OECD Green Growth Studies

Farm Management Practices to Foster Green Growth

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Please cite this publication as:
OECD (2016), *Farm Management Practices to Foster Green Growth*, OECD Green Growth Studies, OECD Publishing, Paris.
http://dx.doi.org/10.1787/9789264238657-en

ISBN 978-92-64-23864-0 (print)
ISBN 978-92-64-23865-7 (PDF)

Series: OECD Green Growth Studies
ISSN 2222-9515 (print)
ISSN 2222-9523 (online)

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Foreword

Green growth strategies in agriculture need to meet global food demand by fostering innovation and improving productivity in a sustainable way. This, as demonstrated by OECD work, is a *sina qua non*.

The agricultural sector has been a highly innovative sector. In many countries, the "Green Revolution" has been the result of scientific developments in agriculture that have brought about a rapid increase in productivity growth, the development of new crop varieties, and increased yields. Major challenges remain, however, as do opportunities in further greening economic activity. Farm management practices that increase productivity, stability and resilience of production systems need to be encouraged and the technology for sustainable development must go well beyond just raising yields. It must also save water and energy, reduce risks, improve product quality and protect the environment. Technologies and farm practices that can contribute to an economically efficient farm sector and provide financial viability for farmers, while at the same time improve environmental performance in a way that is acceptable to society will provide "triple dividends" to green growth.

Based on a literature review, this report analyses the effects on resource productivity and efficiency of key farm management practices with green growth potential as compared to conventional agriculture. The selected practices examined include: soil and water conservation practices; integrated pest management; organic farming; modern agricultural biotechnology; and precision agriculture.

This report was prepared by the OECD Trade and Agriculture Directorate. It was declassified by the OECD Joint Working Party on Agriculture and the Environment (JWPAE) in December 2015 under the title *The Impact of Various Farm Management Practices on Resource Efficiency and Productivity*.

Dimitris Diakosavvas was the project leader and the co-author of this report, which draws on three commissioned consultant papers prepared by Professors Dimitris Psaltopoulos and Dimitris Skouras (University of Patras, Greece), and Professor Justus Wessler (Wageningen University, the Netherlands). Comments from delegates of the JWPAE and OECD colleagues were very much appreciated, in particular those from Peter Kearns, Guillaume Gruère and Bertrand Dagallier (Chapter 6), and Sylvie Poret (Chapter 4). Thanks also to Hana Fratricova from the Ministry of Agriculture and Rural Development of the Slovak Republic.

This work has received financial support from the Ministry of Agriculture, Forestry and Fisheries of Japan and from the Ministry of Agriculture and Rural Development of the Slovak Republic. Theresa Poincet provided invaluable secretarial assistance throughout the production process. The report was edited and prepared for publication by Michèle Patterson, who also co-ordinated its production.

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Executive summary

The efficient use of resources has become a key priority for policymaking in OECD countries and a core element of green growth strategies. This document provides a synoptic review of a selection of farm management practices with green growth potential, such as those relating to soil and water, organic agriculture and Integrated Pest Management (IPM), biotechnology and precision agriculture. The focus on these farm management practices does not, however, imply that other farm practices are not beneficial to green growth.

Key findings

The economic attractiveness of soil and water conservation is highly site-specific, but brings positive environmental impacts

As compared to conventional farming, the evidence on economic productivity of farmers practicing soil and water conservation is mixed: i) there is ambiguity as concerns yields because they are improved under certain agro-ecological regimes and decrease under others; ii) the cost for material inputs, energy and nutrients is reduced in the soil conservation practices, even in the case where inorganic fertilisers are needed to sustain yields under no tillage; and iii) capital inputs are increased in certain soil conservation methods, while labour inputs are almost always increased. On average, their yields tend to be lower, although this varies between OECD countries and between agricultural products.

The effects on natural resource productivity are generally positive. Conservation can have positive spin-off in a number of ways: reduce the use of non-energy materials and waste, and manage nutrients in an environmentally sound way; lower nutrient run-off and reduce GHG emissions, as well as sequester large additional amounts of carbon; produce ecosystem services, especially in the preservation of biodiversity and rural landscapes; and trigger innovations in non-agricultural sectors, such as machinery, the chemical industry and the bio-engineering sectors. However, it may take several years before that the environmental advantages of soil and water conservation management systems can be appreciated and the full extent of the efficient use of resources is measured.

These results, however, should be viewed against increasing demand for food and feed. Even in the case where conservation agriculture is successful in maintaining yields equivalent to those found in conventional agriculture, increasing food demand and the signals of rising prices may put additional stress on soil resources and, in particular, on the conversion of land to agriculture. This can lead to land being converted to agricultural land that may have potential alternative value (e.g. as a nature area). On balance, soil conservation practices may lead to new employment opportunities.

Organic farming provides ecosystem services but its profitability potential is less certain

Evidence from research, field trials and farm experience shows that organic farming is, overall, more environmentally friendly than conventional agriculture. But its economic performance is uncertain as higher price premiums and government support do not fully offset lower yields and higher overall economic costs.

Organic farming creates jobs on farms, with the potential to generate additional off-farm labour, through its links with food processing, marketing and retailing. Moreover, in several countries the positive image of organic farming favours tourism and the creation of associated small businesses in rural areas. Environmental effects for soil, water and biodiversity are positive, but the effects of organic farming on GHG emissions are less certain.

IPM can have win-win-win benefits for profitability, the environment and human health

In most OECD countries, IPM adoption is primarily a response to demands for improved food safety and lower health risks from both consumers and producers. The effects of IPM on yields, farm profits, farm incomes and the environment appear to be positive. By adopting low input and integrated techniques, the use of pesticides can be reduced. Evidence on the employment effects is limited. Agreement on a definition of IPM is needed for policy and impact assessment.

Potential benefits from agricultural biotechnology have not been realised

Despite the controversy it has generated in some countries, the use of biotech crops has increased steadily, although adoption has been uneven across countries and its commercialisation has involved mainly feed crops – and few traits. Today, second- and third-generation products are addressing more complex challenges, such as drought tolerance and nitrogen-use efficiency, but substantial research efforts are needed.

Although caution is necessary in extrapolating from one trait, crop or country to another, from the short term to the long term and from a small sample of farmers to an entire sector, on balance, the evidence suggests that the application of modern biotechnology in agriculture has resulted in: net economic benefit to farmers through reduced pesticide costs, more flexible and less labour-intensive weed management, and the facilitation of zero-tillage cropping systems; reduced GHGs and reduced release of toxic active ingredients into the environment; reduced pressure on land resources thereby reducing pressure on natural habitats from agricultural land-use; major employment effects in the up- and down-stream sectors; and lowered prices for major agricultural commodities, namely cotton, maize, oilseed rape and soybean. However, environmental benefits are context-specific and heavily dependent on thoughtful management practices that avoid the build-up of insect and weed resistance.

An important opportunity to contribute to the agricultural green growth agenda will be missed if the potential risks and benefits of modern agricultural biotechnology cannot be objectively evaluated on the basis of the best available scientific evidence. Imposing high regulatory barriers to respond to uncertainties could result in a high cost to society by restricting or slowing its access to beneficial technologies. However, a key lesson from the analysis is that the economic gains associated with the adoption of biotechnology cannot be realised unless such technology is accepted by society.

Precision agriculture is promising but yet to be proven

Precision agriculture is a whole-farm management approach with the objective of optimising returns on inputs, while improving agriculture's environmental footprint. A wide range of technologies are available, but the most widely adopted precision farming technologies are knowledge-intensive (e.g. GPS guidance). Information on precision agriculture adoption is based on sporadic and geographically dispersed surveys as countries do not regularly collect data.

Precision agriculture can contribute to higher productivity and resource efficiency in regard to both natural resources and farm inputs, thereby mitigating environmental problems associated with agriculture. In addition, precision agriculture has the potential to improve the environmental footprint beyond farm-level (e.g. by its more efficient water productivity management). Its employment effects on farms are variable, but positive in the up- and down-stream sectors. Nevertheless, with low adoption levels, knowledge of the environmental effects of precision agriculture is still limited. Knowledge and technical gaps, high start-up costs with a risk of insufficient return on investment, as well as structural

(e.g. small farm size) and institutional constraints are key obstacles to the adoption of precision agriculture by farmers.

Policy recommendations

- Agricultural policy should be characterised by flexibility to allow for different practices or combinations of practices to apply in the most suitable environments.
- A key policy challenge will be to ensure that the positive and negative environmental externalities that arise from farming systems are internalised. Farmers can then decide which is the most appropriate system to adopt to generate or avoid those externalities.
- Ensure that policies facilitating adoption of farm management practices with green growth potential are coherent with other policies aimed at increasing productivity in a sustainable manner.
- Facilitate the creation and dissemination of credible, science-based information on farmer- and science-led farm management practices.
- Improve the monitoring and assessment of the economic, environmental and social effects of farm-management practices with green growth potential to improve understanding of the benefits and risks involved, and to inform policy decisions to maximise their contribution to green growth.
- Identify factors that prevent the uptake of farm-management practices with green growth potential.
- Support international initiatives to design common guidelines on the definition of IPM and on principles that establish the benchmarks by which to measure its uptake and impact.
- Increase research in farm management practices with green growth potential, reduce regulatory burdens, encourage private-public partnerships, and establish the regulatory frameworks necessary to ensure they meet acceptable bio-safety and environmental standards.

Chapter 1

Investigating farm management practices that may foster green growth

This chapter outlines the structure of the full report. Based on a review of the literature, the report analyses the potential effects of key farm management practices on resource productivity and efficiency compared with conventional agriculture. Although only a selection of farm management practices are analysed, all farm management systems – from intensive conventional farming to organic farming and science-led technologies – have the potential to contribute to green growth. Whether they do or not in practice will depend on whether farmers adopt the appropriate technology and practices. This, in turn, will strongly depend on whether the right policy framework is in place. More intensive farming systems can co-exist with more extensive systems, with the overall effect of increasing productivity and natural resource efficiency in a sustainable manner. The selected practices examined include soil and water conservation practices, integrated pest management, organic farming, modern agricultural biotechnology, and precision agriculture.

The paramount objective of a "Green Growth" strategy in agriculture is to meet global food demand in a sustainable way. This challenge cannot be accomplished by a "business as usual" approach. Developments which can lead to new types of agricultural production and to innovative improvements of existing technologies and practices that are sustainable and environmentally sound, while also contributing to mitigating climate change are needed.

Farm management practices that increase productivity, stability, and resilience of production systems should be encouraged. Technology for sustainable development must go beyond raising yields to saving water and energy, reducing risk, improving product quality and protecting the environment.

Based on a review of the literature, this report analyses the potential effects of key farm management practices on resource productivity and efficiency compared with conventional agriculture. Although only a selection of farm management practices are analysed, all farm management systems – from intensive conventional farming to organic farming and science-led technologies – have the potential to contribute to green growth. Whether they do in practice will depend on whether farmers adopt the appropriate technology and practices. This, in turn, will strongly depend on whether the right policy framework is in place. More intensive farming systems can co-exist with more extensive systems, with the overall effect of increasing productivity and natural resource efficiency in a sustainable manner. The selected practices examined include: soil and water conservation practices; integrated pest management; organic farming; modern agricultural biotechnology; and precision agriculture.

Concerning soil conservation management practices, the report reviews and examines conservation tillage and its variants, conservation crop rotation, and soil nutrient management techniques. For water conservation practices, the report examines land management practices for preparing fields for efficient irrigation and managing excess water, on -farm water delivery systems and the application of irrigation practices, irrigation water use management and protecting water from non-point source pollution and sedimentation.

Organic agriculture is the most developed integrated management practice, occupying almost 1% of agricultural land in the world. Although the rules of organic agriculture vary slightly from country to country, a number of general practices apply to all organic cultivation systems and to the stages of growing, storage, processing, packaging and shipping. Other integrated management practices, such as precision agriculture and IPM, present a "hybrid" approach between conventional practices and organic agriculture.

Modern agricultural biotechnology can be applied to all classes of organism – from viruses and bacteria to plants and animals – and is a major feature of modern agriculture. There are many examples of biotechnology applications to agriculture. They include using micro-organisms to transform materials (e.g. via fermentation), different methods of propagation (e.g. plant cloning or grafting), and genetic alteration (e.g. via selective breeding).

Precision farming is a relatively new management practice made possible by information technology and remote sensing. Precision farming is a whole-farm management approach to optimise crop yields via the systematic gathering and handling of information about the crop and field. It has the potential to contribute to nutrient management by tailoring input use and application more closely to ideal plant growth and management needs. A wide range of technologies are available, but the most widely adopted precision farming technologies are knowledge-intensive (e.g. GPS guidance).

Assessing the resource productivity of these farm practices extends well beyond examining conventional economic productivity results. A broad view of resource productivity is adopted in this report, defined by the ratio of output to the various resources used for production. Managing the natural resource base means matching farm practices with the agro-ecological and socio-economic conditions that will maximise resource productivity (i.e. attain maximum yields with minimum use of resources, such as nutrients, water and soil), maximise environmental and energy productivity (i.e. attain

maximum yields with minimum total emissions and energy use), and maximise the production of public goods (e.g. biodiversity).

The OECD has undertaken several studies related to farm management practices, particularly in the context of analysing the environmental performance of agriculture and understanding the environmental impact of agricultural support policies in OECD countries. The main focus of such work has been on the "green" impacts of the various farming practices examined, and less on the "growth" dimension. This report will focus on both the "green" and "growth" impacts of farm practices.

A few caveats should be mentioned. First, it is difficult to compare the overall impact of these farming practices on green growth to conventional farming systems as there are technical difficulties in defining the appropriate benchmarks for measurement. In addition, the analysis of the number of new jobs potentially "created" by "green agriculture" should take into account the jobs "lost" in more "conventional" segments of the sector. Finally, the impacts are usually context-specific and vary considerably according to crop and agro-ecological environment.

Box 1.1 Assessing the impacts of farm management practices on resource productivity: Defining the concepts

Economic productivity: measures the ability to produce by employing factors of production and resources. As such, the most widely used measures of productivity turn to simple ratios of output relative to inputs used to produce the output. In these ratios or indices the numerator is a measure of the output and the denominator is a measure of the employed resource/factors. Depending on what the numerator measures, productivity measures are categorised as partial or multifactor. In the partial factor productivity context, the numerator measures only the input by one single factor (e.g. hours of labour used for the production of the output), while a multifactor productivity setting measures the change in output per unit of a combination of factors (e.g. combined capital and labour input). Multifactor measures are designed to measure the joint influences of technological change, efficiency improvements, returns to scale, reallocation of resources, and other factors of economic growth, allowing for the effects of capital and labour.

Resource productivity: the ratio of output to the various single resources used in the production. Single resources include non-energy materials, nutrients, water and soil (in terms of productive capability and land-use). Main nutrients include nitrogen and phosphorus, which may lead to surface and groundwater pollution, due to excessive commercial fertiliser-use and intensive livestock farming. For instance, high stress on water resources and the consequent low water productivity are related to the inefficient use of water and to its environmental and socio-economic consequences: low river flows, water shortages, salinization of freshwater bodies in coastal areas, human health problems, loss of wetlands, desertification and reduced food production.

Energy productivity: the ratio of output to energy use. Energy productivity is closely related to the effects on greenhouse gas emissions and on local and regional air pollution. Energy productivity reflects, at least partly, efforts to improve energy efficiency and to reduce carbon and other atmospheric emissions. Energy productivity also is associated to water abstraction and intensity of land-use, which both absorb the largest amount of energy needed by agriculture.

Chapter 2

The role of soil and water conservation in the transition to green growth

This chapter examines soil and water farm management practices and their impact on resource productivity and efficiency. Soil-related problems are interlinked and there is generally no single solution, but rather a wide range of solutions that address multifaceted soil problems. The attempt to institutionalise these solutions and address nation-wide soil problems, however, has led many countries to adopt mandatory soil conservation policies that are often linked to their agricultural policies and support payments. Several land management practices as they affect water conservation are also considered. The practices examined include the preparation of fields for efficient irrigation and management of excess water, on-farm water delivery systems and the application of irrigation practices, irrigation water use management, and protecting water from non-point source pollution and sedimentation. The empirical challenges of assessing these impacts on productivity, efficiency and innovation are discussed.

Key messages

- The evidence concerning traditional economic productivity growth of soil or water conservation practices as compared to those using conventional farming methods shows mixed results.
- Yields are generally lower on farms that use conservation practices, but there are significant differences in yields between OECD countries, agricultural products and over time. Yields on farms that have adopted soil conservation practices improve under rain-fed agro-systems in dry climates.
- The effects of soil or water conservation practices on resource productivity are positive overall, Soil-conservation practices generally reduce the use of non-energy materials and waste, and the management of nutrients is more environmentally sound.
- There is limited but contrasting evidence on how soil and water conservation practices influence employment rates; soil conservation practices seem to have lower labour requirements, while conservation efforts that include the displacement of crops tend to be labour intensive.

Soil conservation practices

A quiet revolution?

