhová, L., Špundová, M., Sedlářová, M., Nožková-Hlaváčková, V., & Pink, D. A. C. (2017). Review of tomato powdery mildew - A challenging problem for researchers, breeders and growers. *Acta Horticulturae*, *1159*, 107–115. https://doi.org/10.17660/ActaHortic.2017.1159.17

Lechenet, M., Dessaint, F., Py, G., Makowski, D., & Munier-Jolain, N. (2017). Reducing pesticide use while preserving crop productivity and profitability on arable farms. *Nature Plants*, *3*(3), 1–6. https://doi.org/10.1038/nplants.2017.8

Lefèvre, A. Benjamin Perrin, Claire Lesur-Dumoulin, Chloé Salembier, Mireille Navarrete (2020). Challenges of complying with both food value chain specifications and agroecology principles in vegetable crop protection, Agricultural Systems, Volume 185, 2020, 102953, ISSN 0308-521X, https://doi.org/10.1016/j.agsy.2020.102953.

Lee, R., den Uyl, R., & Runhaar, H. (2019). Assessment of policy instruments for pesticide use reduction in Europe; Learning from a systematic literature review. In *Crop Protection* (Vol. 126, p. 104929). Elsevier Ltd. https://doi.org/10.1016/j.cropro.2019.104929

Lefebvre, M., Langrell, S. R. H., & Gomez-y-Paloma, S. (2014). Incentives and policies for integrated pest management in Europe: a review. In *Agronomy for Sustainable Development* (Vol. 35, Issue 1, pp. 27–45). https://doi.org/10.1007/s13593-014-0237-2

Letourneau, D. K., Salguero, B., & Montoya-Lerma, J. (2011). *Does plant diversity benefit agroecosystems? A synthetic review Mathematical models and methods for surveillance and control of dengue fever View project*. *May 2014*, 2019. https://doi.org/10.2307/29779633

Li, G., Lv, H., Zhang, S., Zhang, S., Li, F., Zhang, H., Qian, W., Fang, Z., & Sun, R. (2019). TuMV management for brassica crops through host resistance: retrospect and prospects. *Plant Pathology*, *68*(6), 1035–1044. https://doi.org/10.1111/ppa.13016

Liebman, M. and Dyck, E. (1993), Crop Rotation and Intercropping Strategies for Weed Management. Ecological Applications, 3: 92-122. doi:10.2307/1941795

Lindhout, P., de Vries, M., ter Maat, M., Su, Y., Viquez-Zamora, M., & van Heusden, S. (2016). *Hybrid potato breeding for improved varieties*. Burleigh Dodds science publishing limited.

Lindhout, Pim, Meijer, D., Schotte, T., Hutten, R. C. B., Visser, R. G. F., & van Eck, H. J. (2011). Towards F 1 Hybrid Seed Potato Breeding. *Potato Research*, *54*(4), 301–312. https://doi.org/10.1007/s11540-011-9196-z

Lorenz, E., Ulber, B., & Poehling, H. M. (1994). *Influence of different mechanical weed control techniques on the abundance of carabid beetles (Coleoptera, Carabidae) in sugar beets* (F. A. O. of the UN (Ed.); Issue 14).

Machado, W. A., Silva, S. M., Carvalho, S. M., & da Cunha, J. P. A. R. (2019). Effect of nozzles, application rates, and adjuvants on spray deposition in wheat crops. *Engenharia Agricola*, *39*(1), 83–88. https://doi.org/10.1590/1809-4430-Eng.Agric.v39n1p83-88/2019

MacRae RJ, Hill SB, Mehuys GR & Henning J (1990) Farm-scale agronomic and economic conversion from conventional to sustainable agriculture. Advances in Agronomy 43: 155-198.

Mahlein, A. K. (2016). Plant disease detection by imaging sensors – Parallels and specific demands for precision agriculture and plant phenotyping. In *Plant Disease* (Vol. 100, Issue 2, pp. 241–254). American Phytopathological Society. https://doi.org/10.1094/PDIS-03-15-0340-FE

Mahlein, A. K., Oerke, E. C., Steiner, U., & Dehne, H. W. (2012). Recent advances in sensing plant diseases for precision crop protection. In *European Journal of Plant Pathology* (Vol. 133, Issue 1, pp. 197–209). Springer. https://doi.org/10.1007/s10658-011-9878-z

Mailly, F., Hossard, L., Barbier, J.M., Thiollet-Scholtus, M., Gary, C. (2017). Quantifying the impact of crop protection practices on pesticide use in wine-growing systems, *European Journal of Agronomy*, Volume 84, Pages 23-34, https://doi.org/10.1016/j.eja.2016.12.005.

Malézieux, E. (2012). Designing cropping systems from nature. In *Agronomy for Sustainable Development* (Vol. 32, Issue 1, pp. 15–29). Springer. https://doi.org/10.1007/s13593-011-0027-z

Mansion-Vaquié, A.,Wezel, A., Ferrer,A. (2019). Wheat genotypic diversity and intercropping to control cereal aphids, Agriculture, Ecosystems & Environment, Volume 285, 106604, https://doi.org/10.1016/j.agee.2019.106604.

Marcroft, S. J., Sprague, S. J., Pymer, S. J., Salisbury, P. A., & Howlett, B. J. (2004). Crop isolation, not extended rotation length, reduces blackleg (Leptosphaeria maculans) severity of canola (Brassica napus) in south-eastern Australia. *Australian Journal of Experimental Agriculture*, *44*(6), 601–606. https://doi.org/10.1071/EA03087

Martin, E. A., Dainese, M., Clough, Y., Báldi, A., Bommarco, R., Gagic, V., Garratt, M. P. D., Holzschuh, A., Kleijn, D., Kovács-Hostyánszki, A., Marini, L., Potts, S. G., Smith, H. G., Al Hassan, D., Albrecht, M., Andersson, G. K. S., Asís, J. D., Aviron, S., Balzan, M. V., … Steffan-Dewenter, I. (2019). The interplay of landscape composition and configuration: new pathways to manage functional biodiversity and agroecosystem services across Europe. *Ecology Letters*, *22*(7), 1083–1094. https://doi.org/10.1111/ele.13265

Mcdonald, A. J., Riha, S. J., & Ditommaso, A. (2010). Early season height differences as robust predictors of weed growth potential in maize: New avenues for adaptive management? *Weed Research*, *50*(2), 110–119. https://doi.org/10.1111/j.1365-3180.2009.00759.x

Mckenzie, A., & Whittingham, M. J. (2005). *Why are birds more abundant on organic farms Langholm Moor Demonstration Project View project Enhancing the transferability of ecological models View project*. https://www.researchgate.net/publication/228501725

Meissle, M., Mouron, P., Musa, T., Bigler, F., Pons, X., Vasileiadis, V. P., Otto, S., Antichi, D., Kiss, J., Pálinkás, Z., Dorner, Z., van der Weide, R., Groten, J., Czembor, E., Adamczyk, J., Thibord, J. B., Melander, B., Nielsen, G. C., Poulsen, R. T., … Oldenburg, E. (2010). Pests, pesticide use and alternative options in European maize production: Current status and future prospects. *Journal of Applied Entomology*, *134*(5), 357–375. https://doi.org/10.1111/j.1439-0418.2009.01491.x

Midega, C.A.O., Toby J.A. Bruce, John A. Pickett, Jimmy O. Pittchar, Alice Murage, Zeyaur R. Khan, (2015). Climate-adapted companion cropping increases agricultural productivity in East Africa, Field Crops Research, Volume 180, Pages 118-125, https://doi.org/10.1016/j.fcr.2015.05.022.