Soil erosion is a global environmental issue. Much of this erosion, as well as the degradation of soil in general, is due to poor soil management practices, including slash and burn management, deforestation, and overgrazing. The extreme climatic and topographic conditions, and climate changes occurring today only increase soil erosion. Current rates of land and soil degradation are considered to be unsustainable. UNEP (2012) argues that 24% of the global land area has suffered declines in health and productivity over the past quarter-century as a result of unsustainable land-use. Since the 19th century, worldwide damage to organic matter due to land-clearing for agriculture and urban development accounts for an estimated 60% loss of the carbon stored in soils and vegetation.

Increasing amounts of land are being cultivated using intensive farming methods. These methods place great strain on the natural resources upon which they rely and are jeopardising the future of agriculture. Indeed, a study co-authored by the European Commission's Joint Research Centre found that diminished soil biodiversity in the European Union is primarily due to intense use of land for agriculture (Gardi, Jeffery and Salteli, 2013).[1]

Most OECD countries have programmes in place to encourage farm practices that specifically seek to reduce the risk of soil erosion. This includes transferring arable land to grassland, extensive use of pastures, green cover (mainly during the winter period), and promoting soil conservation practices such as tillage conservation, conservation crop rotation, and crop nutrient management practices.

The amount and type of tillage used in crop residue management systems are critical issues for farm managers and policy makers alike, as tillage practices affect nutrient availability, soil structure and aggregate stability, soil strength and temperature, the soil-water relationship, and the crop residue cover. Tillage consumes energy and affects soil carbon sequestration capacity with implications for GHG emissions. Loss of Soil Organic Carbon (SOC) has been primarily attributed to tillage, and tilled soils are viewed as a depleted carbon reservoir (Reicosky, 2003). Likewise, crop rotation practices affect the risk of soil erosion, water runoff, and the chemical and physical properties of the soil.

Conservation tillage methods, which make up some of the most dramatic technological revolutions in crop management, are considered a sustainable alternative to conventional tillage because by maintaining residue cover, it can improve both agronomic and economic efficiency while providing environmental benefits. Moreover, given that fewer tillage field passages are needed, reduced machinery costs, fuel and labour expenditures can boost farm profits. This may, however, be offset by increased pest management costs in some climates and for some crops (Ebel, 2012).

Conservation crop rotation practices can reduce the risk of soil erosion, help prevent water runoff, and improve the chemical and physical properties of soil. These practices can provide supplementary forage and act as a substitute for some agricultural inputs – including fertilisers, herbicides and water – given the significant nitrogen storage capacity and improvement in soil fertility, the suppression of weeds, and soil moisture retention.

Farms that use crop residue management retain more moisture by trapping snow, decreasing water evaporation from the top layer of soil, and improving water infiltration to plant root systems. Environmental benefits include reduced soil erosion and water pollution (via reduced sediment, fertiliser and pesticide runoff), and improved air quality (as soil particulates do not become airborne).

Conservation agriculture is based on the simultaneous application of the following three principles that underpin agricultural production systems: i) continuous minimum mechanical soil disturbance; ii) protection of the soil through permanent maintenance of plant soil cover with crop residues and green manure crops, particularly legumes; and iii) the diversification of rotations and intercropping (Box 2.1). The diversity of production conditions and farmers' needs have led to a wide diversification of practices in the application of these three principles. Conservation agriculture, which integrates ecological management with modern agricultural techniques, corresponds to a family of cropping systems rather than to a single technology or system. In some cases, seeds are sown directly through the crop residues (drilling directly through the stubble), while in others, the soil receives some light preparation to facilitate crops planting. In all cases, changes related to the introduction of conservation agriculture go beyond a mere change in soil tillage techniques and must be considered in a broader context that includes other innovations, such as the use of cover crops and intercropping.

Box 2.1. What is conservation agriculture?

FAO defines conservation agriculture as "an approach to managing agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment" (www.fao.org/ag/ca/1a.html; FAO, 2001). It comprises the following conservation farm practices.

Conservation tillage: Any method of soil cultivation that leaves the previous year's crop residue (such as maize stalks or wheat stubble) on the fields before and after planting the next crop in order to reduce soil erosion and runoff. It minimises (or eliminates) tillage and maintains crop residues as ground cover (practices include no-till, strip-till, ridge-till and mulch-till) (Minnesota Department of Agriculture, 2012). Each of these four methods requires different types of specialised or modified equipment and adaptations in management. No-till and strip-till require that crops are planted crops directly into the residue. With the no-till method, the residue is not tilled at all. With the strip-till method the soil is tilled along narrow strips (zones) with the rest of the field left untilled. With ridge-till method, row crops are planted on permanent ridges about 4-6 inches high, with the previous year's crop residue cleared off the ridge-tops into adjacent furrows, thus making way for the new crop to be planted on the ridges. (However, maintaining the ridges is essential and requires modified or specialised equipment). Mulch-till is any other reduced tillage system that leaves at least one-third of the soil surface covered with crop residue.

Conservation crop rotation: A farm practice whereby several crops are planted in succession in the same field. These crops should include at least one soil-conserving crop, such as perennial hay, or nitrate-trapping and nutrient-enriching crops, such as various legumes. Conservation crop rotation is similar, and frequently practised with, crop cover activities.

Cover crops: All crops that are planted to provide seasonal soil cover on land when the soil would otherwise be bare. Cover crops include various grasses, legumes or forbs and are planted before the main cash crop emerges in spring or after harvest in the autumn. The term "cover crops" includes various practices, such as winter cover crops, catch crops, smother crops, green manure and short-rotation forage crops. Winter cover crops aim to provide the soil with cover over winter in order to reduce water and wind erosion. Catch crops are planted immediately after harvesting the cash crop in order to reduce nutrient leaching. Smother crops are used as an environmentally friendly weed control practice. These crops, such as buckwheat and rye are able to out-compete major weeds. Other cover crops are used as green manure because they are incorporated into the soil in order to improve soil fertility. Finally, cover crops may be used for grazing or green chop to provide forage and are called short-rotation forage crops.

There are clear benefits to conservation agriculture, including evidence that topsoil organic matter increases as do other soil properties and processes involved in the delivery of related ecosystem services. Soil conservation practices protect the soil surface with residue retention, and increase water infiltration and decrease runoff with no tillage, thus reducing erosion due to water and wind (Palm et al., 2014; Verhulst et al., 2012). Water-holding capacity and storage are also improved (reducing the risk of floods) when conservation practices provide a buffer to crop production during drought conditions (Friedrich, Kassam and Shaxson, 2009; Kassam et al., 2009). Finally, conservation agriculture allows for greater precision and timeliness of farm operations, and greater efficiency of inputs. Table 2.1 summarises the effects and benefits of conservation agriculture contrasted with no-tillage (Hobbs et al., 2008).

Table 2.1. Effects of traditional tillage, conservation tillage and conservation agriculture

Issue	Traditional tillage (TT)	Conservation tillage (CT)	Conservation agriculture (CA)
Practice	Disturbs the soil and leaves a bare surface	Reduces the soil disturbance in TT and keeps the soil covered	Minimal soil disturbance and soil surface permanently covered
Erosion	Wind and soil erosion: maximum	Wind and soil erosion: reduced significantly	Wind and soil erosion: the least of the three
Soil physical health	The lowest of the three	Significantly improved	The best practice of the three
Compaction	Used to reduce compaction and can also induce it by destroying biological pores	Reduced tillage is used to reduce compaction	Compaction can be a problem but use of mulch and promotion of biological tillage helps reduce this problem
Soil biological health	The lowest of the three owing to frequent disturbance	Moderately better soil biological health	More diverse and healthy biological properties and populations
Water infiltration	Lowest after soil pores clogged	Good water infiltration	Best water infiltration
Soil organic matter	Oxidizes soil organic matter and causes its loss	Soil organic build-up possible in the surface layers	Soil organic build-up in the surface layers even better than CT
Weeds	Controls weeds and also causes more weed seeds to germinate	Reduced tillage controls weeds and also exposes other weed seeds for germination	Weeds are a problem especially in the early stages of adoption, but problems are reduced with time and residues can help suppress weed growth
Soil temperature	Surface soil temperature: more variable	Surface soil temperature: intermediate in variability	Surface soil temperature: moderated the most
Diesel use and costs	Diesel use: high	Diesel use: intermediate	Diesel use: much reduced
Production costs	Highest costs	Intermediate costs	Lowest costs
Timeliness	Operations can be delayed	Intermediate timeliness of operations	Timeliness of operations more optimal
Yield	Can be lower where planting delayed	Yields same as TT	Yields same as TT but can be higher if planting done more timely

Source: Table 2 in Hobbs, P., K. Sayre and R. Gupta (2008).

Adoption of conservation agriculture and no-tillage techniques is rising rapidly in several countries. According to data collected by the FAO, conservation agriculture has expanded at an average rate of around 7 million hectares per year (from 45 to 125 million) over the period 1999-2013. Since 1990, the rate of adoption globally has been growing exponentially, mainly in North and South America, Australia and New Zealand. The main drivers are stagnating productivity due to soil erosion, loss of soil organic matter and soil structure, soil compaction, the rising costs of production, government policies, the adoption of herbicide-tolerant crops and the potential impacts of climate change (Kassam, Derpsch and Friedrich, 2014).[2]

There are concerted efforts to promote conservation agriculture in smallholder farming systems in South Asia and Sub-Saharan Africa (Hobbs et al., 2008; Valbuena et al., 2012), but whether it is suitable to smallholder systems in the tropics and subtropical countries is unclear (Box 2.2).

It was estimated in 2013 that 10% of the world's cropland area was farmed under conservation agriculture, with the largest areas found in South America (Table A2.1). Five countries account for more than 80% of the total global area under conservation agriculture: the United States (23%); Argentina and Brazil (20%); Australia (11%); and Canada (12%) (Table A1.1). In six countries, the share of cultivated area under conservation agriculture is equal to or larger than 30% (Argentina, Brazil, Australia, Canada, Paraguay and Uruguay) (Figure 2.1 and Table A2.1).

Box 2.2. Innovative approaches to enhance green growth potential in smallholder farming systems

Whilst conservation agriculture has been successfully introduced in high-input and high-yielding smallholder farms in the rice-wheat region of South Asia, this is more challenging in the low-input, low productivity smallholder farm systems of the tropics and subtropics. The most significant obstacles here are the lack of residue produced and the competition from alternate, higher value use.

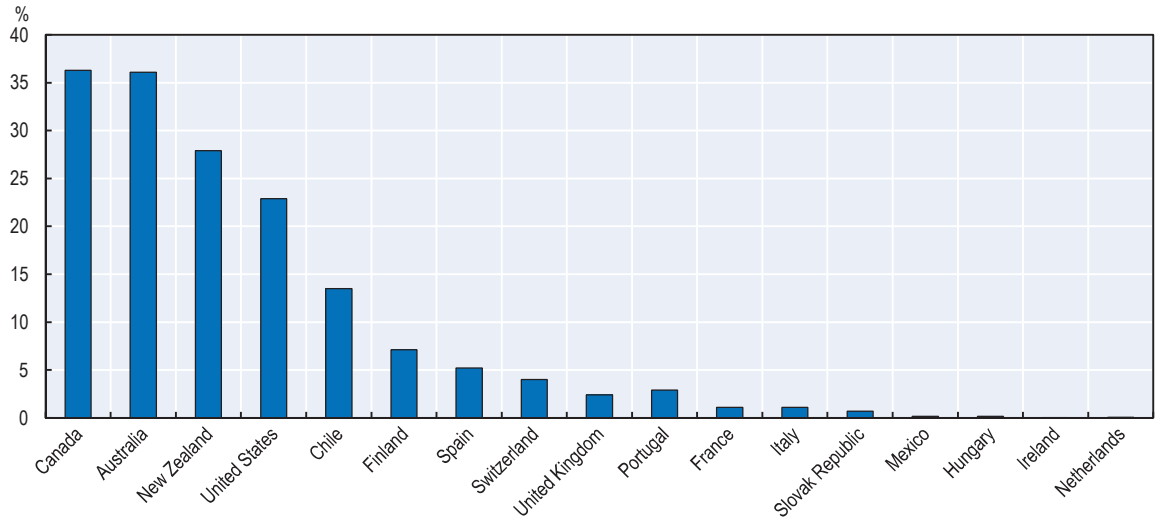
The amount of crop residue retained after harvest, either on the soil surface or incorporated, is a key factor of conservation agriculture. Unlike most temperate zone agriculture and other large-scale farming systems where zero (or reduced) till results in high production and retention of crop residues, that produced by many small scale farms in Sub Saharan Africa, parts of Latin America, and South Asia is low due to low productivity (Palm, et al., 2014; Paul et al., 2013; Thierfelder et al., 2013; Dube et al., 2012; Lahmar et al., 2012; Ngwira, Thierfelder and Lambert, 2012; Giller et al., 2009).

Competing, alternative uses of residues are another constraint. The majority of smallholders are mixed crop-livestock farmers who use most crop residues as animal feed. In some areas, crop residues are burned to clear agricultural fields, while in other areas residues are removed from fields by termites. In many regions of Sub-Saharan Africa, there is also a cultural norm that residues may be grazed by any animal in the community (Wall, 2007). Given that residues provide an important source of animal feed, changing this cultural norm will be difficult.

These limitations point to the need for nuanced approach in the promotion of different conservation agriculture practices. For example, a series of interventions may be more appropriate (Lahmar et al., 2012). The first step would be to increase crop production through nutrient management, followed by soil and water management practices that improve soil quality and water retention, followed by a gradual introduction of conservation agriculture practices if and where appropriate to the soil, climate and socioeconomic conditions. These steps must be based on evidence that the practice or suite of practices result in increased ecosystem services without compromising increased yields.

Sources: Pannell, D., R. Llewellyn and M. Corbeels (2014), "The farm-level economics of conservation agriculture for resource-poor farmers", *Agriculture, Ecosystems and Environment*; Palm, C., H. Blanco-Canqui, F. DeClerck, L. Gatere and P. Grace (2014), "Conservation agriculture and ecosystem services: An overview", *Ecosystems and Environment*,; Brouder, S. and H. Gomez-Macpherson (2014), "The impact of conservation agriculture on smallholder agricultural yields: A scoping review of the evidence", *Agriculture, Ecosystems and Environment*,.

Figure 2.1. Adoption of soil conservation agriculture in OECD countries: Share in total cultivated area,



Source: FAO, AQUASTAT database, website accessed on 2 July 2015.

The initial impetus to reduce soil disturbance and adopt no-till farming in the United States arose in response to the devastation caused by the prolonged drought of the mid-1930s (the dust bowls years). In Canada and Australia, the initial drivers were wind and water erosion, but subsequently factors such as greater productivity and profit, expansion of cropping diversity in sub-tropical and cool temperate environments, and the reduced cost of fertiliser, pesticides, energy and time became important. In the case of countries such as Brazil, Argentina and Paraguay, where no-till farming started in the 1970s and 1980s, the main initial driver was soil degradation due to devastating soil erosion from intense tropical and sub-tropical storms, and from exposed and loose top soil due to intensive tillage.

With the exception of a few countries (e.g. the United States, Canada, Australia, Brazil, Argentina, Paraguay and Uruguay), conservation agriculture has not been "mainstreamed" by farmers or policy makers, and the total arable area under conservation agriculture worldwide remains relatively small (about 9%). The main factors hindering greater adoption, as cited in the literature, include: i) insufficient knowledge (or know-how); ii) farmer attitudes and aspirations; iii) lack of adequate machines; iv) lack of suitable herbicides to facilitate weed management; v) the high opportunity cost of crop residues for feed; vi) lack of herbicide-tolerant crop varieties for some crops and climates; and vii) inappropriate policies (e.g. commodity-based support in some OECD countries) (Kassam, Derpsch and Friedrich, 2014; D'Emden, Llewellyn and Burton, 2008; Thomas et al., 2007; Pannell et al., 2006; Prokopy et al., 2008; Gedikoglou and McCann, 2010; Gedikoglou et al., 2011).[3]

Australia is an example of a country that has largely adopted conservation farm practices. Since the late 1990s, these practices have been used by the majority of crop farmers, driven primarily by the anticipated benefits of higher crop yields resulting from managing soil moisture and improved fertility. In particular, such practices (involving reduced tillage and crop residue retention) have been a key management tool to improve productivity in the dryer inland grain-producing areas, which cover 80% of cropping land. Farmer experimentation with conservation agriculture began in the 1960s; today,of the country's 23.5 million hectares of winter crops, 80-90% are cultivated using conservation agriculture practices (Belloti and Rochecouste, 2014).