Mommer, L., Cotton, T. E. A., Raaijmakers, J. M., Termorshuizen, A. J., van Ruijven, J., Hendriks, M., van Rijssel, S. Q., van de Mortel, J. E., van der Paauw, J. W., Schijlen, E. G. W. M., Smit-Tiekstra, A. E., Berendse, F., de Kroon, H., & Dumbrell, A. J. (2018). Lost in diversity: the interactions between soil-borne fungi, biodiversity and plant productivity. *New Phytologist*, *218*(2), 542–553. https://doi.org/10.1111/nph.15036

Moss, S. (2017). Black-grass (Alopecurus myosuroides): Why has this weed become such a problem in western europe and what are the solutions? *Outlooks on Pest Management*, *28*(5), 207–212. https://doi.org/10.1564/v28_oct_04

Mujjassim Scholar, N. E., Scholar, M. M., Krishna Kumar Rathod Scholar, N., Scholar, N. S., Noor Mujjassim Scholar, C. E., Mujjassim, N. E., & Krishna Kumar Rathod, N. (2019). Cisgenesis and intragenesis a new tool for conventional plant breeding: A review. *~ 2485 ~ Journal of Pharmacognosy and Phytochemistry*, *8*(1).

Osipitan, O.A., Dille, J.A., Assefa, Y., Radicetti, E., Ayeni, A. and Knezevic, S.Z. (2019), Impact of Cover Crop Management on Level of Weed Suppression: A Meta-Analysis. Crop Science, 59: 833-842. doi:10.2135/cropsci2018.09.0589

Pal, J., Scholar, P. D., Chandel, S., & Sharma, R. (2019). CRISPR/Cas9 technology and its potential role in plant disease resistance: A review. *~ 4138 ~ Journal of Pharmacognosy and Phytochemistry*, *8*(3).

Palma, L., Muñoz, D., Berry, C., Murillo, J., & Caballero, P. (2014). Bacillus thuringiensis Toxins: An Overview of Their Biocidal Activity. *Toxins*, *6*(12), 3296–3325. https://doi.org/10.3390/toxins6123296

Pannacci, E., Lattanzi, B., & Tei, F. (2017). Non-chemical weed management strategies in minor crops: A review. In *Crop Protection* (Vol. 96, pp. 44–58). https://doi.org/10.1016/j.cropro.2017.01.012

Pertot, I., Caffi, T., Rossi, V., Mugnai, L., Hoffmann, C., Grando, M. S., Gary, C., Lafond, D., Duso, C., Thiery, D., Mazzoni, V., & Anfora, G. (2017). A critical review of plant protection tools for reducing pesticide use on grapevine and new perspectives for the implementation of IPM in viticulture. *Crop Protection*, *97*, 70–84. https://doi.org/10.1016/j.cropro.2016.11.025

Pinto, K.M.S., do Nascimento, L.C., de Souza Gomes, E.C. *et al.* Efficiency of resistance elicitors in the management of grapevine downy mildew *Plasmopara viticola*: epidemiological, biochemical and economic aspects. *Eur J Plant Pathol* **134,** 745–754 (2012). https://doi.org/10.1007/s10658-012-0050-1

Ponisio, L. C., M'Gonigle, L. K., Mace, K. C., Palomino, J., de Valpine, P., & Kremen, C. (2015). Diversification practices reduce organic to conventional yield gap. *Proceedings of the Royal Society B: Biological Sciences*, *282*(1799), 20141396. https://doi.org/10.1098/rspb.2014.1396

Poux, X., & Aubert, P.-M. (2018). *An agroecological Europe in 2050: multifunctional agriculture for healthy eating. Findings from the Ten Years For Agroecology (TYFA) modelling exercise* (Issue September). https://www.iddri.org/en/publications-and-events/study/agroecological-europe-2050-multifunctional-agriculture-healthy-eating

Power, A.G. (1988). Leafhopper response to genetically diverse maize stands. Entomologia Experimentalis et Applicata Vol 49 (3), https://doi.org/10.1111/j.1570-7458.1988.tb01182.x

Prodorutti, D., Palmieri, L., Gobbin, D., & Pertot, I. (2006). First report of Armillaria gallica on highbush blueberry (Vaccinium corymbosum) in Italy. *Plant Pathology*, *55*(4), 583. https://doi.org/10.1111/j.1365-3059.2006.01420.x

Prodorutti, D., Pertot, I., Giongo, L., & Gessler, C. (2007). Highbush blueberry: cultivation, protection, breeding and biotechnology. *The European Journal of Plant Science and Biotechnology*, *1*(1), 44–56.

Rallo, L., Barranco, D., Díez, C. M., Rallo, P., Suárez, M. P., Trapero, C., & Alfaro, F. P. (2018). Strategies for olive (Olea europaea l.) breeding: Cultivated genetic resources and crossbreeding. In *Advances in Plant Breeding Strategies: Fruits* (Vol. 3, pp. 555–600). Springer International Publishing. https://doi.org/10.1007/978-3-319-91944-7_14

Remáč, M. (2018). Directive 2009/128/EC on the sustainable use of pesticides. *European Union*.

Reineke, A., Thiéry, D. Grapevine insect pests and their natural enemies in the age of global warming. *J Pest Sci* 89, 313–328 (2016). https://doi.org/10.1007/s10340-016-0761-8

Riemens, M. M., Groeneveld, R. M. W., Kropff, M. J. J., Lotz, L. A. P., Renes, R. J., Sukkel, W., & van der Weide, R. Y. (2010). Linking Farmer Weed Management Behavior with Weed Pressure: More than Just Technology. *Weed Science*, *58*(4), 490–496. https://doi.org/10.1614/ws-09-048.1

Rietman, H., Bijsterbosch, G., Cano, L. M., Lee, H. R., Vossen, J. H., Jacobsen, E., Visser, R. G. F., Kamoun, S., & Vleeshouwers, V. G. A. A. (2012). Qualitative and quantitative late blight resistance in the potato cultivar Sarpo Mira is determined by the perception of five distinct RXLR effectors. *Molecular Plant-Microbe Interactions*, *25*(7), 910–919. https://doi.org/10.1094/MPMI-01-12-0010-R

Rosa-Schleich, J., Loos, J., Mußhoff, O. & Tscharntke, T. (2019). "Ecological-economic trade-offs of Diversified Farming Systems – A review," *Ecological Economics*, vol. 160, pp. 251–263, doi: 10.1016/j.ecolecon.2019.03.002.

Rossi, V.Salinari, F., Poni, S. Caffi, T.Bettati,T. (2014). Addressing the implementation problem in agricultural decision support systems: the example of vite.net, Computers and Electronics in Agriculture, Volume 100, Pages 88-99, ISSN 0168-1699, https://doi.org/10.1016/j.compag.2013.10.011.

Rugini, E., & De Pace, C. (2016). *Olive Breeding with Classical and Modern Approaches* (pp. 163–193). Springer, Cham. https://doi.org/10.1007/978-3-319-48887-5_10

Runhaar, H. A. C., Melman, T. C. P., Boonstra, F. G., Erisman, J. W., Horlings, L. G., de Snoo, G. R., Termeer, C. J. A. M., Wassen, M. J., Westerink, J., & Arts, B. J. M. (2017). Promoting nature conservation by Dutch farmers: a governance perspective. *International Journal of Agricultural Sustainability*, *15*(3), 264–281. https://doi.org/10.1080/14735903.2016.1232015

Sankaran, S., Mishra, A., Ehsani, R., & Davis, C. (2010). A review of advanced techniques for detecting plant diseases. In *Computers and Electronics in Agriculture* (Vol. 72, Issue 1, pp. 1–13). Elsevier. https://doi.org/10.1016/j.compag.2010.02.007

Sansavini, S., Donati, F., Costa, F., & Tartarini, S. (2004). Advances in apple breeding for enhanced fruit quality and resistance to biotic stresses: new varieties for the european market. *Journal of Fruit and Ornamental Plant Research*, *12*(Special ed.), 13–52.

Scala et al. V. (2020), "Tramesan Elicits Durum Wheat Defense against the Septoria Disease Complex," Biomolecules, vol. 10, no. 4, doi: 10.3390/biom1004060

Schaart, J. G., van de Wiel, C. C. M., Lotz, L. A. P., & Smulders, M. J. M. (2016). Opportunities for Products of New Plant Breeding Techniques. *Trends in Plant Science*, *21*(5), 438–449. https://doi.org/10.1016/j.tplants.2015.11.006

Schaart, J., Riemens, M., van de Wiel, C., Lotz, B., & Smulders, R. (2015). Opportunities of New Plant Breeding Techniques. *Wageningen UR (University and Research Centre)*, *21*(5), 438–449. http://edepot.wur.nl/357723

Schoffner, AV & Tooker J.F. (2013). The potential of genotypically diverse cultivar mixtures to moderate aphid populations in wheat (Triticum aestivum L.)Arthropod-Plant Interactions (2013) 7:33–43, DOI 10.1007/s11829-012-9226-z

Scholten, O. E., van Heusden, A. W., Khrustaleva, L. I., Burger-Meijer, K., Mank, R. A., Antonise, R. G. C., Harrewijn, J. L., Van haecke, W., Oost, E. H., Peters, R. J., & Kik, C. (2007). The long and winding road leading to the successful introgression of downy mildew resistance into onion. *Euphytica*, *156*(3), 345–353. https://doi.org/10.1007/s10681-007-9383-9

Seufert, V., Ramankutty, N., & Foley, J. A. (2012). Comparing the yields of organic and conventional agriculture. In *Nature* (Vol. 485, Issue 7397, pp. 229–232). Nature Publishing Group. https://doi.org/10.1038/nature11069

Shekoofa, A., Safikhan, S., Raper, T.B. & Butler S.A. (2020) "Allelopathic Impacts of Cover Crop Species and Termination Timing on Cotton Germination and Seedling Growth," *Agronomy*, vol. 10, no. 5, p. 638, doi: 10.3390/agronomy10050638

Skelsey, P., Rossing, W. A. H., Kessel, G. J. T., & Van Der Werf, W. (2010). Invasion of Phytophthora infestans at the landscape level: How do spatial scale and weather modulate the consequences of spatial heterogeneity in host resistance? *Phytopathology*, *100*(11), 1146–1161. https://doi.org/10.1094/PHYTO-06-09-0148

Steen, K., Therkildsen, O., Green, O., & Karstoft, H. (2015). Detection of Bird Nests during Mechanical Weeding by Incremental Background Modeling and Visual Saliency. *Sensors*, *15*(3), 5096–5111. https://doi.org/10.3390/s150305096

STOA (2016). Precision agriculture and the future of farming in Europe, European Parliament Think Tank. https://www.europarl.europa.eu/thinktank/en/document.html?reference=EPRS_STU(2016)581892

STOA (2019). STOA workshop, Farming without agro-chemicals Participants' booklet. STOA

Stockem, J., de Vries, M., van Nieuwenhuizen, E., Lindhout, P., & Struik, P. C. (2020). Contribution and Stability of Yield Components of Diploid Hybrid Potato. *Potato Research*. https://doi.org/10.1007/s11540-019-09444-x

Stubbs, T.L. & A. C. Kennedy, "Microbial Weed Control and Microbial Herbicides," *Herbicides - Environmental Impact Studies and Management Approaches*, Jan. 2012, doi: 10.5772/32705.

Su, Y., Viquez-Zamora, M., den Uil, D. *et al.* Introgression of Genes for Resistance against *Phytophthora infestans* in Diploid Potato. *Am. J. Potato Res.* **97,** 33–42 (2020). https://doi.org/10.1007/s12230-019-09741-8

Suffert, M., Wilstermann, A., Petter, F., Schrader, G., & Grousset, F. (2018). Identification of new pests likely to be introduced into Europe with the fruit trade. *EPPO Bulletin*, *48*(1), 144–154. https://doi.org/10.1111/epp.12462

Tabashnik, B., Brévault, T. & Carrière, Y. Insect resistance to Bt crops: lessons from the first billion acres. Nat Biotechnol 31, 510–521 (2013). https://doi.org/10.1038/nbt.2597

Taesdale, J.R., Brandsaeter, L.O., Calegari A., Neto, F.S., 2007. Chapter 4 Cover Crops and Weed Management. Book Non-chemical Weed Management Principles, Concepts and Technology , eds. Upadhyaya & Blackshaw, ISBN-13: 978 1 84593 290 9

Thorbek, P., & Bilde, T. (2004). Reduced numbers of generalist arthropod predators after crop management. *Journal of Applied Ecology*, *41*(3), 526–538. https://doi.org/10.1111/j.0021-8901.2004.00913.x

Töpfer, R.; Hausmann, L.; Eibach, R. (2011), Molecular Breeding, Editors : Adam-Blondon, A. F.; Martinez-Zapater, J. M. Book chapter: Genetics, genomics, and breeding of grapes, pp.160-185 ISBN : 9781578087174

Topping, C. J., Aldrich, A., & Berny, P. (2020). Overhaul environmental risk assessment for pesticides. *Science*, *367*(6476), 360–363. https://doi.org/10.1126/science.aay1144

Troggio, M., Gleave, A., Salvi, S., Chagné, D., Cestaro, A., Kumar, S., Crowhurst, R. N., & Gardiner, S. E. (2012). Apple, from genome to breeding. In *Tree Genetics and Genomes* (Vol. 8, Issue 3, pp. 509–

529). https://doi.org/10.1007/s11295-012-0492-9

Urbaneja, A., González-Cabrera, J., Arnó, J., & Gabarra, R. (2012). Prospects for the biological control of Tuta absoluta in tomatoes of the Mediterranean basin. *Pest Management Science*, *68*(9), 1215–1222. https://doi.org/10.1002/ps.3344

Urkan, E., Guler, H., & Komekci, F. (2016). A Review of Electrostatic Spraying for Agricultural Applications. *Tarım Makinaları Bilimi Dergisi*, *12*(4), 229–233.

van Eerdt, M. M., Spruijt, J., van der Wal, E., van Zeijts, H., & Tiktak, A. (2014). Costs and effectiveness of on-farm measures to reduce aquatic risks from pesticides in the Netherlands. *Pest Management Science*, *70*(12), 1840–1849. https://doi.org/10.1002/ps.3729

van Evert, F., Gaitán-Cremaschi, D., Fountas, S., & Kempenaar, C. (2017). Can Precision Agriculture Increase the Profitability and Sustainability of the Production of Potatoes and Olives? *Sustainability*, *9*(10), 1863. https://doi.org/10.3390/su9101863

Varnholt, K. Ch, S. Dj, D., Walker F., & Gerhards,R. (2015). “Allelopathic effects and weed suppressive ability of cover crops,” *Plant Soil Environ.*, vol. 62, no. No. 2, pp. 60–66, Jun. 2016, doi: 10.17221/612/2015-PSE

Vasileiadis, V. P., Otto, S., Sattin, M., Andrea, V., Zoltán, P., Rita, B., Jozsef, K., Xavier, P., Per, K., Rommie, van der W., Elzbieta, C., Camilla, M., & Scuola, S. (2011). General Recommendations for IPM Development in European Maize Based Cropping Systems : Innovative Methods and Tools. *Maize Based Cropping Systems (MBCS) Case Study - Guide Number 2*.