The hot, arid conditions in Australia have created a major impetus for the expansion of moisture conservation through direct seeding and stubble retention after harvest. The economic benefits from yield increases through no-till systems in the cereal grains sector is 1 tonne per hectare, with increased planting opportunities in prolonged dry years. Other sectors (cotton and sugar) have followed suit. A

national survey conducted in 2012 by the Conservation Agriculture Alliance of Australia and New Zealand (CAAANZ) indicates that the main catalyst for changing tillage practices included the perceived risks stemming from soil erosion and drought that farmers believed threatened the viability of their farms. In addition, the changes in conservation farming practices and the success gained in terms of yield led to further research into productivity gains and the need to reduce cost input resources. Although this research was primarily productivity-driven, it was to provide significant complementary benefits to the environment, in particular the emergence of precision agriculture (Chapter 6).

In the United States, agricultural land devoted to "no-till" farming has increased across all major crops. In 2010, approximately 35.5% of US cropland planted to eight major crops had no tillage operations (Ebel, 2012; Horowitz, Ebel and Ueda, 2010). Soybean farmers had the highest percentage of planted area with no-till (almost 50%), followed by maize (around 30%) and cotton farmers (24%). More area is planted to maize than to any other field crop in the United States. Of all the major crops analysed, rice farmers had the lowest percentage of planted acres with no-till (16.3%).

Crop nutrient management is an important conservation strategy that has implications on production costs. Crop nutrient management refers to the type, quantity and time of application of major nutrients. Farmers are frequently unaware of the nutrient needs of their soils; the continued application of fertilisers does not increase yields, but does increase contamination and production costs. It is estimated that the over-application of inorganic and organic fertilisers has boosted nutrient capacity in the soil by about 2 000 kg of nitrogen, 700 kg of phosphorus, and 1 000 kg of potassium per hectare of arable land in Europe and North America in the last 30 years (World Bank, 1996). Integrated nutrient management is related to precision agriculture and is discussed in Chapter 6.

It is evident that all soil-related problems are interlinked and there is no single solution – or rather, there is a wide range of solutions addressing the multifaceted soil problems. The attempt to institutionalise these solutions and address nation-wide soil problems has led many countries to adopt mandatory soil conservation policies linked, or not, to their agricultural policies.

In the European Union, an integrated soil conservation directive was proposed in 2006, but has not progressed since. However, the cross compliance regulations in the European Union provide a coherent soil conservation policy for agriculture. Cross compliance is the set of conditions which must be met by farmers who claim direct payments under the Common Agricultural Policy (e.g. the Single Farm Payment Scheme). These conditions constitute the minimum farming requirements and for which the farmer is not compensated. Additional requirements and their associated payment may be covered by agri-environmental schemes. Good Agricultural and Environmental Conditions (GAECs) are legal requirements made up of either existing laws or existing good practices in EU member states before the introduction of cross compliance. Concerning soil conservation, GAECs requirements relate to soil erosion, soil organic matter, soil structure, and ensuring a minimum level of maintenance.

For soil erosion, GAECs require minimum soil cover, minimum land management reflecting site-specific conditions and the retention of terraces when possible. For soil organic matter, standards are set for crop rotations and arable stubble management. Soil structure recommendations include appropriate use of machinery and minimum livestock stocking rates. Finally, cross compliance requirements in the European Union ensure that the ratio of permanent pasture to total agricultural area is maintained at the 2003 level. Permanent pasture is defined as land that has been under grass for at least five years and has not been ploughed for other crops during that time. There are also many voluntary agri-environmental programmes which compensate farmers for agreeing to produce further environmental and conservation public benefits, in addition to what is envisaged through cross compliance.

In the United States, the Food Security Act (1985 Farm Bill) introduced two important compliance conservation practices to preserve soil and water resources (collectively referred to as conservation compliance). These two provisions, still in force, require that in exchange for certain US Department of Agriculture (USDA) programme benefits, producers agree to maintain a minimum level of conservation on highly erodible land and not to convert wetlands into cultivated land. In addition, many voluntary programmes exist for soil and water conservation.

The Agricultural Management Assistance Program provides financial and technical assistance to agricultural producers who voluntarily want to adopt water management, water quality, and erosion control practices by incorporating conservation into their farming operations. The Environmental Quality Incentives Program is a voluntary programme that provides financial and technical assistance to agricultural producers through contracts of up to a maximum term of ten years. Assistance is provided to help plan and implement conservation practices that address natural resource concerns and for opportunities to improve soil, water, plant, animal, air and related resources on agricultural land and non-industrial private forestland.

The Conservation Stewardship Program (CSP) is a voluntary conservation programme that encourages producers to address resource concerns in a comprehensive manner by: undertaking additional conservation activities, and improving, maintaining, and managing existing conservation activities. Two types of payments are provided through five-year contracts: annual payments for installing new conservation activities and maintaining existing practices; and supplemental payments for adopting a resource-conserving crop rotation. Participants are paid for conservation performance: the higher the operational performance, the higher their payment.[4]

Productivity and efficiency gains, but types of soil and crops critical to the overall gains

Economic outcomes are context specific

Soil is an asset, whose returns are composed of three elements: i) the value of soil as an input to agricultural production; ii) the value of soil as a capital element which − depending on the amount and productivity − affects the potential resale value of the land; and iii) the value that soil provides above and beyond production (i.e. provision of ecosystem services). These elements determine the potential resale value of the farmland.

The returns to soil conservation practices and their effects on farm productivity and efficiency have been a widely discussed in agricultural economics.[5] At the farm level, the economic impacts of soil erosion and soil degradation are often related to productivity slowdown and decreasing returns observed in some countries.

Changes in prices (input or output) may have contradictory effects on soil erosion. An increase in the output price creates an incentive for increased soil erosion due to the fact that higher output price could encourage farmers to expand production to less productive land or to shift less productive agricultural land to other uses. Policies that increase incentives for stimulating production on economically marginal land may have disproportionately large and unintended consequences for the environment (OECD, 2009). Lubowski et al. (2006) found that in the United States land brought into or retained in cultivation due to crop insurance policies is, on average, less productive, more vulnerable to erosion, and more likely to include wetlands and imperilled species habitats than cultivated cropland.

Input costs are likely to vary under soil conservation practices relative to conventional ones. Conservation tillage has a small cost advantage over conventional tillage, although site-specific conditions could alter this in various ways. Adoption of conservation (or zero) tillage implies that farmers can use smaller tractors and make fewer passes over the field, resulting in lower fuel and repair costs. Conservation tillage also reduces the cost of machine ownership (i.e. interest and depreciation) because some machines are no longer needed. Similarly, most findings confirm the expectation that fuel costs are lower than those incurred under conventional tillage.

Reduced input costs, however, might not be observed because reducing tillage can lead to greater use of pesticides to combat weeds, pests and diseases. Herbicide costs could be higher, at least initially, and thus offset any cost savings associated with less labour, fuel, machine repairs and overhead. Most developed-country studies find, nevertheless, that conservation agriculture demonstrates at least minor cost savings (FAO, 2001).

Uri (1999) found that that in the United States, while the real price of crude oil does not affect the rate of adoption of conservation tillage, it does impact the extent to which it is used. In general, conservation tillage is more profitable in steep-sloping, high rainfall tropical regions (e.g. Latin America) than in flatter temperate areas (e.g. Canada and the United States), since the former would be subject to a higher risk of erosion under conventional tillage (FAO, 2001).

A comparative study of conservation agriculture and conventional tillage in Wisconsin (United States) found that short-run average costs under conservation agriculture exceeded long-run average costs by about 7% (Mueller et al., 1985). The short-run average costs per hectare for conservation tillage were greater than for conventional tillage. However, after adjustments to capital, conservation tillage costs fell below those of conventional tillage in the long run.

Concerning the impact on fertiliser use, Uri (1997) finds there is some increase in fertiliser use by maize farmers adopting conservation tillage in the United States. Additionally, if the application of fertilisers under conservation tillage requires greater management skill, then application costs could rise even if application rates do not.

FAO (2001) reviewed 40 studies of the financial net present values (NPVs) for conservation agriculture and related agronomic approaches (intercropping, contour farming, green manure), almost all in developed countries. Of these, 34 studies indicated that the NPV of conservation agriculture would be positive. Knowler and Bradshaw (2007) reported that 10 out of 11 reviewed studies of the economics of conservation agriculture for Sub-Saharan Africa found a positive NPV.

Erenstein and Laxmi (2008) reviewed several studies (a mix of on-farm trials, field station trials, and farmer surveys) of the economics of zero tillage in the Indo-Gangetic Plains. The authors noted that "cost and profitability comparisons are sometimes complicated by site specificity and methodological differences". Nevertheless, the results consistently showed benefits, both cost savings and increased yields. On average, slightly more than half of the benefits were due to cost savings and slightly less than half to yield increases.

Overall, results from the literature tend to indicate that, in most cases, it would be profitable to adopt conservation agriculture or parts of it (Pannell et al., 2014). There appears to be a small cost advantage over conventional soil farm practices (5-10%), although results vary widely from site to site, with many studies showing soil conservation practices as less profitable. There are also differences in analysing cases in developed versus developing countries (Pannell et al., 2014; FAO, 2001; Uri, 1999).

There are a number of possible explanations for the diverse results. The approaches adopted may be too simplistic or partial, and the opportunity costs of resources used in conservation agriculture are not taken into account. For example, the analysis includes only the direct financial cost of inputs, while agronomic and management factors, such as the opportunity cost of mulching crop residues – which may have a non-cash value for feeding livestock or for burning to enhance pest control that would be lost if the residues are used for soil cover – or the opportunity cost of labour used for weed control are omitted. Secondly, assumptions about agronomic impacts may be overly optimistic. For example, data are obtained from field stations under well-controlled conditions rather than directly from farms. Finally, issues of risk and uncertainty are overlooked (Pannell et al., 2014). The published literature highlights the high level of heterogeneity and the need for case-specific analysis (Pannell et al., 2014).

Higher yields are attained under rain-fed agro-systems in dry climates

It is difficult to establish a robust conclusion as to whether conservation agriculture can maintain crop yields as well as be effectively applied in widely differing farming contexts. For example, although soil moisture retention can be higher with conservation agriculture, resulting in higher and more stable yields during dry seasons, the amounts of residues and soil organic matter levels required to attain higher soil moisture content remains unknown. Empirical evidence suggests that, overall, the effects on yields are mixed, depending on prevailing environmental conditions, including types of soil and crops, and could vary over time.

Evidence on yield effects of zero tillage is highly variable (Giller et al., 2009). Where zero tillage is combined with mulching, a commonly described pattern is for yields to fall initially and then to increase over the subsequent decade or so, eventually exceeding yields in conventional tillage-based agriculture (Pittelkow et al., 2015; Giller et al., 2009; Rusinamhodzi et al., 2011). However, trial data also reveal cases where yield is largely unaffected, and some survey data indicate increases and decreases in different cases.

The economic impact of crop residue management is also highly context-specific, depending on such factors as human population and livestock density, cropping intensity, access to alternative feed sources, land and markets, and non-agricultural income. Apart from the long-term yield effect of mulching with zero tillage, mulching can generate higher soil moisture content in the immediate following year, resulting in higher yields, especially in dry years. However, there is evidence that if mulching is important for high yields in dry areas, yields after mulching can be lower in high-rainfall conditions. It is clear that agro-ecological conditions play a major role in determining the benefits of conservation agriculture.

Pittelkow et al. (2015) have synthesised information from more than 5 000 observations obtained from 610 studies. They show that farming which uses a combination of conservation agriculture techniques can produce equivalent or greater yields than conventional farming under certain conditions. In particular, key finds are as follows: i) the use of "no-till" alone negatively impacts yields (-11.9%);[6] ii) yield decline is minimised when all three principles are applied, as compared to only a single principle applied; iii) no-till significantly enhances yields (7.3%) under rain-fed agriculture in dry climates when the other two conservation agriculture principles are also implemented due to improved water infiltration and greater soil moisture conservation; iv) no-till reduces yields in the first few years following adoption, regardless of whether the other two conservation agriculture principles are implemented; v) no-till yield losses tend to diminish with time, although it does not outperforms conventional tillage after ten years; and vi) there is no evidence that one principle outperforms the other.[7]

The results presented by Pittelkow et al. (2015) have important policy implications. First, to maximise yields, conservation tillage should be implemented in cropping systems which employ residue retention and crop rotation. The transition to no-till integrated with the other two conservation agriculture principles is challenging as it represents a holistic change in management requiring adaptation at the individual farm-level and crop residues can have significant feed value. Second, conservation agriculture could become an important climate-change adaptation strategy in ever-drier regions of the world. However, expansion of conservation agriculture in these areas should be done with caution, as implementation of the other two principles is often challenging in resource-poor and vulnerable smallholder farming systems, thereby increasing the likelihood of yield losses rather than gains.

Van de Puttea et al. (2010) present a meta-regression analysis (47 European studies, 563 observations) that compares crop yields under conventional tillage, reduced tillage, and no-tillage practices. Their analysis shows that while the introduction of conservation tillage in Europe may indeed have some negative effect on yields, these effects can be expected to be limited. Surprisingly, they find that no-tillage performs worse under drier climatic conditions. They argue that this is due to the fact that in wetter climatic conditions negative effects, such as an increased prevalence of pests, seem to outweigh possible gains stemming from increased water availability. On clay and sandy soils, however, this negative effect of no-tillage is counteracted and all conservation tillage techniques perform better under drier climatic conditions. Another important finding concerns cereals-only rotations, where relative yields under conservation tillage tend to decrease with time. The authors suggest that conservation tillage can be a viable option for European agriculture from the viewpoint of agricultural productivity. Potential negative effects on agricultural productivity can be strongly reduced by applying sufficiently deep tillage and by practicing crop rotation, including crops other than cereals.

deVita et al. (2007) examined the effect of no-tillage and conventional tillage on durum wheat under rainfed Mediterranean conditions over a three-year period (2000-02) at two locations (Foggia and Vasto) in southern Italy. Higher yields were obtained in Foggia with no tillage (rather than conventional tillage) in the first two years. In contrast, mean yield and quality parameters in Vasto were similar for the two treatments during the first two years and higher for conventional tillage during the third year. This was attributed to the high correlation between rainfall and yields, with a system of no-tillage supporting higher levels of soil moisture. In this case, soil conservation practices are more productive (more output and less input) than conventional practices. In contrast, a study for wheat and maize in the Pampas, Argentina, found that although the adoption of limited tillage systems leads to soil improvement, it also generates the necessity to increase the use of nitrogen fertilisers in order to sustain yields (Alvarez and Steinbach, 2009).

Li et al. (2007) present a 15-year field experiment conducted in Shanxi, the People's Republic of China (hereafter "China") that compares the long-term effects of no-till and residue cover with conventional tillage in a winter wheat monoculture. Crop yield and water use efficiency tended to be higher under no-tillage than under conventional tillage, especially in the years of low rainfall. This suggests that the change in soil structure provided a better environment for crop development. Thus, no-tillage is a more sustainable farming system which can improve soil structure and increase productivity with positive environmental impacts in the rain-fed, dry farming areas of northern China.

Farooq et al. (2011) plotted the yield difference between the full conservation agriculture package and conventional treatments against rainfall using results from 25 studies and found a declining trend in yield advantage of conservation agriculture as rainfall increased, with yields of conservation agriculture being mostly higher than conventional systems where annual rainfall was below 560 mm. In their meta-analysis of maize production under conservation agriculture, Rusinamhodzi et al. (2011) found that conservation agriculture led to no difference in yield stability under conditions of drought or excess rainfall.

Brouder's and Gomez-Macpherson's (2014) review of the evidence study also finds that the very few studies that fully reported critical data or meta-data show that in the short-term zero tillage generally resulted in lower yields than did conventional tillage. Occasionally, these decreases could be linked to direct effects (e.g. increased soil compaction in rice), but failure to adapt other management tools (e.g. weed control) to the conservation agriculture system was a common and confounding indirect effect. The authors argue that it is not possible to make strong general conclusions about benefits of conservation agriculture and zero tillage on yields and resource use efficiency of smallholder farmers as there too few field studies.

Greater precision and timeliness of farm operations result in higher efficiencies of input use

Soil conservation practices allow large farms to use technological advances, such as controlled traffic farming and GPS-based precision farming that lead to higher levels of efficiency of energy and input use. These efficiencies have led some countries to implement policy initiatives such as the carbon credit scheme for offset markets from conservation tillage that has been operating in Alberta, Canada for several years. The scheme, based on conservation agriculture, is in the process of integrating controlled traffic farming and GPS-based precision farming (Lindwall and Sonntag, 2010).Soil conservation practices, which increase soil water content by increasing infiltration and reducing runoff and evaporation, improve water use efficiency and buffers crops against drought. Mulch cover also buffers the soil against temperature extremes. For example, in rain-fed semi-arid highlands of Mexico, soil water content during dry periods was 10-20 mm higher in maize fields under conservation agriculture than in those with conventional tillage and residue removal. There is clear evidence that mulch reduces soil erosion (Giller et al., 2009).

Concerning nutrient productivity, Moussa-Machraouia et al. (2010) conducted a study in Tunisia where they found that no-tillage significantly improved soil content, especially for K, K_2O, P_2O5 and N, while Soil Organic Matter (SOM) and Soil Carbon (SOC) are enhanced but not to a significant extent.