Walter, D.R., Ratsep, J., HAvid, N.D. (2013). Controlling crop diseases using induced resistance: challenges for the future. Journal of Experimental Botany, Volume 64, Issue 5, Pages 1263–1280. https://doi.org/10.1093/jxb/ert026

Weisberger D, Nichols V, Liebman M(2019) Does diversifying crop rotations suppress weeds? A meta-analysis. PLOS ONE 14(7): e0219847. https://doi.org/10.1371/journal.pone.0219847

Weiss, M., Jacob, F., & Duveiller, G. (2020). Remote sensing for agricultural applications: A meta-review. *Remote Sensing of Environment*. https://doi.org/10.1016/j.rse.2019.111402

White, S., & Shaw, D. (2010). Breeding for host resistance: The key to sustainable potato production. In A. Lees, J. G. Hansen, & H. Schepers (Eds.), *Twelfth EuroBlight Workshop*. PPO.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L. J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., De Vries, W., Majele Sibanda, L., … Murray, C. J. L. (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. In *The Lancet* (Vol. 393, Issue 10170, pp. 447–492). Lancet Publishing Group. https://doi.org/10.1016/S0140-6736(18)31788-4

Wilson, C., & Tisdell, C. (2001). Why farmers continue to use pesticides despite environmental, health and sustainability costs. *Ecological Economics*, *39*(3), 449–462. https://doi.org/10.1016/S0921-8009(01)00238-5

Wolfe, M. S., Brandle, U., Koller, B., Limpert, E., Mcdermott, J. M., Miiller, K., & Schaffner, D. (1992). Barley mildew in Europe: population biology and host resistance. In *Euphytica* (Vol. 63).

Worrall, D., Holroyd, G.H., Moore, J.P., Glowacz, M., Croft, P., Taylor, J.E., Paul, N.D. and Roberts, M.R. (2012), Treating seeds with activators of plant defence generates long-lasting priming of resistance to pests and pathogens. New Phytologist, 193: 770-778. doi:10.1111/j.1469-8137.2011.03987.x

Wyckhuys, K. A. G., Bentley, J. W., Lie, R., Nghiem, L. T. P., & Fredrix, M. (2018). Maximizing farm-level uptake and diffusion of biological control innovations in today's digital era. In *BioControl* (Vol. 63, Issue 1, pp. 133–148). https://doi.org/10.1007/s10526-017-9820-1

Yardim, E. N., & Edwards, C. A. (2002). Effects of weed control practices on surface-dwelling arthropod predators in tomato agroecosystems. *Phytoparasitica*, *30*(4), 379–386. https://doi.org/10.1007/BF02979685

Zanetti, F. Monti, A., Berti, M.T. (2013). Challenges and opportunities for new industrial oilseed crops in EU-27: A review, Industrial Crops and Products, Volume 50, Pages 580-595, https://doi.org/10.1016/j.indcrop.2013.08.030.

Zhang, C., Dong, Y., Tang, L. et al. Intercropping cereals with faba bean reduces plant disease incidence regardless of fertilizer input; a meta-analysis. Eur J Plant Pathol 154, 931–942 (2019). https://doi.org/10.1007/s10658-019-01711-4

Zhang, H., Zhang, J., Lang, Z., Botella, J. R., & Zhu, J.-K. (2017). Genome Editing—Principles and Applications for Functional Genomics Research and Crop Improvement. *Critical Reviews in Plant Sciences*, *36*(4), 291–309. https://doi.org/10.1080/07352689.2017.1402989

Zhang, J., Khan, S. A., Hasse, C., Ruf, S., Heckel, D. G., & Bock, R. (2015). Full crop protection from an insect pest by expression of long double-stranded RNAs in plastids. *Science*, *347*(6225), 991–994. https://doi.org/10.1126/science.1261680

Zhu, X., Chen, B., Zhu, L., & Xing, B. (2017). *Effects and mechanisms of biochar-microbe interactions in soil improvement and pollution remediation: A review **. https://doi.org/10.1016/j.envpol.2017.04.032

Annex. EU geographical zones

Annex 1 shows the main crops grown in the three EU geographical zones: North, Central and South. The zones and the Member States (EU-27) belonging to each are shown in Table I-1 and Figure I-1.

European agriculture includes a wide range of farm types and sizes, crops, livestock and farming practices. Regional differences in geography influence the development of crop protection practices and the applicability of specific practices at the local level. The continuing developments in crop protection need to take into account these regional differences.

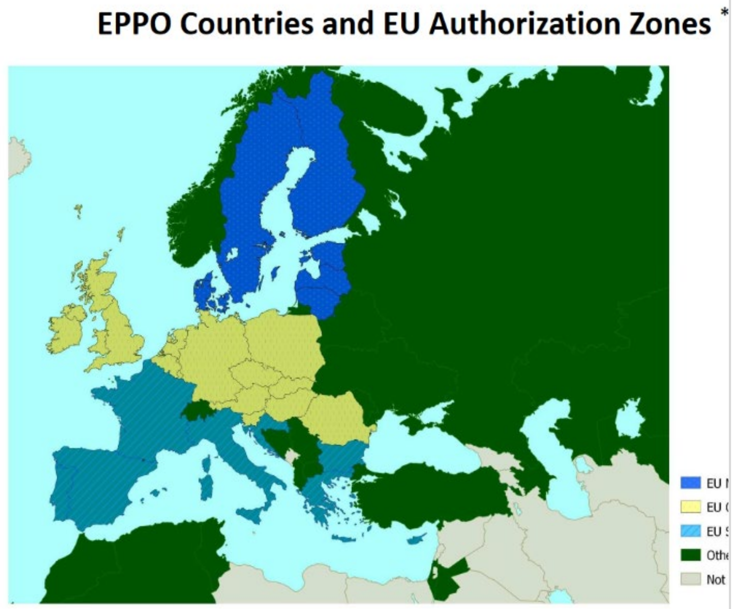
Natural features affecting agricultural production include latitude, altitude, topography, soil type and climate. These factors influence the type and variety of crops grown and their yields, as well as the occurrence of pests, diseases and weeds. Natural features may influence farm and field sizes, which are important factors with respect to the selection and use of farm machinery and equipment used for crop protection.

The geographical zones are used for assessment of the main crops grown, determining crop protection strategies, and the registration of crop protection products.

Table I-1: EU geographic zones and their Member States (EU-27)

Denmark	Belgium	Bulgaria
Estonia	Germany	Cyprus
Finland	Hungary	France
Latvia	Ireland	Greek
Lithuania	Luxembourg	Italia
Sweden	Netherlands	Croatia
	Austria	Malta
	Poland	Portugal
	Slovenia	Spain
	Slovakia	
	Czech Republic	
	Romania	

Figure I-1: EU zones used for the assessment of the main crops and crop protection strategies. UK is not included in the analysis.



The following sections show the cultivated areas of arable crops; vegetable crops; fruits, berries and nuts; and grapes and olives in the three EU zones.[56] Cultivation areas are expressed in 1 000 ha.

Table I-2 shows the total area of the different crop categories per zone and percentage. Temporary grasses and grazing are included in this table for completeness but are not further elaborated.

Table I-2: Cultivated area of crops (1 000 ha)

	North		Central		South	
	Area (1 000 ha)	**Area (%)**	**Area (1 000 ha)**	**Area (%)**	**Area (1 000 ha)**	**Area (%)**
Arable crops	7 556	74 %	29 127	93 %	43 780	66 %
Vegetables	66	1 %	535	2 %	1 426	2 %
Fruits, berries and nuts	38	0.4 %	350	1 %	2 836	4 %
Grapes	0.05	0 %	429	1 %	2 705	4 %
Olives	0	0 %	1.3	0 %	5 092	8 %
Temporary grass and grazing	2 534	25 %	958	3 %	10 373	16 %
Total	**10 194**	**100 %**	**31 300**	**100 %**	**66 213**	**100 %**

Cultivated areas of arable crops per zone

Arable crops make up 74 %, 93 % and 66 % of the total cultivated area in each of the EU zones (Table I-2).

Major cereal crops grown in the EU North zone include wheat and spelt (average yield 4.1 t/ha); barley (3.5 t/ha); oats (2.6 t/ha) and triticale (3.2 t/ha).

Major cereal crops grown in the EU Central zone include wheat and spelt (average 5.8 t/ha); grain maize and corn-cob-mix (8.0 t/ha); barley (5.4 t/ha); triticale (4.9 t/ha) and oats (3.4 t/ha).

---

[56] Data sourced from the EUROSTAT apro_cpsh1 database and combined for all MS in a zone. Data is from 2018. Missing data is replaced with data from 2015. Data accessed on 23 April 2020. Some crops are combined into one group, for example cereals is one group of several cereal species.

Major cereal crops grown in the EU South zone include wheat and spelt (average 5.8 t/ha); barley (4.4 t/ha); grain maize and corn-cob-mix (8.8 t/ha); triticale (3.4 t/ha); oats (2.6 t/ha) and rye (2.5 t/ha).

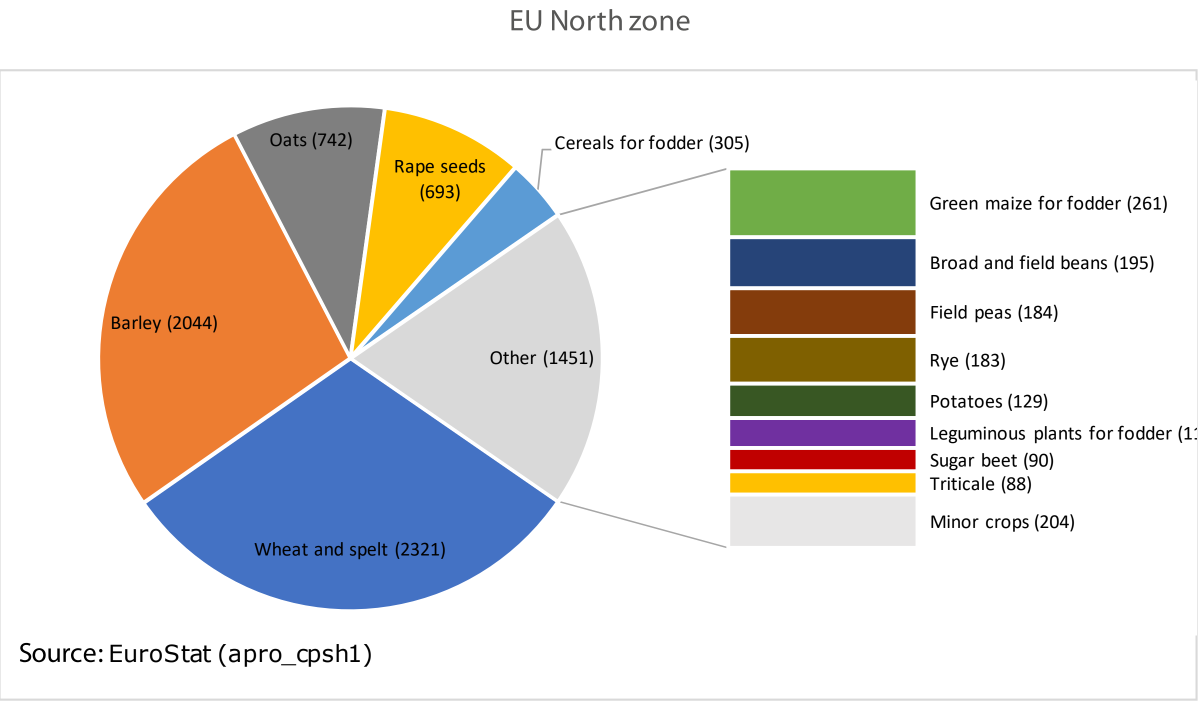
Major oilseed crops in the EU North zone include 475 000 ha winter rape and turnip rape seeds (average 2.6 t/ha) and 218 000 ha spring rape and turnip rape seeds (1.5 t/ha).

Major oilseed crops in the EU Central zone include sunflower seed (average 3.0 t/ha), soya (2.7 t/ha) and rape seed. Rape seed includes 2802 ha winter rape and turnip rape seeds (3.0 t/ha) and 23 000 ha spring rape and turnip rape seeds (2.1 t/ha).

Major oilseed crops in the EU South zone include sunflower seed (average 3.0 t/ha), soya (2.7 t/ha) and rape seed. Rape seed includes 2753 million ha winter rape and turnip rape seeds (3.0 t/ha) and 43 000 ha spring rape and turnip rape seeds (2.1 t/ha).

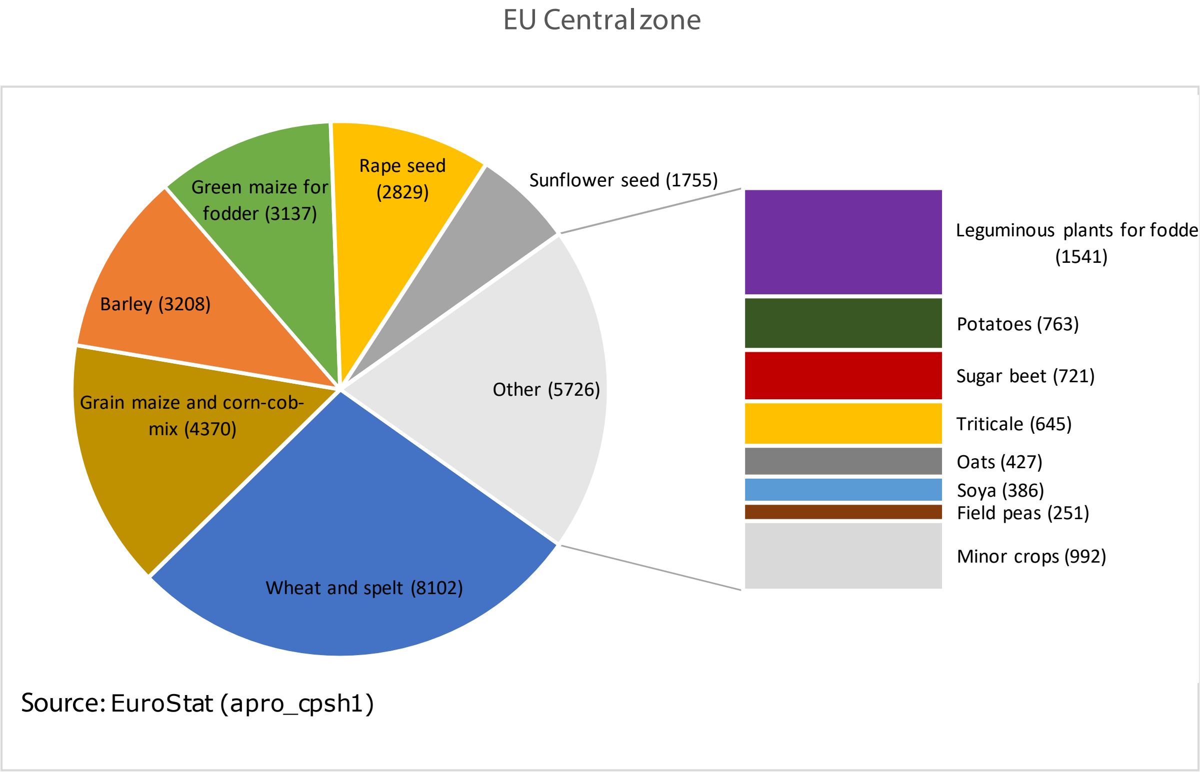
In the North zone, maize is mainly produced for silage (green maize, average 47.1 t/ha).

In the Central and South zones, grain maize is the predominate type (grain maize and corn-cob-mix, average yield 8.0 and 8.8 t/ha in Central and South zones respectively). Other types of maize include seed, sweet maize and maize production for agro-fuel or gas.