Moussa-Machraouia et al. (2009) found that long-term conservation tillage increased soil organic matter in the top 20 cm by 21.4%, total N by 31.8% and P by 34.5% in the 0–5 cm layer, compared with traditional tillage. The authors also found that the largest yield improvements coupled with greatest water use efficiency were achieved by no-tillage with straw cover.

Loke et al. (2012), in a long-term (32 years) study of wheat production in semi-arid South Africa, found that no-tillage had higher SOC levels than the stubble mulch and ploughing treatments in the 0–50 mm soil layer, but the ploughed plots recorded higher SOC levels below 100 mm of soil depth. No-tillage and stubble mulch enhanced Soil Total Nitrogen (STN) throughout the soil profile, compared with ploughing. The authors suggest that to maintain or improve SOM in specific soil types (Plinthosol), priority should be given to no-tillage and stubble mulch management practices.

Hobbs et al. (2008) review the role of conservation agriculture in sustainable agriculture and present the benefits of conservation agriculture as an improvement on conservation tillage. Their paper concludes that conservation agriculture is a more sustainable and environment-friendly management system for cultivating crops. Case studies from Asia and Mexico show that agricultural conservation practices in these two different environments have raised production sustainably and profitably.

The potential of soil conservation farm practices to mitigate climate change is uncertain

Soil conservation practices, particularly no-till, have been promoted as a means to potentially mitigate climate change by sequestering carbon (West and Post, 2002; Lal, 2004). However, this optimistic view has been challenged and it is now recognised that soil carbon storage with soil conservation practices compared to conventional ones shows considerable variation (Govaerts et al., 2009; Luo et al., 2010). The potential of soil conservation farm practices for storing carbon depends on a variety of factors including, antecedent soil carbon concentration, cropping system, management, soil type, and climate.

There are many uncertainties remaining in understanding the relationship between tillage, soil carbon, and other greenhouse gases (Vanden Bygaart et al., 2003). Reduced-tillage or no tillage may increase soil carbon compared with conventional tillage, but these increases are often confined to near-surface layers (<10 cm) and, as such, the observed increase is a redistribution of organic carbon, not a net accumulation.

Baker et al. (2007) argue that reduced tillage has not been shown to cause a consistent increase in soil organic carbon. Boddey et al. (2010) and Franzluebbers (2009), however, argue against the claims made by Baker et al. Blanco-Canqui and Lal (2008) found that the impact of no-tillage farming on soil organic carbon and nitrous oxide were soil specific: no-tillage farming increases soil organic carbon concentrations in the upper layers of some soils, but it does not store soil organic carbon more than plough tillage soils for the whole soil profile.

Palm et al. (2014) review of global literature found that there is clear evidence that topsoil organic matter increases with conservation agriculture and with it other soil properties and processes that reduce erosion and runoff and increase water quality. However, the impacts on other ecosystem services are less clear. Only about half of the 100+ studies that compare soil carbon sequestration with no-till and conventional tillage indicate increased sequestration with no till. Combining no-till with residue retention increases the potential for carbon sequestration by increasing biomass inputs to the soil. The study by Govaerts et al. (2009) found that out of 100 comparisons, soil carbon stock in no till was lower in seven cases, higher in 54 cases, and equal in 39 cases as compared to conventional tillage in the 0- to 30 cm soil depth after five years or more of no till implementation. These studies were primarily from Canada and the United States, and to a lesser extent from Brazil, Mexico, Spain, Switzerland, Australia and China.

The meta-analysis by (Luo et al., 2010) found increased soil carbon in the topsoil (0-10 cm) on conversion of conventional tillage to no tillage, but no significant difference over the soil profile to 40 cm due to a redistribution of carbon in the profile (Luo et al., 2010). Eve et al. (2002) reported that,

on average, a farmer in the US Corn Belt who changes from conventional tillage to reduced tillage would sequester only 0.33 more metric tons of CO_2 per acre per year over a 20-year period, while the change from conventional tillage to the more restrictive no-till would sequester 0.64 more metric tons of CO_2 per acre per year.

In addition to minimum soil disturbance, the level of carbon sequestration depend on suitable crop rotations or associations, and on the amount of the biomass from the production system that is retained as surface mulch and is being incorporated or sequestered into the soil. Crop rotations effects on soil carbon are often mixed (Corsi et al., 2012). High-residue producing crops may sequester more carbon than crops with low residue input. Intensification of cropping systems such as increased number of crops per year, double cropping, and addition of cover crops can result in increased soil carbon storage under no tillage (West and Post, 2002; Luo et al., 2010). West and Post (2002) found interactions with crop rotations and tillage practice; in general, crop rotations sequestered more carbon than monocultures on conversion to no tillage, though there were notable exceptions with corn-soybean rotations with less soil carbon than monoculture maize.

A review study was undertaken by FAO of the scientific literature concerning the impacts and benefits of the two most common types of agriculture, "traditional tillage agriculture" and "conservation agriculture, a no-till system", with respect to their effects on soil carbon pools (Corsi et al., 2012). The results on carbon sequestration in tillage agriculture were compared with conservation agriculture. The review shows that conservation agriculture permits higher rates of carbon sequestration in the soil compared with tillage agriculture. When no carbon sequestration or carbon loss is reported in agricultural systems, this is most frequently associated with any one, or with a combination, of the following reasons: i) soil disturbance; ii) mono-cropping; iii) specific crop rotations; iv) poor management of crop residues; and v) soil sampling extended deeper than 30 cm.

Although the amount of residues retained in the system is a key component to the amount of carbon stored in the soil, there is little indication of the amount of residues needed to maintain or increase soil carbon. In fact, insufficient levels of surface residue combined with no till does not result in increased soil organic matter, soil moisture or related ecosystem services and can even result in decreased yield (Palm et al., 2014). The amount of residues required to increase soil carbon and benefits derived from it depends on the crop types, yields obtained, and the balance between carbon inputs and decomposition which vary with soils and climate.

The effects of these three types of soil practices on soil carbon stocks are generally analysed separately in the literature. Nevertheless, these conservation agriculture components interact. For example, the types of crops, intensity of cropping and duration of the cropping systems determine the amount of inputs and thus the ability of conservation agriculture to store more carbon than conventional tillage. Intensification of cropping systems with high above and below ground biomass (i.e. deep-rooted plant species) input may allow conservation agriculture systems to store more soil carbon relative to conventional tillage (Luo et al., 2010).

Conservation agriculture also reduces power and energy requirements. Not tilling the soil decreases fuel consumption, requires less working hours, and slows the depreciation rate of equipment per unit of output. Not only do these factors contribute to emission reductions of farm operations, but also from the machinery manufacturing processes. In addition, crop residues left on fields return the carbon fixed in crops to the soil through photosynthesis, thereby improving soil health and fertility. This, in turn, lowers fertiliser use and CO_2 emissions.

Several studies report higher GHGs emissions (nitrous oxide and methane) with conservation farm practices compared to conventional, while others find lower emissions. With no till, residues are returned to the soil resulting in surface mulches that may lower evaporation rates, and hence increase soil moisture and labile organic carbon (Galbally et al., 2005). This consequently increases N_2O emissions compared to conventional till. Increased bulk density with conservation agriculture compared to conventional till may also increase emissions.

However, lower soil temperatures and better soil structure under no till may reduce the incidence of soil saturation and reduce emissions of N_2O. There are no definitive conclusions but rather contradictory findings on N_2O emissions from conservation agriculture compared to conventional practices. The inconsistent results of N2O emissions with conservation agriculture practices are potentially due to the lack of comparability of studies and methodological issues on the measurement of N_2O in the field (Palm, et al., 2014).

There are very few studies that examine the impact of different conservation agriculture practices on all relevant GHGs, including soil carbon sequestration and the resulting net global warming potential. One of the few comprehensive studies conducted over multiple years found no differences in either N_2O or CH_4 emissions between conservation agriculture and conventional till in a long-term dryland cropping trial in central Mexico (Dendooven et al., 2012a and Dendooven et al., 2012b). Conservation agriculture was found to have a significantly lower global warming potential in comparison to conventional till due solely to changes in soil carbon.

West and Marland (2002) estimate the carbon dioxide emissions from the use of machinery and other agricultural inputs (fertilisers, pesticides, seeds, etc.) for three tillage practices in the non-irrigated areas of the United States. The authors undertake a full carbon cycle analysis on US agriculture and find that changing from conventional tillage to no-tillage does not increase CO_2 emissions, and in most cases contributes to a decrease. They also find that changing from conventional tillage to no-tillage offers an opportunity to both increase carbon sequestration and simultaneously reduce carbon emissions from agriculture.

Lower labour requirements, but availability of off-farm labour critical to adoption

Much attention has focused on the apparent reduction in labour requirements under conservation agriculture due to decreased demand for labour to prepare land at the beginning of the growing season. Some estimates put this reduction at 50-60% during this time period. In the case of smallholders, conservation tillage is more likely to lead to labour savings in cases where herbicides are used for weed control, but less likely where farmers employ manual weeding. In the latter case, conservation tillage could even require more labour than conventional tillage agriculture.

Herren et al. (2012) report that most no-till farm operations have lower labour requirements per productive unit of output and per unit of land. Overall, due to the fact that yields from no-till farms were consistently greater than those from conventional farms, the economic return to no-till farm labour was significantly higher.

The level of a farm household's off-farm income is a factor influencing their decision to adopt new technologies. The existing literature, however, seems to suggest that the effect of off-farm income on adoption is ambiguous – increasing the adoption of some practices while decreasing the adoption of others. Off-farm employment would be expected to decrease the availability of labour and could thus impede the adoption of labour-intensive conservation farm practices.

A study by Gedikoglu et al. (2011), based on a survey of 3 104 livestock farmers in Iowa and Missouri (United States), found that the off-farm employment of farm operators has a significantly positive impact on the adoption of capital-intensive practices at the expense of more labour-intensive practices. In particular, adopting the practice of injecting manure into the soil, which is a capital-intensive procedure (and which contributes to the compaction of topsoil due to the use of heavy machinery) is preferred to non-mechanical (and more soil-conserving) spreading due to its time-saving advantages. The same results are supported by previous studies which found that in regions where off-farm employment plays a major role, farmers are less likely to divert labour to conservation practices if the economic returns from off-farm labour are higher than the perceived benefits from investing scarce labour in soil conservation (Neill and Lee, 2001; Moser and Barrett, 2003; Jansen et al., 2006; Lee et al., 2006; Wollni et al., 2010).

At a watershed or even higher spatial-level, the application of soil and water conservation practices can be very beneficial for the rural economy and for job creation. Pincus and Moseley (2013) analyse the impact of watershed restoration practices on Oregon's (United States) economy using input-output analysis. They find that the sustained programme of restoration work conferred significant benefits to the economy. They also note that these impacts largely accrue to rural areas in need of economic development opportunities due to the decline in traditional resource management activities. They estimate that in addition to approximately 16 jobs that are supported per million dollars invested in ecological restoration, a sustained investment in restoration has created both new local organisational capacity in watershed councils and other community-based partners and business opportunities, especially in rural areas.

In a more "holistic" investigation, Herren et al. (2012) apply an integrated dynamic global modelling approach to assess the job-creation capacity of green agriculture. The authors specified the adoption of actions such as sustainable management practices (e.g. no-till cultivation, natural fertilisation), research and development, integrated pest control and rural value-added food processing, and assumed that investments of initially USD 100 billion and subsequently USD 180 billion per annum, to facilitate these actions will be induced through subsidies and shifts in taxation. These investments were assumed to be directed either to green agriculture or to conventional agriculture. Projections showed that if the green agriculture option is chosen, farm and food employment in 2050 is 3% higher than that associated with the conventional agriculture option.

Water conservation practices

Agriculture accounts for around 70% of the water used in the world today (45% in the OECD area). Rapidly growing water demand from cities, industry and energy suppliers, and the effects of climate change will make less water available for irrigation in the future. Farmers must receive the right signals to increase water use efficiency and improve agricultural water management, while preserving aquatic ecosystems.

The scope for the sustainable management of water resources in agriculture concerns the responsibility of water managers and users to ensure that such resources are allocated efficiently and equitably, and used to achieve socially, environmentally and economically beneficial outcomes. This includes: irrigation to smooth water supply across the production seasons; water management in rain-fed agriculture; management of floods, droughts, and drainage; and conservation of ecosystems and associated cultural and recreational values.

Conservation water management practices include land management practices to prepare fields for efficient irrigation and management of excess water, on-farm water delivery systems and the application of irrigation practices, irrigation water use management, and protecting water from non-point source pollution and sedimentation. Non-point source pollution comprises constituents such as nutrients, and organic and toxic substances from diffuse sources, such as runoff from agricultural land development and use. Soil conservation practices, especially conservation tillage and conservation crop rotation are also considered water conservation practices because they enhance soil water content due to minimum soil disturbance and maintenance of soil cover, reduction of water runoff and improved infiltration.

Correct initial land levelling conserves water by reducing runoff and allowing uniform distribution of rainfall and irrigation water. For example, in Texas (United States), correct levelling can reduce water use-by 20-30% and increase crop yields by 10-20% (Texas Water Development Board). Furrow diking conserves water by capturing precipitation or irrigation water in small dams made by earth in the furrows. Knowledge about weather conditions, the capacity of the soil to absorb and retain water, and the capacity of crops to utilise water, depending on root depth and soil properties at different depths, can provide crucial information for water conservation.

There are three basic types of water delivery: surface (gravity), sprinkler, and drip irrigation. The highest levels of water conservation are attained through drip irrigation, which can be very effective

with certain crops and on uneven terrain. Sprinklers, especially those of the older high-pressure technology, are not efficient, particulary under conditions of high temperatures and windy conditions. For this reason, modifications to low-energy precision application and low-elevation spray application have been introduced. The case of Israel offers a unique insight into what an integrated water management system looks like in practice, in addition to providing lessons on how to efficiently manage a scare resource (Box 2.3).

Farming practices that seek to minimise non-point source pollution and sedimentation include the creation of various types of buffer areas, grass filter strips, grass waterways, forested riparian buffers, terraces, diversions, water and sediment control basins, etc. A buffer area (buffer strip or buffer zone) is an area of natural or established vegetation managed to protect critical resource areas, such as wetlands, water bodies, waterways or even wells, from significant degradation due to land disturbance and nutrient chemical runoff.

Grass filter strips are planted between the field and surface water (rivers, streams, lakes and drainage ditches) to protect water quality. They slow the runoff from fields, trapping and filtering sediment, nutrients, pesticides and other potential pollutants before they reach surface waters. Filter strips also are planted around drainage tiles. Grass waterways are a type of broad and shallow conservation buffer designed to prevent soil erosion while draining runoff water from adjacent cropland. Grass waterways also help prevent gully erosion in areas of concentrated flow.

Forested riparian buffers are rows of trees or shrubs or maintained grass that is planted alongside rivers, streams, lakes or wetlands and are designed primarily for water quality and wildlife habitat purposes. Forested riparian buffers prevent potential pollutants in agricultural runoff (sediment, nutrients, pesticides, pathogens) from reaching surface waters. Terraces are earthen or stone embankments, channels, or combined ridges and channels built across the slope of the field (USEPA, 1993). They may reduce the topsoil erosion rate and lessen the sediment and pollutants content in surface water runoff. In the United States, terraces have been reported to reduce soil loss by 94 to 95%, nutrient losses by 56 to 92% and runoff by 73 to 88% (Cestti, Srivastava and Jung, 2003).

A diversion is similar to a terrace but its purpose is to direct or divert surface water runoff away from an area, or to collect and direct water to a pond. Diversions are used with filter strips above them in order to trap sediments and protect the diversion, and with vegetative cover in the diversion ridge. A water and sediment control basin is a small earthen ridge-and-channel or embankment built across a small watercourse or area of concentrated flow within a field.

A good example of integrated water conservation policy with direct implications for agriculture is the European Union's Water Framework Directive (WFD) introduced by "Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy". The WFD classification scheme for the ecological status of surface water includes five categories: high, good, moderate, poor and bad. The WFD requires river, lakes, ground and coastal waters to reach good ecological and chemical status by 2015. Thus, the WFD has very serious implications for farming practices and land management as well as water management concerning diffuse pollution and water consumption. One of the most important measures to achieve this goal includes reducing emissions of nitrogen (N) and phosphates (P_2O_5) from manure and mineral fertilisers into the environment. This action incurs a considerable cost to the farming sector and, in certain cases, the cost is far beyond what can be achieved within the budget of agri-environmental measures (OECD, 2012).

Box 2.3. The efficient management of water resources in Israel

A notable feature of Israeli agriculture has been its capacity to increase the efficiency of water-use in agriculture. Efficiency has been improved in physical (technical) terms of water use per tonne of output (or hectare irrigated), in terms of economic water-use efficiency (value of output per unit of water used and through reducing the sector's use of fresh drinking quality water while increasing use of recycled water).