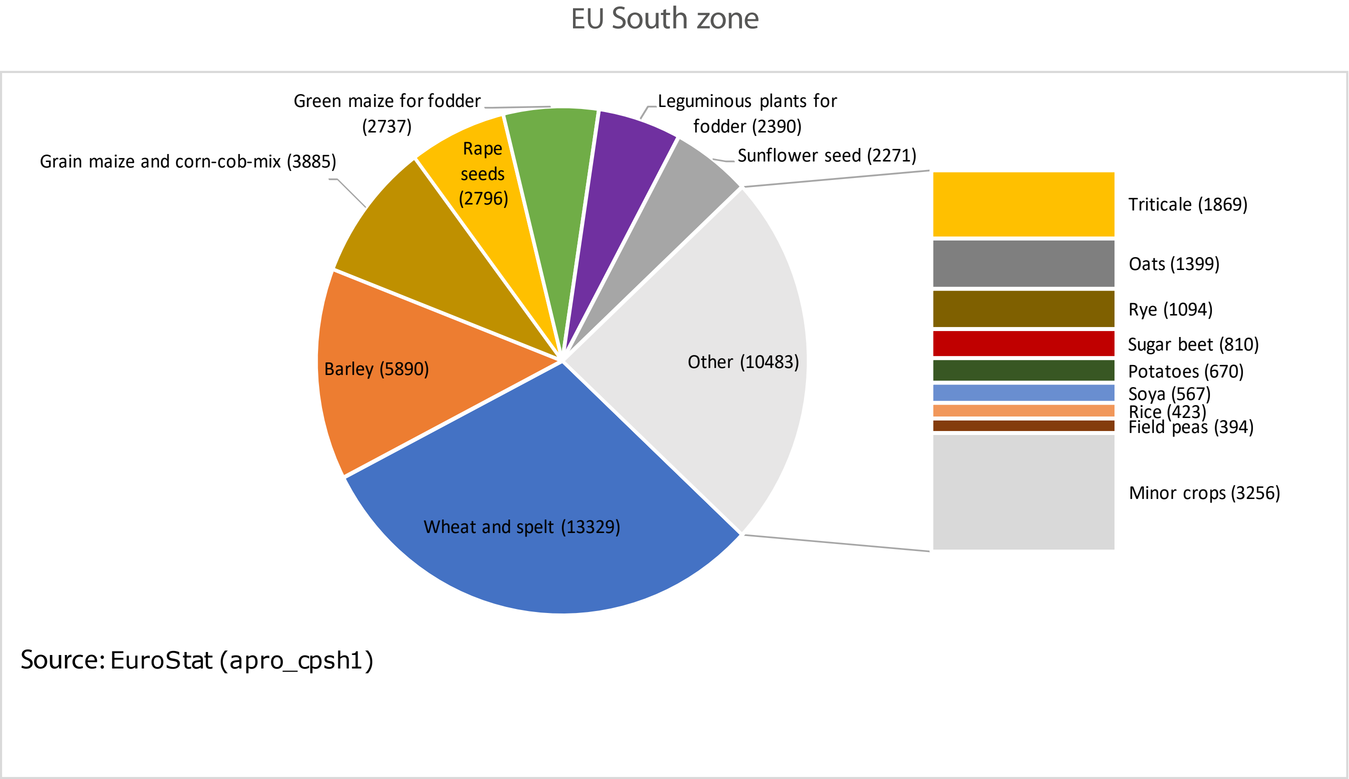
Source: EuroStat (apro_cpsh1)

Figure I-2: Arable crops grown in EU North zone (1 000 ha)



Source: EuroStat (apro_cpsh1)

Figure I-3: Arable crops grown in EU Central zone (1 000 ha)



Source: EuroStat (apro_cpsh1)

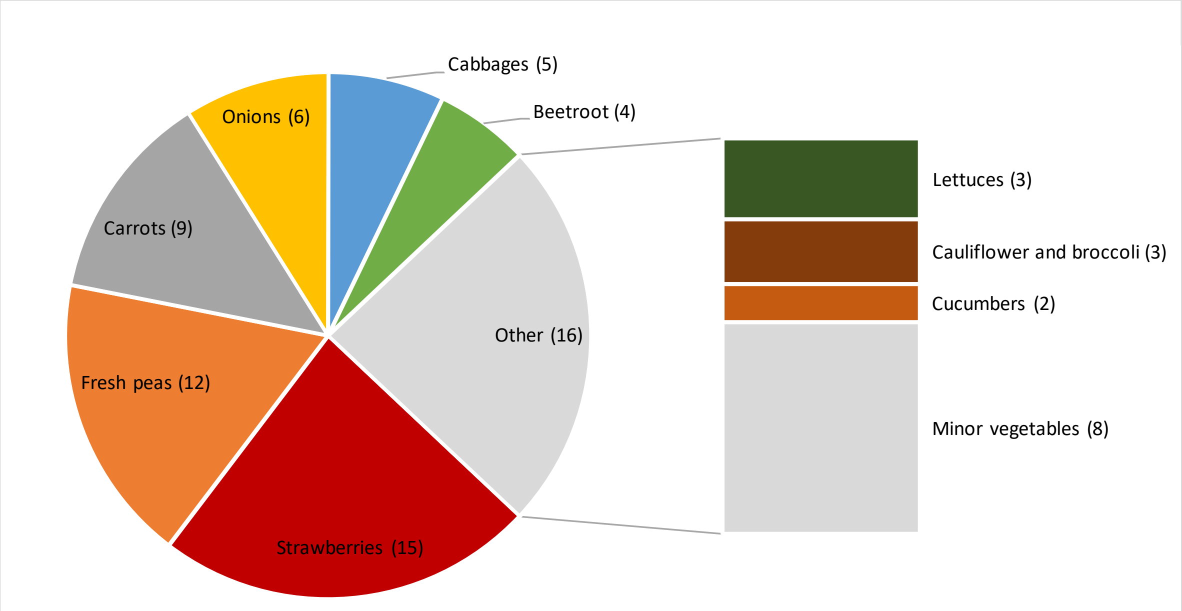
Figure I-4: Arable crops grown in EU South zone (1 000 ha)

Cultivated areas of vegetable crops per zone

Vegetable crops make up 1 %, 2 % and 2 % of the total cultivated area in each of the EU zones (Table I-2).