Efficient water management has been the foundation of much of Israel's success in agriculture in arid, semi-arid and dry sub-humid zones. The invention and development of drip irrigation in Israel from the 1960s has been the key innovation behind the rise in technical water-use efficiency, as well as shift towards other pressurised irrigation systems (i.e. sprinklers, micro-sprinklers, micro-jets) with flood irrigation no longer being used. Water-use efficiency is increased through lowering runoff and evaporation losses and reducing leaching of water and contaminants below the root zone. The success of drip irrigation lies in the provision of optimum conditions for plant uptake of water and nutrients. Drip systems also facilitate the more efficient agronomic use of saline, brackish and marginal water.

Initially, drip irrigation met with limited interest and was not without problems, such as pipe clogging and breakage. This changed in the 1980s with further refinements to drip systems, including developments towards the next generation of drip technology including computerised systems and pressurised drippers, which enable the stable distribution of water. In Israel over half the irrigated area is now under drip irrigation.

A more recent development has been sub-surface drip irrigation (SDI), with about 5-10% of the irrigated area currently under SDI systems. These systems are positioned within the soil to: conserve water; control weeds; minimise runoff and evaporation (reducing evaporation by up to 20%); increase longevity of piping and emitters; ease use of heavy equipment in the field; and prevent human contact with low-quality water. Additional motivation for SDI comes in the form of savings, as the extensive labour costs involved with the seasonal installation and collection of surface drip system piping is eliminated. SDI also provides the opportunity to manipulate root distribution and soil conditions in arid climates in order to better manage environmental variables including nutrients, salinity, oxygen and temperature.

Source: OECD (2010), *Review of Agricultural Policies: Israel*, http://dx.doi.org/10.1787/9789264079397-en.

High productivity, efficiency and innovation impacts, but empirical assessment is challenging

Water-conservation practices target the quantity and quality of water and can be implemented at all stages of water storage, delivery and use both on- and off-farm. In principle, water conservation measures are resource-efficient because they attain their yields by managing the water-retention capacity of soil. Water conservation practices work best in rain-fed cultivations. Almost all types of buffer zones attain a significant reduction in pesticide and nutrient concentrations in water and are thus environmentally efficient.

Water-conservation techniques are also energy-efficient because water-saving practices reduce energy needs and emissions. Such practices contribute to the production of public goods. They reduce negative externalities mainly by reducing sedimentation as well as through the associated reduction of flood risks, the protection of watercourses, and the supply of cleaner water.

Water conservation practices are associated with well-known green innovations in the irrigation industry, such as drip irrigation. They also utilise a rich knowledge base to develop promising water management innovation systems for rain-fed agriculture, including a broad array of water-harvesting practices, conservation farming systems, water conservation techniques, and integrated soil fertility management.

Despite these positive developments, empirical assessment of the economic productivity gains in terms of yields from applying water conservation practices is difficult. The complexity involved in making simple predictions of water savings (on the field level) and yield increases, as illustrated by Burt and O'Neill (2007, and referred to by Perry et al., 2009), have been highlighted in the literature. The authors, using information from a large-scale study undertaken by the Irrigation Training and Research Centre of the California Polytechnic State University (United States) examined the methods of growing tomatoes (and the yields attained) on 187 furrow-irrigated fields and 164 drip irrigated-fields, with typical field sizes of 50 ha. After comparing yields and applied water depth, the authors argued that it would be risky to assume that drip irrigation confers immediate major benefits across-the-board.

Warda and Pulido-Velazquez (2008) consider irrigation conservation practices at the basin level and reach a controversial conclusion. They suggest that "where return flows are an important source of downstream water supply, reduced deliveries from the adoption of more efficient irrigation measures will redistribute the basin's water supply, which could impair existing water right holders who depend on that return flow".

This would indicate that water conservation subsidies will not provide farmers with the economic incentives to reduce water depletion, and it is therefore unlikely that new water will be made available for alternative uses. In fact, depletion is likely to increase as a result of subsidies. For example, drip irrigation is important for many reasons, including greater water productivity and food security, but it does not necessarily save water when considered from a basin level. Subsidies for irrigation efficiency have been found to increase water use as higher crop yields lead to higher evapotranspiration with no return flow or recharge in aquifers (OECD, 2015).

At the farm level, improved irrigation methods reduce water use per cultivated area and thus energy needs, which results in lower emissions.[8] Improved irrigation techniques produce higher levels of resource (water), environmental and energy productivity than conventional irrigation methods. But increased water productivity may result in a "slippage effect", where saved water may be used to irrigate previously non-irrigated land. For example, while it is generally acknowledged that an improved irrigation infrastructure has the potential to deliver significant water savings to the farmer, the adoption of "green innovations", such as drippers, may not necessarily lead to a net environmental benefit if the farmer opts to direct these water savings into increased production or to sell the saved water to other producers (assuming the existence of a water-trading system).

In addition, some water conservation methods are associated with resource costs including (at times prohibitive) increases in energy demand. For example, evidence from Australia suggests that if adopting a pressurised system would undoubtedly result in a reduction of inefficiencies such as evaporation and seepage, changing to a new system would result in increased energy demand compared to existing gravity-fed channel delivery systems. Evidence shows that certain Australian irrigators are opting not to update their irrigation and delivery systems due to the increased energy costs of pressurised water systems.

Off-farm water conservation

Non-irrigation water conservation measures such as buffer zones and terraces have significant resource productivity impacts because they increase infiltration and reduce runoff while protecting the nearby environment from non-point source pollution and sedimentation. Moreover, buffer zones and grass waterways support habitats and biodiversity.

Kay et al. (2009) provide a comprehensive review of the literature and present the efficiency of buffer strips and wetlands in removing nutrients (total nitrogen, nitrates, total phosphorus and soluble phosphorus) contained in runoff agricultural water. The reported percentages show a large deviation, ranging from 5% to 100%. The same results, with less variation, are reported for pesticide substances as (Table 2.2) (Kay et al., 2009).

These results indicate the need to change the way in which herbaceous riparian buffers are implemented adjacent to channelized headwater streams, and also suggest that their use should be paired with upland management practices, riparian wetland creation, and/or in-stream habitat practices that are capable of addressing the chemical and physical habitat degradation exhibited by channelled agricultural headwater streams. Their research highlights the risk embedded in fragmented approaches versus integrated watershed management practices.

Table 2.2. Changes in pesticide concentrations in runoff due to the creation of buffer zones

Pesticide	Effect of buffer zone	Reference
Atrazine	53% reduction	Arora et al. (2003)
	25–49% reduction	Popov et al. (2006)
Chlorpyriphos	83% reduction	Arora et al. (2003)
Metolachlor	54% reduction	Arora et al. (2003)
	30–61% reduction	Popov et al. (2006

Notes

1. The study states that in 56% of EU territory there is a varying degree of potential threats, with intense land exploitation estimated as the main pressure on soil biodiversity. More specifically, using information from the European Soil Data Centre (ESDAC) and other European databases the study found that 1% of EU land is exposed to "extremely high" threats, 4% to "very high" and 9% to "high" threats. Intense farming, based on nitrogen load, is identified as the most significant menace, followed by organic carbon losses, invasive species, compaction, erosion and contamination. Due the combined effect of high intensity agriculture, many invasive species and an increased risk of organic carbon loss, the potential pressures were found to be particularly high in the United Kingdom and central Europe.
2. Moreover, there has been more extensive adoption of some the components, particularly conservation tillage, although not in association with the other two components of the conservation agriculture "package" (Friedrich, Derpsch and Kassam, 2014).
3. A voluminous literature, both theoretical and empirical, exists on the adoption of agricultural practices and technologies. Recent reviews with emphasis on adoption of conservation practices include Pannel, et al. 2006, Prokopy et al., 2008; Gedikoglou and McCann, 2010.
4. See: www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/financial/ama/
5. For example, in 1947 Ciriacy-Wantrup examined the capital returns to soil conservation practices.
6. Pittelkow et al. (2015) that the largest yield declines occur when no-till is implemented alone (-9.9%) or with only one other conservation agriculture principle (-5.2 and -6.2% for residue retention and crop rotation, respectively.
7. On average, the individual effects of residue retention and crop rotation reduce the negative impacts of no-till by 4.8% and 3.8%, respectively. However, in dry climates these principles each have a much stronger effect on rainfed crop yields, reducing yield losses by 10% and 11%, respectively.
8. A comprehensive experimental study with mathematical modelling to carried out to investigate the effects of cropping practices on water balance variables in California (United States) found that cropping practices do not significantly affect soil water content; rather crop rotation and soil spatial variability largely influence water distribution and availability in the sub-surface system Islam et al. (2006).

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Annex 2A

Adoption of conservation agriculture

Table A2.1. Extent of the adoption of conservation agriculture, more recent year

	Total ('000 ha)	As % of cultivated area (%)
OECD countries		
Australia	17695	36.1
Canada	18313	36.3
New Zealand	162	27.9
United States	35613	22.9
Chile	180	13.5
Finland	200	7.1
Spain	792	5.2
Switzerland	17	4.0
United Kingdom	150	2.4
Portugal	32	2.9
France	200	1.1
Italy	380	1.1
Slovak Republic	35	0.7
Mexico	41	0.2
Hungary	5	0.2
Germany	200	n.a.
Ireland	0.2	0.0
Netherlands	0.5	0.0
Non-OECD countries		
Argentina	29181	68.7
Paraguay	3000	54.4
Uruguay	1072	37.3
Brazil	31811	43.8
Bolivia	706	18.4
Kazakhtan	2000	7.9
Zambia	200	5.3
Russia	4500	3.8
Colombia	127	8.0
South Africa	368	3.0
Mozambique	152	2.7
China	6670	2.9
Ukraine	7100	1.8
World	157434	10.9

Source: FAO, AQUASTAT database, website accessed on 2 July 2015.

Chapter 3

What does organic farming mean for green growth?

Organic agriculture is an approach to food production that seeks to develop environmental and economically sustainable production systems with a strong emphasis on the use of local, renewable resources and minimum use of external inputs. Since the 1970s, a global market has developed for organic products, and legally enforced production standards have been introduced to benefit producers and consumers. Over the last two decades, organic farming has become one of the most thriving segments of the agricultural sector in several OECD countries. This chapter discusses the various policy approaches used by OECD countries to support organic farming, and the potential impacts of organic farming on resource efficiency and productivity.

Key messages

- There is inconclusive empirical evidence on the economic performance of organic farming compared with conventional agriculture; higher prices and government support tend to compensate for lower yields and often higher input costs.
- Organic farming is more labour-intensive than its conventional counterpart and entails lower health risks for producers.
- On balance, the empirical evidence shows positive environmental effects on soil, water and biodiversity, but effects are mixed on GHG emissions.

A rapidly growing sector

Organic agriculture is an approach to food production that seeks to develop environmental and economically sustainable production systems with a strong emphasis on the use of local, renewable resources and minimum use of external inputs. Since the 1970s, a global market has developed for organic products, and legally enforced production standards have been introduced to benefit producers and consumers.

There are many definitions of organic agriculture. At its simplest, it is a production system that relies on ecological processes, such as waste recycling, organic-based fertilisers (e.g. manure and vegetable-based compost) and natural pesticides (e.g. predator animal species), rather than synthetic inputs, such as chemical fertilisers and pesticides. Use of antibiotics and other products related to health is limited or not allowed to treating sick animals, and not for enhancing yields.[1] Other definitions of organic agriculture go much further. For example, the definition provided by the International Federation of Organic Agriculture Movements (IFOAM) includes, for example, animal welfare, biodiversity and social justice.[2] It is necessary, however, to distinguish between certified organic agriculture and an agriculture that follows organic methods of production but which is not officially certified.

Although the rules of organic agriculture differ slightly from country to country, some general practices apply to all organic cultivation systems and to the stages of growing, storage, processing, packaging and shipping. First and foremost, organic cultivation avoids or limits the use of synthetic chemical inputs, including fertilisers and pesticides, and the over-use of antibiotics and food additives. Each country adopts a List of Allowed and Prohibited Substances for organic agriculture.

In addition, organic agriculture does not use genetically modified organisms, cultivars techniques such as irradiation, bio-solids, or non-human sewage sludge for fertilising or feeding of animals. The land under cultivation must be free from all prohibited synthetic chemicals for a period of usually three years in order to be declared organic. Cultivators must record the production and sales for auditing, maintain strict physical separation of organic certified production from non-certified production, and accept periodic on-site inspections by the certified bodies.

Over the last two decades, organic farming has become one of the most thriving segments of the agricultural sector in several OECD countries. The sales of organic food and drink reached USD 72 billion world-wide in 2013, an almost five-fold expansion from USD 15 billion in 1999 (FiBL/IFOAM, 2015). Organic agriculture is expanding in all OECD countries in response to increased consumer demand for perceived healthy and environmentally friendly food products. Organic farming is no longer limited to farmers for whom organic production is part of a holistic life-style and who sell through specialist outlets, but has extended into the mainstream of the agri-food chain as an economic opportunity to satisfy a niche market at premium prices. It nevertheless continues to account for only a relatively small share of total agricultural production and food consumption in most countries. Despite strong growth, organic farming accounts for a modest proportion of global agricultural land (1%) (Table A3.1).

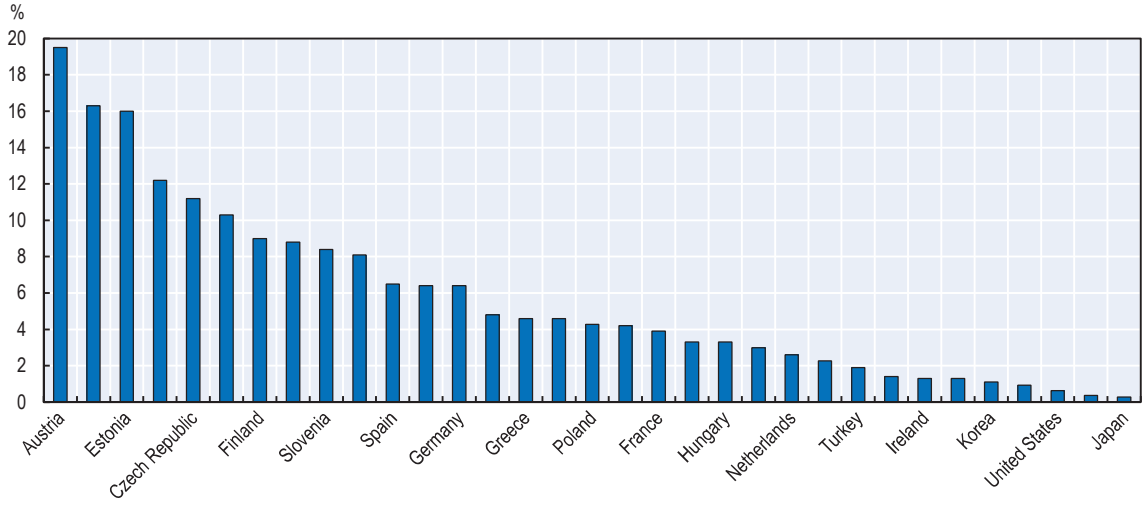
By region, the share is highest in Oceania (4.1%), followed by Europe (2.4%) and Latin America (1.1%). In the EU27, the share of organically managed land is 5.7%. Globally, 43.1 million hectares of land are under organic cultivation (including in-conversion areas) globally. Australia is the country with the greatest acreage in organic agriculture (97% of which is extensive grazing area), followed by Argentina, and the United States. In 2013, there were 2 million producers, more than three-quarters of whom were located in Asia, Africa and Latin America. India has the most producers (650 000), followed by Uganda (189 610) and Mexico (169 703).

In several OECD countries, organic agriculture is the most rapidly growing agricultural sector, between 15-30% annually, albeit from a very low base. Compared with 1999, when data on organic agriculture worldwide were available for the first time, the acreage of land in organic farming has almost quadrupled. In 2013, organic agricultural land worldwide increased by 15% compared with 2012, mainly because of a sharp growth in fully certified organic land in Australia where rangeland areas have come under organic production to meet the strong demand for organic beef. On average, organic agriculture accounts for about 2% of total agricultural land across the OECD area, but varies considerably: from under 0.2% in Japan to 20% in Austria (Figure 3.1). The main organic markets are in fruits and vegetables, fresh poultry and eggs, and fresh milk, butter and cheese. In certain countries, cereals are also important.

Demand for organic products is concentrated in North America and Europe, which represent more than 90% of global revenues. This is indicative of the extreme disparity between production and consumption. In 2013, the largest market for organic products, by a wide margin, was the United States, with USD 32 billion of organic food sales, followed by Germany, with USD 10 billion, and France with USD 6 billion. The highest annual per capita consumption was in Switzerland (USD 279) and Denmark (USD 216). Denmark, Switzerland and Austria have the highest share of organic food sales.

Growth of organic farming has largely been led by demand from consumers in high-income countries who favour organic produce for a variety of reasons, including the perceived benefits to health and the environment, perceived improvements in food quality and taste, accessibility of fresh produce, and the support it provides to small-scale local producers, communities and markets. Obstacles to adoption by farmers include high managerial costs, the risks in shifting to a new way of farming, and limited knowledge of organic farming and marketing systems (Greene and Ebel, 2012; Greene, et al., 2009).

Figure 3.1. Organic agriculture in OECD countries: Share in total agricultural land, 2013



Note. Data include conversion land.
Source: Research Institute of Organic Agriculture (FiBL) and the International Federation of Organic Agriculture Movements (IFOAM) (FiBL/IFOAM) (2015), www.organic-world.net/yearbook-2015.html.

Wide-ranging policy approaches used by OECD governments

Across the OECD area, a wide range of policy approaches is employed to address issues in organic agriculture. Policy options include those that are enabling (e.g. providing certification and labelling frameworks, and research and extension services); enforcing (e.g. establishing regulations and standards); and encouraging (e.g. providing financial incentives, bringing together agents along the production chain to establish partnerships and procurement policies).

Governments justify policy intervention in the organic sector on the basis of the "infant industry" argument or the provision of public environmental benefits (Jaeck, Lifran and Stahn, 2013; Halpin, Daugbjerg and Schvartzman, 2011; DEFRA, 2002). The infant-industry justification is based on the costs of converting from conventional to organic production. The conversion period can last for several years, during which time farmers must use organic methods of production, but cannot market their products as being organic. When yields decrease and/or costs increase, the loss of profits can impede that adjustment. This tends to be the case for small-scale farm operations, in particular.

The market-failure justification is based on cases where the market does not remunerate the environmental benefits generated by organic farming systems. This is compounded where farms – organic or conventional – are not held to account for the environmental damage they cause. However, the valuation of such environmental externalities, whether beneficial or harmful, is fraught with difficulty. A further example of market failure can occur when there is imperfect information available to market participants on the potential health benefits associated with reduced pesticide residues on organic food, leading to the potential misallocation of resources.

While in some OECD countries it is largely market forces that drive the development of the organic sector, several governments, mostly in Europe, offer farmers financial aid (and other incentives) to convert to, and continue in, organic production. In the European Union, most countries provide support for organic farming via Pillar 2 of the CAP – in addition to the standard Pillar 1 payments – with per-hectare payment for agri-environmental measures under "Axis 2". Additional funding is also available under Axes 1 and 3 for forestry and improved rural life and diversification.

In France, the government launched a new organic Action Plan in 2013 to restructure the country's organic farming sector. Among other goals, the programme aims to double the land surface used for organic cultivation and to boost consumption of organic products (Box 3.1). The plan provides higher direct payments for farmers, both during and following conversion periods; financial support for supply-chain actors; it set a goal of achieving 20% of organic products in public procurement of food; makes more funds available for research and dissemination; supports better training and education of farmers and supply-chain actors; and ensures appropriate adaptation to organic farming, as stipulated by the EU regulations, including the rules on organic farming regulation.

In virtually all OECD countries, market-based policy approaches, including certification and labelling schemes, are now in place or being developed in order to aid consumer choice. But the proliferation of different labels and standards can be confusing to consumers. Differences in certification and labelling schemes, both public and private, can inhibit trade flows, and differences in government approaches to equivalency assessments may also hinder trade (OECD, 2015).

Several governments have undertaken information campaigns and promotional activities to encourage consumption of organic products. In a few countries, notably in Europe, government procurement policies encourage or require the purchase of organic food by public institutions such as schools and hospitals.[3]

The major agricultural producer countries have adopted a set of rules and established institutions for certifying, auditing, inspecting and monitoring organic cultivation. In the United States, the Organic Foods Production Act (OFPA) was passed in 1990, with the aim of developing a national standard for organic food and fibre production. OFPA mandated the USDA to develop regulations to explain the law

to producers, handlers and certifiers. OFPA called for the National Organic Standards Board to be set up, in order to make recommendations. The final rules were implemented in the autumn of 2002.[4]

Box 3.1. The French organic agriculture sector

This is a dynamic sector in France. Between 2007 and 2012, the area of land devoted to organic farming almost doubled, going from 557 000 ha to more than 1 million hectares; over the same period, the number of organic farmers has more than doubled, up from 12 000 to 24 500; the number of processors and retailers of organic products has also shown the same positive development, rising from 6 400 to 12 300. The turnover generated from the sale of organic food to consumers increased from EUR 2 billion to EUR 4.1 billion; and the input of organic products in the catering sector has been increasing, resulting in a 7% rise in turnover, up to EUR 169 million in the community catering industry in general. In 2012, the organic sector employed more than 36 700 people (producers, processors, distributors, etc.), compared with 18 400 in 2007, and occupied 3.8% of Utilized Agricultural Area (over 2.47 million hectares). According to a survey commissioned by Agence Bio, the number of consumers who regularly buy organic products has risen to 43% in 2012.

The first Organic Action Plan was in place from 2007 to 2012. On 31 May 2013, a new action plan, the *Ambition Bio 2017*, was launched to further develop the organic sector. Six major goals were defined:

- *Develop organic production:* An incentive system encourages farmers to keep their fields under organic management. A grant of EUR 160 million a year for conversion to organic (or to support the continuation of organic cultivation) will be provided in the context of Pillar II support of the EU Common Agricultural Policy (CAP) for the period 2014 to 2020.
- *Restructure the sector:* Two priorities were outlined. The first is to support the cultivation of protein crops (such as canola, sunflower and soy) in order to reduce dependence on imports for feed proteins. Secondly, to improve the organisation of the sector, improved data on prices of production and distribution are needed. For this purpose, national and regional observatories will be strengthened and co-ordinated. A special fund dedicated to organic farming, "Bio Future Fund" *(Avenir Bio*), will be managed by the French Organic Agency and will receive an extra EUR 1 million annually, in addition to the EUR 3 million it already receives annually. *Avenir Bio* informs consumers, co-ordinates professionals, and identifies necessary changes to structure the sector and finance projects.
- *Develop organic markets and consumer information:* In the case of community catering, the plan is for organic production to achieve a share of 20%. Public awareness campaigns will also be conducted; these will be designed to appeal particularly to the younger generation through targeted advertisements, organised school visits to organic farms, and community garden projects.

Box 3.1. The French organic agriculture sector (*cont.*)

- *Encourage research* and *development*: R&D for the organic sector will receive more finance via the CAS DAR (*Compte d'affectation spéciale pour le développement agricole et rural*) programme that will run from 2014 to 2020, and the results will be communicated more effectively to the public.
- *Educate farmers and processors*: This point addresses the offer of training and advanced training, with special attention paid to improving collaboration between the administration in the agricultural sector and the experts in organic agriculture. Continuing education programmes will be launched for farmers, and specific courses and training that are already offered by agricultural schools will be developed and expanded.
- *Adapt to EU regulations*: This point focuses on the specific implementation by farmers of special features in the EU regulations for the organic sector. Two bodies have been created to ensure closer liaison in the future between the regions and the Ministry of Agriculture.

Further information can be found at the Ministry of Agriculture's website: www.agriculture.gouv.fr/ambition-bio-2017.

Federal legislation defines three levels of processed, multi-ingredient organic foods. First, products made entirely with certified organic ingredients and methods that are labelled "100% organic"; second, products with at least 95% organic ingredients are labelled "organic"; and third, products containing a minimum of 70% organic ingredients that are labelled "made with organic ingredients". The last category cannot display the USDA Organic seal. All organic growers, processors and distributors are required to meet the national standard and be certified by a USDA-accredited state (or private) group unless their sales of organic products are less than USD 5 000 annually (Greene and Ebel, 2012).

In the European Union, comprehensive organic legislation has been in place since 1992 (Council Regulation EEC 2092/91). However, many member countries already had organic production

legislation in place and were operating organic production rules long before EU-wide legislation was introduced. Examples are found in France, where organic certification was introduced in 1985, and in Germany, where organic food labels have been in use since 1928. The original 1992 EU legislation was later amended by Council Regulation EC 834/2007 that outlined the objectives and principles of organic agriculture and fixed the general production rules, which was completed by the implementing Regulation EC 889/2008, with detailed production and labelling rules, and control requirements.

In 2010 and 2012, the legislative framework was enhanced with the introduction of two regulations for organic aquaculture and wine production, while work on poultry production, greenhouse production, feed production and food processing is currently underway. The European organic food logo has been obligatory since July 2010. EU member countries vary in the number and type of measures they choose to adopt to support organic farming (a comprehensive description and review of the public support measures in place for organic farming, including a categorisation of the mix of the measures used can be found in Sanders et al., 2011).

In Japan, the Japanese Agricultural Standard (JAS) was implemented in 2001 and underwent a thorough revision in 2005. In Canada, certification has been implemented at the federal level since 2009, while in Australia standards were introduced in 1991 and are now undergoing their sixth revision. Finally, India, an important exporter of organic products, regulates the certification of organic products through the National Standards for Organic Production, which has been recognised by the European Union, the USDA and other agencies in major importing countries.

Can organic farming compete with conventional agriculture?

Yields are lower, while total economic costs of production are variable

A major factor affecting profitability is the yield obtained by organic production. Yields per hectare are generally lower on organic farms due to the lower input intensity of such farming. Organic crop farms use less pesticides and fertilisers per hectare than their conventional counterparts, although for fuel and lubricants the amounts are comparable. Where conventional farms use chemicals, organic farms usually resort to mechanical techniques (e.g. for weeding) and their fields have to be worked as often as those on conventional farms. For livestock, organic farms have lower stocking densities. They grow less fodder maize than their conventional counterparts, but the proportion of pasture in their utilised agricultural land is higher.

Given that organic farms use fewer inputs, their level of intermediate consumption per unit of production is lower than that of conventional holdings. However, fixed costs per unit of production are in general higher on organic farms (McBride, et al., 2015; Lampkin, Gerrard and Moakes, 2014; EC, 2013).

Comparing the yields of organic and conventional agriculture is not a straightforward exercise. Seufert et al. (2012) have carried out a meta-analysis based on 62 study sites and 316 organic-to-conventional yield comparisons on 34 different crop species. In general, the authors find that the average organic–to-conventional yield ratio is 0.75 or, in other words, that organic yields are 25% lower than conventional yields.

However, these results present significant variability across crop types and species. Yields of organic fruits and oilseed crops show a small and not statistically significant difference. Perennial organic cultivations show better performance over annual crops, and legumes out-perform non-legumes. The authors examine further the possible sources of these differences and attribute them to four reasons. First, they argue that organic systems are, frequently, nitrogen-constrained and, when organic systems receive higher quantities of nitrogen, their performance is improved.[5]

Second, the authors argue that it is difficult to manage phosphorus in organic systems. Evidence shows that organic crops perform better on weak acid, rather than weak alkaline soils, and it has already been established that under strongly alkaline and acidic conditions phosphorus is less readily available

to plants because it forms insoluble phosphates. Thus, organic plants are more dependent on fertilisers and soil modifications.

The third reason suggested is the relation between water and yields, with organic systems performing better than conventional systems under rain-fed conditions, as well as under drought and excessive rainfall. On the other hand, conventional crops perform better with irrigation. This may be attributed to the fact that organic systems are nutrient-limited, as explained above, and do not respond to irrigation in the same way as conventional systems. Moreover, due to the soil management practices employed in organic agriculture, soils have better water-holding capacity and higher infiltration rates and thus are able to withstand droughts or excessive rainfall.

Finally, organic yields depend on knowledge and good management practices. The authors found that when best-management practices are applied on both conventional and organic systems, the latter perform better. Organic yields are low in the first years after conversion and then gradually increase, due to improvements in soil fertility and management skills. They further suggest that "improvements in management techniques that address factors limiting yields in organic systems and/or the adoption of organic agriculture under those agro-ecological conditions where it performs best may be able to close the gap between organic and conventional yields".

Ponisio et al. (2014) in a meta-analysis of 115 studies found that organic yields are 19.2% lower than conventional yields. This is a similar figure as estimated by De Ponti et al. (2012), but smaller than the yield gap of 25% estimated by the meta-analysis of Seufert et al. (2012). Ponisio et al. (2014) also showed that diversification practices, such as multi-cropping and crop rotation, substantially reduce the organic-to-conventional yield gap (to 9% and 8%, respectively). In addition, the researchers found the yields depended upon the type of crop grown.

Market premiums and government support are instrumental in sustaining farmer income

Higher prices and government support tend to compensate for lower yields and generally higher total economic costs. The premiums reflect the perceived collective benefits of organic farming practices. These premiums are offset to varying degrees by the higher production and certification costs, but appear to provide some parity between gross margins for organic versus non-organic producers.

An important point to consider is what will happen to these premiums as the organic sector expands. If the organic sector grows in a manner similar to other food and fibre sectors, it could be expected that the production, processing, delivery and retail costs per tonne will decrease over time. Anecdotal evidence suggests this is indeed happening (Lampkin, Gerrard and Moakes, 2014). Examples range from economics in production systems (e.g. more effective pest control) to increased efficiency in transport and to more efficient use of processing plants.

The Mcbride et al. (2015) study, which examined the profitability of certified organic field crop production (maize, wheat and soybeans) in the United States, found additional economic costs of organic versus conventional production were more than offset, on average, by higher returns from organic systems for maize and soybeans, although not for wheat. Thus, organic maize and soybeans have higher average per-acre profits when controlling for other factors when compared to conventional maize and soybeans. The profit potential from organic farming is primarily due to the significant price premiums paid for certified organic crops. The study also confirms lower yields and mostly higher per hectare total economic costs (variable and fixed costs) for organic farming.

In the European Union, the share of government payments in net value added is generally higher for organic farm (Bellon and Penvern, 2014; Lampkin, Gerrard and Moakes, 2014; EC, 2013). Chavas et al. (2009) report the economic and risk analysis of a long term (1993-2006) series of data collected under the Wisconsin Integrated Cropping Systems Trial in the United States. When the authors estimated net return using only market prices (i.e. no government programmes or organic price premiums), the no-till maize-soybean system was the most profitable grain system, and rotational grazing the most profitable forage system. Once government programmes were included, returns were

seen to increase for all the cash grain systems, especially for continuous maize, with increases of 50-190%.

When organic price premiums were included with the government payment, returns to the organic grain system increased by 85-110% and by 35-40% under the organic forage system. These are higher returns than any of the mid-western standards of no-till corn-soybean, continuous corn, or intensive alfalfa production. The authors conclude that under high grain prices, if organic price premiums remain high, the gap spread among grain systems will increase to the advantage of organic grain and organic forage production. One option that the authors observed in response to this changing market is that of parallel production. Under this system, some growers are converting some of their farms to organic production, while also maintaining conventional production systems on others.

There is no clear pattern in the economic performance of organic farming compared to conventional farming

The fact that organic producers in the United States enjoy higher returns is not always translated into higher incomes. Organic farmers are not significantly better-off in terms of farm household income, than conventional farmers. Although the average gross cash income for certified organic farms is higher than that for conventional farms, organic farms face significantly higher production costs. These costs are explained by higher labour costs, insurance expenses and marketing charges (Uematsu and Mishra, 2012). The authors also find that organic farmers are very active in hedging the greater risk and uncertainty inherent in organic farming. Their findings suggest that insurance premiums are USD 12 000 per year higher for organic farms than for conventional farms and that organic farms pay up to USD 120 000 more for marketing fees than conventional farms. Nevertheless, the study is based on a very small sample (65 certified organic farms), which might not be representative of the organic sector in the United States.[6]

The EC (2013) study, which compared the financial performance of organic holdings with that of conventional holdings for the dairy sector in Austria, Germany and France, and for the field crop sector (cereals, oilseeds and protein crops) in the same three countries plus Spain and Poland, found there is no clear pattern because each country and sector has different rates of income per unit of labour: organic farming practices have lower yields as they are more extensive – except for labour-use, where it is more intensive, but the higher prices tend to compensate for this; cost of production is not always lower as their level of depreciation per unit of production is comparable or higher than that of conventional farms; and income per unit of labour is often lower, although agri-environmental and animal welfare payments could compensate this.

The comprehensive study undertaken by the French National Institute for Agricultural Research (INRA) indicate the difficulty in drawing an unequivocal conclusion concerning the economic performance of organic farming in France compared with conventional farming, based on a literature review due to: i) unclear definitions of organic farming (e.g. farms in conversion or certified); ii) the small size of organic farms; iii) methodological problems; and iv) multiplicity and heterogeneity of the economic performance indicators used in various studies (Bellon and Penvern, 2014).

Environmental gains per area

Positive environmental effects for soil, water and for GHG emissions per area, but mixed results for GHG emissions per unit of production

In terms of resource productivity, organic agriculture performs better than conventional farming. Organic agriculture is, by definition, low in pesticide - and nutrient-use (organic cultivations are frequently found to be nutrient-deficient) and due to the utilisation of compost, residues and wastes, organic agriculture also has high resource productivity, concerning waste material. Organic practices enhance soil properties (the organic matter that is left on the field allows water to infiltrate the soil and

be retained, enabling organic cultivations to perform better than conventional systems during periods of drought and heavy rain).