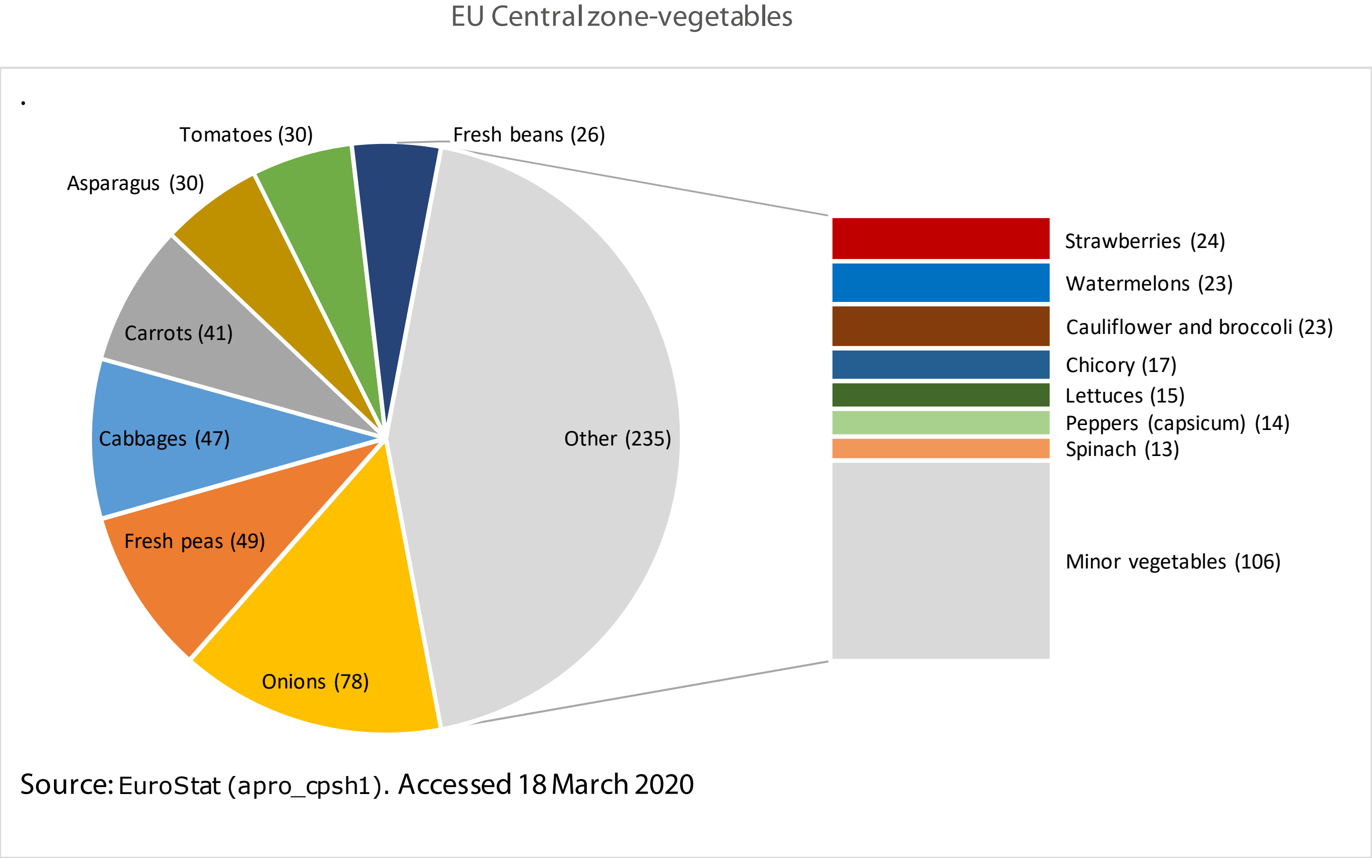
The figures below show the open field cultivated area (1 000 ha) of vegetable crops in each zone.

North zone-vegetables



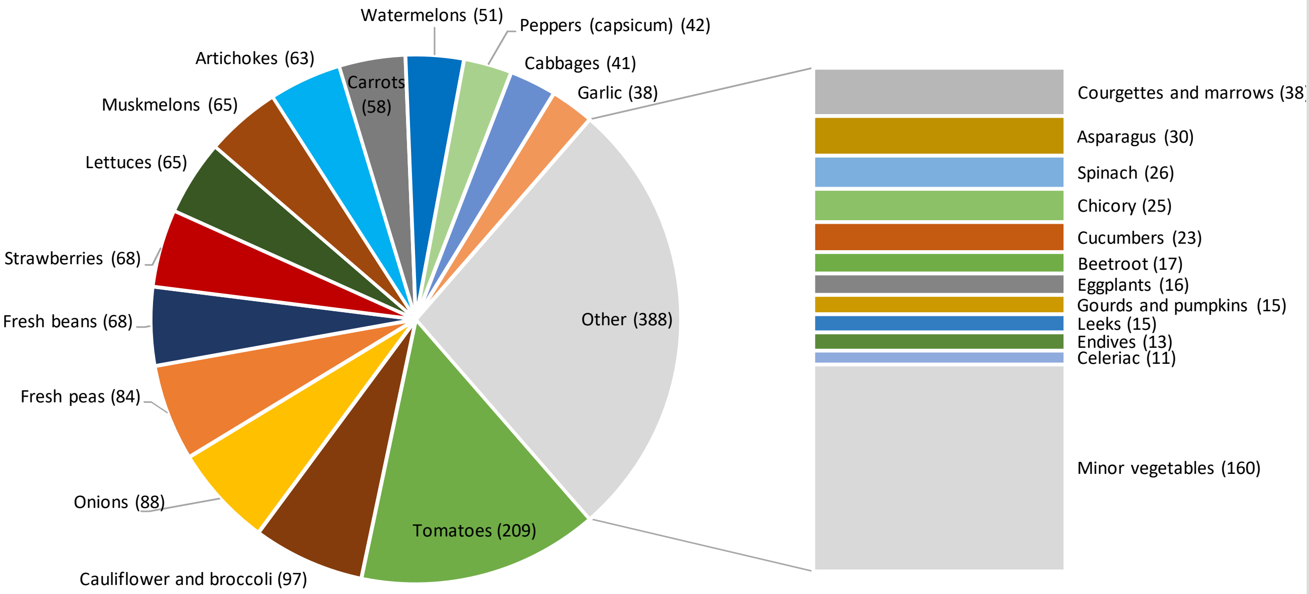
Source: EuroStat (apro_cpsh1). Accessed 18 March 2020

Figure I-5: Vegetable grown crops in EU North zone (1 000ha)



Source: EuroStat (apro_cpsh1). Accessed 18 March 2020

Figure I-6: Vegetable crops in EU Central zone (1 000 ha)


EU South zone- vegetables

Source: EuroStat (apro_cpsh1). Accessed 18 March 2020

Figure I-7: Vegetable crops in EU South zone (1 000 ha)

Cultivated areas of fruits, berries and nuts per zone

Fruits, berries and nuts occupy 0.4 %, 1 % and 4 % of the total cultivated area in each of the EU zones (Table I-2).

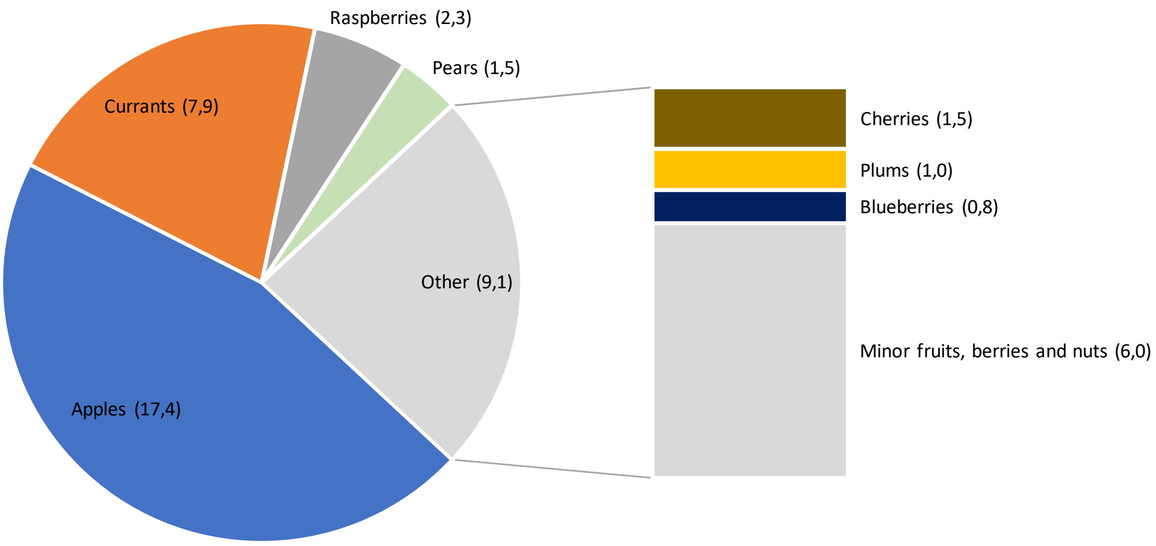
The figures below show the cultivated areas (1 000 ha) of types of fruits and berries in the three zones.

The average yield of apples for fresh production for each zone is: North, 17.0 t/ha; Central, 26.6 t/ha; and South, 68.3 t/ha.