In essence, the way that organic agriculture is practised has direct impact on soil and water conservation, biodiversity and climate change. Due to the absence of synthetic fertilisation, organic farmers pay attention to soil conditions, and organic practices aim to enhance organic matter and Soil Organic Carbon (SOC) and maintain the soil structure in a good condition. These aims imply the use of crop rotation, the return of organic matter to the soil, and management of residues, year-round soil coverage with inter-tillage, under-sown crops and perennial forage.

In principle, such practices should result in decreased erosion and improved flood control: higher drought tolerance; reduced soil acidification, due to the absence of ammonia emissions; improved soil fertility; higher levels of biodiversity (especially in soil organisms and higher soil fertility due to careful nutrients management). By definition, no synthetic chemical pesticides are used – thus, the impact on contamination associated with pesticides use is positive. With regard to nutrients, the use of nutrients is reduced, overall, and nutrients come only from animal manure; hence, concentrations of nutrients in run-off are generally lower.

Finally, organic practices could be considered as mitigation and adaptation strategies for climate change. Mitigation is achieved through the avoidance of chemical fertilisers (and the consequent reduction in CO_2 and N_2O emissions) and the increased levels of SOC attained under organic agricultural systems. Adaptation is achieved because organic systems are thought to be better adapted to droughts and to offer restoration from floods, increase biodiversity and reduce toxicity, while most organic cultivations are production activities that reduce risks and minimise production costs. Moreover, organic farming could also enhance the diversification and resilience of the system.

However, organic farming could require more use of ploughing than would be the case if herbicides were used. It has been argued that, on some soils, repeated ploughing compacts deep layers of soil and reduces yields; water runs off compacted soils more easily, which, in turn, increases erosion (New Scientist, 2002).

Measuring the relative GHG emissions of organic and conventional agriculture is complex and affected by the metric used (e.g. per area *vs* emissions per unit of food produced, the time scale employed, and whether changes in land use caused by changing production strategies are included). Overall, there is no evidence that organic agriculture invariably has lower emissions, although some organic practices certainly do (e.g. the use of legumes to supply nitrogen inputs to pastoral-based livestock production) and could be applied more widely in other production systems.

Gomiero et al. (2011) carried out a comparative review of the environmental performance of organic agriculture versus conventional farming and found that under organic management soil loss is greatly reduced and soil organic matter content increases. Furthermore, soil bio-chemical and ecological characteristics also appear to be improved, and organically managed soils have a much higher water-holding capacity than conventionally managed soils, resulting in much larger yields, under conditions of water scarcity. It is suggested that the higher levels of organic matter and the practice of minimum tillage in organic systems increase the water percolation and retention capacity of the soil, reducing irrigation needs. Thus, organic agriculture's resource productivity gains, concerning water and soil, are very high. In the case of water quality, in particular, several studies show that nitrogen leaching can be reduced by 40-64% through organic farming practices (Schader et al., 2012; Schader, 2009).

The 2014 INRA study, which compared the environmental performance of organic farming in relation to conventional agriculture both globally and in France, concluded that: i) higher environmental performance when use of natural resources (energy, water and phosphorus) is assessed per area used both for crops and livestock, but this advantage of organic farming decreases or even reverses when expressed per unit of output; direct and indirect energy consumption is lower, particularly for arable crops and bovine, but higher for vegetable production and when the duration of fattening of animals is increased (e.g. pigs to the fattening, table fowls); less need for irrigation and thus water use; less

phosphorus consumption, although this advantage is partly counterbalanced by the fact that, as soils farmed organically have lower phosphorus content, the phosphorus nutrition of soils could become a limiting factor of the output (Guyomard, 2014).

With respect to water quality, organic farming generally results in lower or similar nitrate-leaching rates than conventional agriculture. However, the ploughing-in of legume crops (a necessary process on organic farms) and continued manure breakdown may lead to nitrate leaching into aquifers and waterways at identical rates to conventional farms. The environmental effects of using livestock manure in organic systems will depend on how the manure is stored, and when and how it is applied.

The impact of organic agriculture on energy use can be analysed on the basis of different functional units such as "area", or the weight of output from the farming system as a reference. Lampkin (2007) identified that most product- and area-related energy use assessments of organic farming to date show lower energy use per hectare. Lower energy use (direct and indirect) for organic farming is also reported in France, particularly for arable crops and dairy, but higher for horticulture (Bellon and Penvern, 2014).

In terms of energy productivity, Gomiero et al. (2008) claim that organic agriculture, along with other low-input agriculture practices, results in less energy demand compared with intensive agriculture, and could represent a means of improving energy savings and CO2 abatement if adopted on a sufficiently large scale. Gomiero et al. (2011) describe energy use in different agricultural settings and conclude that organic agriculture has higher energy efficiency (input/output) but, on average, exhibits lower yields and hence reduced productivity.

Pimentel (2006) argues that, in several respects, energy use actually does not differ significantly between conventional and organic farms. For example, the energy cost of lorries taking grain to market in the United States is the same per kilometre; the same amount of energy is needed to manufacture and run a tractor; the energy cost of pumping irrigation water is the same per hectare on conventional and organic farm; and the energy tied up in seed, or livestock-breeding stock differs little between conventional and organic farms. Nevertheless, substantial differences do exist between energy use on conventional and organic farms, particularly those associated with the energy required to manufacture, ship and apply pesticides and nitrogen-based fertilisers.

Schader (2009) examined the differences in energy use per ha between organic and conventional farm types in Switzerland, based on a representative farm sample. As well as pig and poultry farms, conventional mixed farms have the highest total level of energy use (60 GJ/ha), while average energy use, expressed as a sum of all energy-use components in dairy, suckler cow, other grassland, arable and speciality crop farms, ranges from 20 to 30 GJ/ha. The energy use of organic farms is about one-third lower (10-20 GJ/ha), except on mixed farms, where average energy use is approximately 50% less than on conventional farms. Schader (2009) attributes the lower quantities of purchased feedstuffs (particularly concentrates), to lower-stocking densities, the ban on mineral nitrogen fertilisers, and the absence of highly intensified specialised pig and poultry farms.

In terms of environmental productivity and the effects of organic agriculture on climate change, the empirical evidence – despite differences in methodology – appears to produce similar results. FAO (2011) carried out a comprehensive literature review that integrated 45 scientific publications and 280 datasets into a single data matrix. Quantitative evaluation of this dataset revealed strong scientific evidence for higher SOC contents in soils under organic farming. This is also in accordance with the findings of Leifeld and Fuhrer (2010) and Gattinger (2012).

Lynch, MacRae and Martin (2011), analysed about 130 studies to form a comparison of farm-level energy use and the global warming potential (GWP) of organic and conventional production sectors. They concluded that:

> "The evidence strongly favours organic farming with respect to whole-farm energy use and energy efficiency both on a per hectare and per farm product basis, with the possible exception of poultry and fruit sectors. For GWP, evidence is insufficient except in a few

sectors, with results per ha more consistently favouring organic farming than GWP per unit product. Tillage was consistently a negligible contributor to farm energy use and additional tillage on organic farms does not appear to significantly deplete soil carbon. Energy offsets, biogas, energy crops and residues have a more limited role on organic farms compared to conventional ones, because of the nutrient and soil building uses of soil organic matter, and the high demand for organic foods in human markets" (Lynch, MacRae and Martin, 2011).

FAO (2011) refers to studies that have shown no marked difference between GHG emissions under organic and conventional systems: however, soil carbon changes were not included in these studies – and they can have a major impact, especially on plant products. On the contrary, Gattinger (2012) in a meta-analysis of 19 studies involving 101 comparisons, found that organic agriculture has significantly lower N_2O emissions, which are more pronounced for arable land. Furthermore, Gattinger's (2012) meta-analysis of seven studies involving 27 comparisons that allowed assessments of emissions per weight of produced crop found that nitrous oxide emissions per kg of yield were higher with organic than with conventional agriculture, due to an average of 26% lower yields in organic agriculture.

Scialabba and Lindenlauf (2010) also examine the mitigation and adaptation potential of organic agricultural systems according to three main features: farming system design, cropland management and grassland and livestock management. They find that an important potential contribution of organically managed systems to climate change mitigation lies in the careful management of nutrients and the reduction of N_2O emissions from soils.

Another high mitigation potential of organic agriculture may be found in carbon sequestration in soils. In a first estimate, the potential emission reduction resulting from abstention from the use of mineral fertilisers is calculated to be about 20% and the compensation potential by carbon sequestration to be about 40-72% of the world's current annual agricultural GHG emissions; nonetheless, as the authors argue, further research is needed to consolidate these numbers.

Preserving biodiversity is a key environmental benefit of organic farming

Concerning the contribution to biodiversity and the provision of public goods, a considerable body of research reveals that organic farm holdings score better than do conventional ones, although the literature also highlights a wide variety of results depending on the biodiversity indicators, arthropod groups considered, and agro- ecosystems studied (Bellon and Penvern, 2014). There is a higher abundance of arthropods (insects such as spiders, mites, centipedes, millipedes) in organic agriculture systems. This appears to be linked to the absence of chemical pesticides, the lower density of crops, and the higher incidence of weeds, which provide a food source. The greater abundance of microbial activity, anthropoids and weeds attracts other forms of wildlife higher up the food chain, such as birds, although more frequent mechanical weeding on organic farms can damage nesting birds, worms and invertebrates. Evidence also suggests that organic systems perform better in respect to floral and faunal biodiversity. Through the use of crop rotation, organic farming can encourage landscape diversity, which in turn produces a diversity of habitats, to the benefit of local wildlife populations. The actual impact of organic systems on the landscape is, however, very difficult to quantify.

Schader et al. (2012) conclude that the effects of organic farming on biodiversity are among the most frequently studied and are among the undisputable environmental benefits of organic agriculture. They refer to various meta-studies that show clear differences between organic and conventional farming systems (Bengtsson et al., 2005; Fuller et al., 2005; Hole et al., 2005). While these differences vary among taxonomic groups, for each species-group large differences were found, with an average of about 50% greater species diversity on organic farms.

Crowder et al. (2010) state that ecosystem function is degraded by reducing species number (what the authors call "richness"), and by skewing the relative abundance of species ("evenness"). The ecological effects of disrupted evenness has not received much attention, while conservation efforts often focus on restoring or maintaining species number, reflecting the well-known impacts of richness

on many ecological processes. The authors argue that organic farming methods mitigate this ecological damage by promoting "evenness".

Moreover, the effects of evenness among natural enemy groups were seem to be independent and complementary. Their results "strengthen the argument that rejuvenation of ecosystem function requires restoration of species evenness, rather than just richness. Organic farming potentially offers a means of returning functional evenness to ecosystems." Even concerning landscape and habitat diversity, organic farming may perform better as a result of more diverse crop rotation and higher implementation rates of structural elements, such as hedges and fruit trees. Nevertheless, the effects on the landscape are farm- and site-specific (Norton et al., 2009).

Gomiero et al. (2011) also found that organic farming systems generally support a larger floral and faunal biodiversity than conventional systems, although, when properly managed, the latter can also improve biodiversity. But, more importantly, they argue that the landscape surrounding conventionally farmed land also appears to have the potential to enhance biodiversity in agricultural areas. Sandhu et al. (2010) argue that organic agriculture plays a vital role in the provision of ecosystem services, such as biological control, pollination, soil formation and nutrient cycle in agriculture – which are important for the sustainable supply of food and fibre.

Does organic farming trigger innovations?

In relation to the potential of organic farming to trigger innovations, an important element in green growth processes, some observers consider organic farming as an innovation in itself (Padel, 2001). But recent studies have found that organic farmers have little technology in product form and the main innovations that enable competitive advantage, or allow higher labour productivity, occur in the form of processes, organisation and marketing (Tereso et al., 2012).

Moreover, organic farming has the potential to trigger innovations in many fields of science and engineering and create innovations in order to overcome its constraints. For example, breeding must produce varieties with efficient nutrient uptake and use (Wolfe, et al. 2008). Innovation could also be triggered in the chemical industry to respond to the needs for biological pest control and the development of biopesticides or other substances that are permitted by in organic agriculture.

The sector has a strong tradition of involving farmers and other practitioners in innovation processes, which means that these are often better adapted to local conditions and can be taken up more easily by practitioners.

On the other hand, based on IFOAM's organic principle of "care", several new technologies are excluded. These include modern breeding and multiplication techniques or innovations in the field of molecular sciences. These bans are justified as precaution is needed whenever there are serious potential risks to human health, the environment and society. There is, however, benefit in excluding such technologies given that the organic sector is motivated to develop innovative alternatives (ETP, 2015).

Organic farming creates jobs

Organic farming is more labour intensive compared with conventional production practices

Although studies assessing the impact on employment of soil and water conservation practices are rare, the relevant research literature is richer in the case of organic farming. This can possibly be attributed to two facts. First, low-input production systems, such as organic farming, target the sustainable use of nutrients, soil conservation and the optimised use of water. Secondly, organic farming especially in the developed world, has always been perceived as a competitive means of on- and off-farm (the latter through its economy-wide linkages) diversification and as a reaction to rising consumer demand for safe, high-quality food.

Many studies found that labour requirements per hectare on organic farms are higher than their conventional counterparts (e.g. Hird, 1997; Jansen, 2000; Lataccz-Lohmann and Renwick, 2002) given that they have more labour-intensive production activities (e.g. complex rotation systems, mixed farming); that there is a higher share of labour-intensive crops (e.g. fruit and vegetables), less mechanisation, more on-farm processing and trading, and higher requirements for information (Morison et al., 2005).

It has been argued, however, that labour needs in organic farming vary according to industry and country characteristics. For example, organic horticulture farms need considerably more labour, while organic cereal-livestock and dairy farms might not require any more labour than their conventional counterparts.

Offerman and Nieberg (2000) reviewed over 40 European studies between 1990 and 1997, and found that labour use per hectare is, on average, 10-20% higher on organic farms, although considerable variability exists between countries. Häring et al. (2001) suggest that, despite the fact that organic farming requires a higher level of labour than conventional farming, it has had no significant effects on employment in rural regions in Europe because of its relatively small size. (Greer et al., 2008) finds that higher labour requirements compared to conventional farming practices are used by organic kiwi farms in New Zealand, while Clavin and Moran (2011) found that labour needs of organic cattle farms in Ireland were 15% higher than those on conventional cattle farms.

The positive employment effects associated with organic farming are also reported by Jacobsen (2003), who uses a computable general equilibrium model to assess the impacts of two alternative policy scenarios (a subsidy for organic farmers and the use of taxes levied on fertilisers and pesticides) in Denmark. The study estimates significant positive employment effects associated with the expansion of organic production, both in the primary and the food processing sector. However, only the tax scenario results in a net increase in the employment of the total (conventional and organic) agro-food sector.

A survey of 1 144 organic farms in the United Kingdom and Ireland found higher labour intensity per organic farm (i.e. 97% and 27%, respectively) relative to conventional farms, despite the fact that comparisons were complicated by a variety of factors such as different farm sizes, crop variations, horticulture and livestock farming, and the inclusion of on-farm organic marketing activities (Morison et al., 2005). The study concludes that if 20% of all farms were to become organic, this would result in the creation of 19% more jobs in farming in the United Kingdom and 6% more in Ireland.

As reported by Herren et al. (2012), the same data were analysed by the UK Soil Association (2006), which found that, on a weighted basis, the labour requirements on organic farms were, on average, 32% higher than on comparable non-organic farms (Green and Maynard, 2006). Another study (Lobley et al., 2005), which surveyed 302 organic and 353 non-organic farms in three English regions, confirmed that organic farms provide more jobs than their non-organic counterparts (64% more jobs per farm; 39% more jobs per hectare). This same study revealed a greater reliance in organic farming on non-family labour (an average of four employees per farm, compared to 2.3 in the conventional sector) and that organic farmers were more likely to diversify into other business activities (mainly trading and processing) compared with non-organic farmers.

In an economy-wide context, Mon and Holland (2005) applied input-output analysis to the investigation of the economic impact of organic apple production in Washington State (United States). The authors compared the economic impact of organic versus conventional apple production. Results showed that organic apple production was more labour-intensive than conventional production and that it produced higher returns to labour and capital.

Lobley et al. (2009) argue that, despite the relatively small contribution of the sector to food production, organic farmers in the United Kingdom are more likely to diversify their operations and adopt innovative marketing arrangements, which generate more local employment, both on- and off-farm. The same study identified small-scale and locally orientated organic producers who manage a

more diverse range of marketing channels compared to those focussing on national and/or regional markets. However, their input-output analysis revealed that, despite the capacity of small-scale organic producers to generate high economy-wide employment effects at the local level, it is the large-scale organic producers who account for the largest employment and income benefits in the organic sector.

In a similar context, the Organic Farming Research Foundation (2012) reports that production and manufacturing of organic products in the United States creates 21% more jobs than the equivalent non-organic activity, due to larger labour requirements, the smaller size of organic farms, and reliance on the organic certification industry. Similarly, a study in Maine found that organic agriculture (especially vegetable and fruit farming) creates more jobs (8%) per farm and sells more locally than its conventional counterparts (Maine Organic Farmers and Gardeners Association, 2010). Workers in these jobs were on average more likely to be younger and female than is the case on conventional farms.