Blueberry production is mainly concentrated in Germany, Poland, France, the Netherlands, Italy and Spain. Average yields of blueberries in the three zones is: North, 1.2 t/ha; Central, 5.5 t/ha; South, 5.7 t/ha.

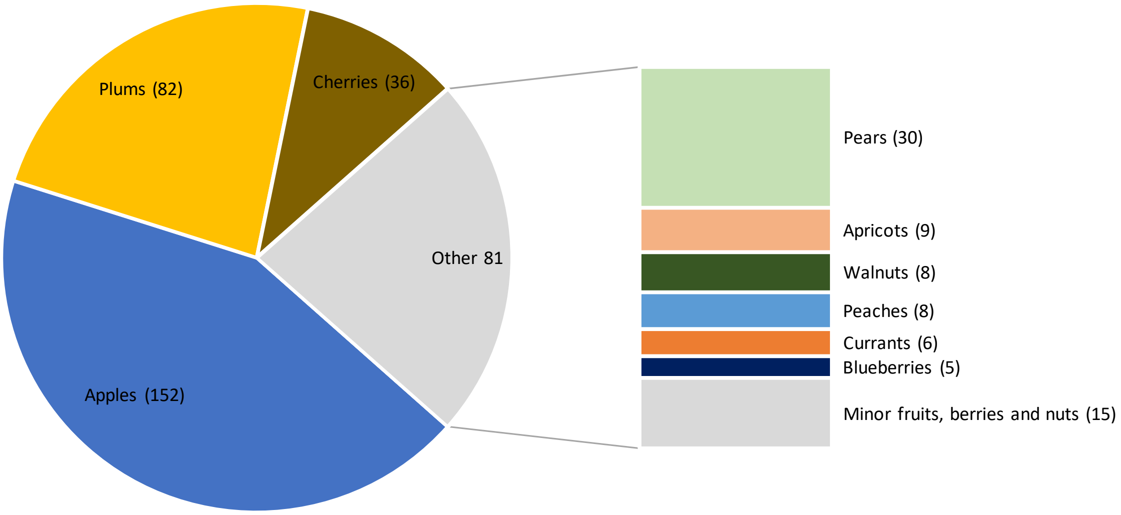
Average yield of blackcurrants in the three zones is: North, 1.1 t/ha; Central, 4.3 t/ha; South, 3.5 t/ha.

By far the largest producer of blackcurrants in the EU is Poland.



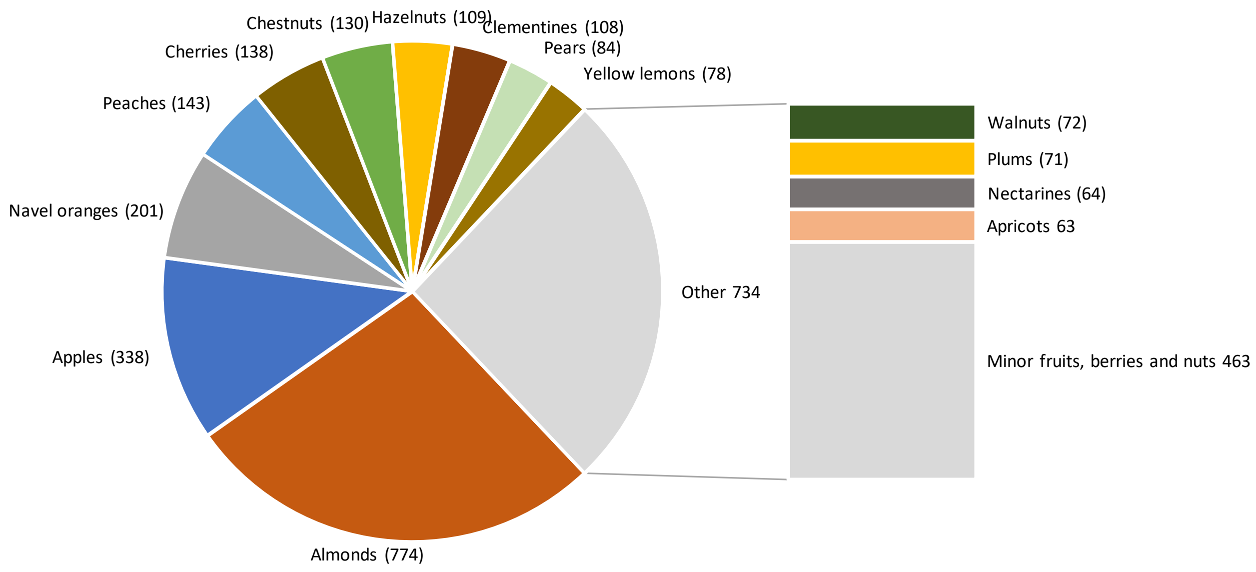
Source: EuroStat (apro_cpsh1). Accessed 18 March 2020

Figure I-8: Fruits, berries and nuts in EU North zone (1 000 ha)



Source: EuroStat (apro_cpsh1). Accessed 18 March 2020

Figure I-9: Fruits, berries and nuts in EU Central zone (1 000 ha)



Source: EuroStat (apro_cpsh1). Accessed 18 March 2020

Figure I-10: Fruits, berries and nuts in EU South zone (1 000 ha)

Cultivated area of grapes and olives per zone

Grapes and olives are mainly cultivated in the Central and South zones of the EU. Vegetable crops make up 0 %, 1 % and 12 % of the total cultivated area in each of the zones (Table I-2).

The majority of grapes are produced for wine, table use or raisins.

The cultivation of grapes in the North zone comprises 50 ha, which are for the production of wine. No olives are cultivated in the North zone.

In the Central zone, 429 000 ha of grapes are cultivated, of which 419 000 ha are for wine, 9 000 ha for table use, and 1 000 ha for other purposes. Grape production occupies about 1 % of the overall cultivated area. Olives are cultivated on 1 300 ha and all production is for oil, with an average yield of 3.0 t/ha.

In the South zone, 2.7 million ha of grapes are cultivated, of which 2.6 million ha are for wine, 87 000 ha for table use, and 25 000 ha for raisins. The grape cultivation area is about 4 % of the total cultivated area in the zone. Olives are cultivated on 5.1 million ha, of which 4.8 million ha is for oil and 311 000 ha for table use. The average yield is 2.7 t/ha. Olives occupy about 8 % of the cultivated area.

Average yields of grapes for wine in the three zones are: North, 1.2 t/ha; Central, 8.7 t/ha; South, 8.5 t/ha.

QA-02-21-005-EN-N

Crop protection in prevailing agricultural systems in the European Union is highly dependent on plant protection products (PPPs) to protect plants against harmful weeds, pests and diseases. The use of PPPs is a cause of health, environmental and public concerns, and a key question is whether their use can be reduced while maintaining adequate yields.

This study provides an overview and description of current and new crop protection practices, including mechanical techniques, plant breeding, biocontrol, induced resistance, applying ecological principles, precision agriculture (PA), and emerging plant protection products. The potential and impact of the new crop protection practices is assessed.

It may be feasible to design resilient systems that are economically viable, have limited environmental impact and help improve biodiversity. Diverse cropping systems would have a natural resilience to weeds, pests, and diseases, and potentially reduce the dependency on PPPs, enabled by PA technologies. The main challenge is to integrate new varieties, mechanisation, and biocontrol tools in these systems. Continuous development of all crop protection practices is needed to ensure sufficient control of pests, weeds and diseases.

The drivers and enablers for implementing alternative crop protection practices are identified, and an analysis of key legislation to support their use is presented.

This is a publication of the Scientific Foresight Unit (STOA)
EPRS | European Parliamentary Research Service

ISBN 978-92-846-7685-9 | doi: 10.2861/044114 | QA-02-21-005-EN-N