There have been arguments that labour needs in organic farming depend on industry and country characteristics. In Australia, Wynen (1994) found that both in the cereal-livestock and dairy sectors, labour requirements on organic and non-organic establishments were not very different. Offermann and Nieberg (2000) and Lobley et al. (2009) showed that organic horticulture farms need considerably more labour, but Wynen (2002; 2001) has shown that organic cereal-livestock and dairy farms in Australia do not require more labour than their conventional counterparts, while Tzouvelekas et al. (2001) showed that organic olive oil farms in Greece require less labour than conventional ones.

However, if higher labour requirements can be positively perceived in regions with high unemployment, in other cases the restricted availability of farm workers may be a constraint for the development of organic farming. The importance of industry and country characteristics are further confirmed by Tyburski (2003), who argues that the fact that the average size of organic farms in Poland is three times that of conventional farms raises doubts as to the ability of organic farming to generate employment in that country.

Notes

1. For example, antibiotic use in the United States is not allowed in livestock products that are marketed as certified organic.
2. These principles include: "to consider the wider social and ecological impact…; to process organic products using renewable resources; to progress toward an entire production, processing and distribution chain which is both socially just and ecologically responsible" (www.ifoam.org/partners/advocacy/Cop15/IFOAM-CC-Guide-Web-1.pdf).
3. For an overview of the quantitative targets in the Action Plans of EU member countries, see www.orgap.org/org-libary.html.
4. The standards specify that: land will have no prohibited substances applied to it for at least three years before the harvest of an organic crop; use of genetic engineering, ionising radiation and sewage sludge are not permitted; and soil fertility and crop nutrients are to be managed through tillage and cultivation practices, crop rotations and cover crops, supplemented with animal and crop waste materials and synthetic materials from the allowed National List of Substances. Farmers must use organic seeds and other planting stock unless they are not commercially available. Crop pests, weeds and diseases are to be controlled primarily through management practices, including physical, mechanical and biological controls. When these practices are not sufficient, a biological, botanical, or synthetic substance on the National List of approved substances may be used. (see

   www.ams.usda.gov/sites/default/files/media/Guide%20for%20Organic%20Crop%20Producers_0.pdf; blogs.usda.gov/2012/03/22/organic-101-what-the-usda-organic-label-means/; www.ams.usda.gov/grades-standards/organic-standards).

5. Berry et al. (2002) provide evidence that supports this argument.
6. Uematsu and Mishra (2012) study is based on data from 65 of 2 689 farms sample that have any certified organic acreage obtained from the 2008 Agricultural Resource Management Survey, developed by the Economic Research Service and the National Agricultural Statistical Service. They found that, although the average gross cash income for certified organic farms is approximately USD 1 million higher than that for conventional farms, organic farms face significantly higher production costs. On average, organic farms spend USD 310 000 to USD 361 000 more on labour, of which USD 230 000 to USD 300 000 is directed to hired farm workers.

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Annex 3A

Share of organic agricultural land

Table 3A.1. Organic agricultural land and share of total agricultural land, by country 2005 and 2013

Country	2005		2013		Change (%)
	Area ('000 ha)	Share (%)	Area ('000 ha)	Share (%)	(2013/2005)
OECD					
Australia	11 767	2.6	17 150	4.2	46
Austria	480	16.7	527	19.5	10
Belgium	23	1.7	63	4.6	174
Canada	579	0.9	869	1.3	50
Chile	23	0.2	24	0.1	3
Czech Republic	255	6.0	474	11.2	86
Denmark	134	5.2	169	6.4	26
Estonia	60	7.2	151	16.0	153
Finland	148	6.7	206	9.0	40
France	550	2.0	1 061	3.9	93
Germany	807	4.7	1 061	6.4	31
Greece	289	3.5	384	4.6	33
Hungary	129	3.0	140	3.3	9
Iceland	5	0.2	10	0.4	94
Ireland	35	0.8	53	1.3	50
Israel	5	0.9	8	1.4	65
Japan	8	0.2	11	0.3	36
Korea	6	0.3	21	1.1	245
Italy	1 069	8.4	1 317	10.3	23
Luxembourg	3	2.5	5	3.0	39
Mexico	308	1.8	501	2.3	63
Netherlands	49	2.5	49	2.6	0
New Zealand	47	0.4	107	0.9	128
Norway	43	4.2	52	4.8	21
Poland	160	1.1	662	4.3	315
Portugal	212	5.7	272	8.1	29
Slovak Republic	90	4.8	167	8.8	85
Slovenia	23	4.8	39	8.4	66
Spain	623	2.5	1 610	6.5	159
Sweden	223	7.0	501	16.3	125
Switzerland	117	11.0	128	12.2	9
Turkey	93	0.2	461	1.9	395
United Kingdom	613	3.8	568	3.3	-7
United States	1 641	0.5	2 179	0.6	33

Table 3A.1. Organic agricultural land and share of total agricultural land, by country 2005 and 2013
(*cont.*)

Country	2005		2013		Change (%)
	Area ('000 ha)	Share (%)	Area ('000 ha)	Share (%)	(2013/2005)
Non-OECD					
Argentina	2 682	2.0	3 191	2.7	19
Brazil	842	0.3	705	0.3	-16
Colombia	46	0.1	32	0.1	-31
Costa Rica	10	0.3	7	0.5	-24
World	29 021	0.7	43 091	1.0	48

Note. Data include conversion land.

Source: Research Institute of Organic Agriculture (FiBL) and the International Federation of Organic Agriculture Movements (IFOAM) (FiBL/IFOAM) (2015), *The World of Organic Agriculture 2015*, www.organic-world.net/yearbook-2015.html.

Chapter 4

Unleashing the green growth potential of integrated pest management

This chapter examines the principles, concepts and practices of integrated pest management practices (IPM) and their impact on resource efficiency and productivity. It is argued that IPM can have win-win-win benefits for profitability, the environment and human health. In most OECD countries, IPM adoption is primarily in response to demand for improved food safety and lower health risks from both consumers and producers.

Key messages

- In most OECD countries, the adoption of Integrated Pest Management (IPM) is primarily in response to demands from both consumers and producers to improve food safety, and to lower health and environmental risks.
- Results are generally positive and span over the economic, environmental and social arenas, but the lack of a common Integrated Pest Management (IPM) definition makes any assessment difficult.
- The effects on yields, farm profits and farm incomes appear to be uniform and positive. By adopting low input and integrated techniques, the use of pesticides can be reduced without compromising yields and without affecting farmers' incomes, as cost savings outweigh production losses.

Agreement on a definition of Integrated Pest Management is needed for policy and impact assessment

Many definitions of the term Integrated Pest Management (IPM) exist as a result of its long history and evolution (Box 4.1). The lack of a single definition is a significant impediment not only to a common understanding of the term, but to its use in policy and its measurement.

So many different definitions have considerable implications for the way IPM is adopted on the field and the methodology by which IPM policy efforts are measured. For example, the definitions vary considerably in their treatment to pesticides (OECD, 1999). Some definitions appear neutral on the use of chemical pesticides, while others argue for reduced pesticide use, and yet others insist that pesticides should be used only as a last resort, when all other approaches have failed. The holistic approach implies the simultaneous management of multiple pests and the integrated use of multiple suppressive tactics.

For policy purposes, the most influential definitions are those provided by the FAO and by the European Union (which are very similar) and those of the United States Department of Agriculture (USDA), the US Environmental Protection Agency (EPA) and the International Organisation for Biological Control (IOBC). The OECD has not endorsed a particular definition of integrated pest management and uses the existing definitions of organisations such as the FAO or the IOBC.

There is a wide range of practices applied within IPM strategies due to the fact that IPM is adapted to local geographic and weather conditions, soil type, pest pressure and crop needs that vary enormously from region to region, even within the same country. IPM is usually deployed in several steps, each involving various practices. In general, the standard procedures include: i) the preventive suppression of potentially harmful organisms; ii) the identification and monitoring of these organisms; iii) a decision-making procedure based on pre-defined action thresholds; iv) information from monitoring; and v) if and when needed, suppression actions.

For this reason IPM never prescribes ready-to-use recipes or "one-size-fits-all" management practices. For each case, a unique package of practices is proposed and a tailor-made strategy adapted to local requirements is developed. However, over the years, certain practices have been found to contribute significantly more than others and in a wider range of environments.

Taking into account the wide range of IPM practices and the environmental diversity in which these practices are applied, a detailed and restrictive definition of IPM does not seem to be either possible or desirable. However, a harmonised definition of the principles and on the decision-making process of IPM may be feasible. For example, a harmonised definition may ensure that the use of chemical pesticides must be a last-resort farm practice and, when exercised, must be undertaken in a way that minimises potential risks to human beings and the environment, respecting levels that are far

below the corresponding levels for conventional agriculture. On decision-making grounds, a harmonised definition may ensure that IPM follows specific stages supporting a holistic and agro-ecological approach to farm management with clearly defined decision rules and objectives.

A serious criticism is that contemporary IPM is far different from how it was envisioned by its proponents and has become Integrated Pesticide Management instead of Integrated Pest Management (Ehler, 2006). Critics argue this has come about because, in the effort to provide a quick-fix solution, the holistic and integrated approach to pest management has been lost. The holistic approach implies the simultaneous management of multiple pests and the integrated use of multiple suppressive tactics.

Box 4.1. What is Integrated Pest Management (IPM)?

Reviews bring the number of IPM definitions to above 65 (Ehler, 2006; Prokopy and Kogan, 2003; Bajwa and Kogan, 2002). The early scientific definitions of IPM express a strong ecological inclination by stressing the need for the integrated use of multiple, suppressive tactics and the simultaneous management of multiple pests without neglecting the use of economic or treatment thresholds when applying pesticides. The historical roots of IPM can be found in the convergence of the related terms of Integrated Control or Integrated Pest Control that were developed in the early 1960s in the United States, and the term Pest Management developed in the same period in Australia (Kogan, 1998), where it was used by ecologists and entomologists. A typical example of the scientific approach to define IPM is given by Prokopy (2003) as: "a decision-based process involving coordinated use of multiple tactics for optimising the control of all classes of pests (insects, pathogens, weeds, vertebrates) in an ecologically and economically sound manner".

The FAO definition: "IPM means the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimise risks to human health and the environment. IPM emphasises the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms". FAO (2014) suggests the following six main steps as typical for an IPM approach: prevention and or suppression of harmful organisms; monitoring of harmful organisms; decision making based on monitoring and concerning with whether and when to use what pest management inputs with priority given to sustainable non-chemical methods; pesticide application should be considered as a last resort when there are no adequate non-chemical alternatives and the use of pesticides is economically justified; selection of pesticides which are as specific as possible for the target and have the least side effects on human health, non-target organisms and the environment; and monitoring of the success of the applied pest management measures.

The EU definition: "IPM means careful consideration of all available plant protection methods and subsequent integration of appropriate measures that discourage the development of populations of harmful organisms and keep the use of plant protection products and other forms of intervention to levels that are economically and ecologically justified and reduce or minimise risks to human health and the environment. 'Integrated pest management' emphasises the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms" (Article 3 of Directive 2009/128/EC).

The USDA definition: "IPM is a sustainable approach to managing pests by combining biological, cultural, physical and chemical tools in a way that minimizes economic, health and environmental risks". "IPM is an effective and environmentally sensitive approach to pest management that relies on a combination of common sense practices. IPM programs use current, comprehensive information on the life cycles of pests and their interactions with the environment. This information, in combination with available pest control methods, is used to manage pest damage by the most economical means, and with the least possible hazard to people, property, and the environment. IPM programs take advantage of all pest management options possibly including, but not limited to, the judicious use of pesticides (US EPA)". The US EPA (2014) proposes a four-step procedure: prevention, avoidance, monitoring and suppression.

Other organisations, such as the International Organisation for Biological Control (IOBC), place IPM within the framework of Integrated Production and define IPM as "a concept of sustainable agriculture based on the use of natural resources and regulating mechanisms to replace potentially polluting inputs. The agronomic preventive measures and biological/physical/chemical methods are carefully selected and balanced taking into account the protection of health of both farmers and consumers and of the environment. Emphasis is placed on a holistic systems approach involving the entire farm as the basic unit, on the central role of agro-ecosystems, on balanced nutrient cycles, and on the welfare of all species in animal husbandry".

Complexity of the concept hinders adoption

Despite some notable examples of IPM, adoption has been limited due to its complexity. The brief exposition of IPM's adoption across the major agricultural economies of OECD countries presented in Annex 4.A suggests that in most European and North American countries IPM adoption was, primarily, a response to demands for higher food safety and health from both consumers and producers. In the

European Union, the United States and Canada, where consumer surveys have been carried out, a major issue is still the harmonisation of IPM concepts and strategies among member states and provinces and the co-ordination of actions at the federal (United States and Canada) or EU level.

The examples presented suggest that these countries have identified the most critical stages in IPM adoption and have attempted to provide cost-effective solutions. In these countries, monitoring and early detection of pest populations above action thresholds is the major (and most costly) issue and thus efforts target the development of monitoring and announcement systems. Training is also an issue and training courses and material have been developed, distributed and delivered through various and innovative ways (Box 4.2).

In the European Union, tremendous variability of IPM concepts, efforts, targets and measurement are depicted in the National Action Plans of EU member states, rooted in the different historical pathways followed by EU countries. Analysis of the Action Plans shows that what is argued as the statutory adoption of IPM in 2014 is rather pesticide control, driven by the Sustainable Use Directive and Plant Protection Products Directive (Directive 128/2009 and Regulation 1107/2009).

The lack of harmonisation prohibits the development of nation- or EU-wide schemes for the certification of products under the IPM production technology. This is a potential drawback in the efforts to communicate this technology to consumers. The lack of harmonisation and co-ordination makes monitoring of adoption rates and assessment of IPM efforts more difficult. Information dissemination and knowledge transfer are also critical issues in all countries.

Box 4.2. Netherlands: Farming with Future

In the Netherlands, the national network project, Farming with Future, adopted a stakeholder management approach to mobilize the support and contribution of stakeholders in the development and introduction of IPM in practice (Wijnands et al., 2014). The Dutch approach for knowledge development and dissemination in the Farming with Future project appears to be effective. It functioned as a transfer point to transfer knowledge on sustainable crop protection methods and provided support to stakeholders wishing to transform their ambitions into concrete activities. The authors argue that "one could also use the term knowledge circulation or co-creation to refer to this process of sharing, applying, and developing knowledge further in an interactive process usually within heterogeneous groups. An important aspect within knowledge circulation is the interchange of scientific and tacit knowledge found within the different parties involved".

Wide-ranging positive on- and off-farm economic impacts, but limited empirical evidence

In an economic analysis framework, IPM should be viewed as a damage abatement technology. The economic impacts of IPM are primarily observed on the farm in terms of yields, production costs and product prices, and off the farm in terms of social benefits from improved environment and health. These economic impacts, in turn, can have significant consequences on the level of future IPM uptake and the design of policy. Positive economic effects may attract farmers, while negative economic effects may discourage the future uptake of IPM. If, however, off-farm welfare impacts are taken into account, it may be in the interest of society to encourage IPM adoption by various incentives.

The economic impacts of IPM are closely related to the use and effects of pesticides and their role in production. Early economic thinking considered pesticides in the same way as other inputs to agricultural production functions, with a yield increasing effect just like labour, capital and fertilisers.

Farm practices that reduce the use of dangerous pesticides can have win-win-win benefits for profitability, the environment, and human health in intensive systems. IPM uses a combination of practices, especially improved information on pest populations and predators, to estimate pest losses and adjust pesticide doses accordingly.

In its simplest form, IPM should be considered as a responsive activity which may use chemical pesticides or other suppression methods according to pest levels. In this sense, monitoring is the critical element in deciding the use of preventive or responsive pesticide application. If the cost of monitoring is

less than pesticide cost, IPM responsive activities will be preferred over preventive activities. If monitoring is costless, preventive pesticide application activities will always be sub-optimal.

If the difference between optimal pesticide applications under different pest levels is large, and the cost of monitoring is relatively small, then responsive application will produce a higher level of expected profits than preventive application. However, even if the variance of the amount of required pesticide is large, farmers may still use prevent applications if the price of pesticides is relatively cheap or the cost of IPM is relatively high. Technology can be used to reduce the costs of monitoring and thereby induce more responsive applications.

Why do farmers adopt IPM practices?

At the farm level, the economic impacts of IPM adoption are related to the costs and revenues associated with the chosen IPM technology. Cost savings may accrue if reductions in pesticide use outweigh the additional costs of practising IPM. The fact that there is contradicting evidence as regards pesticide use under IPM technology highlights the need to adopt a common definition of IPM that will allow scientists to build a coherent evaluation framework. Revenues are more certain, as yields are not affected significantly under IPM, and prices are at least equal to the conventional product.

Despite strong political support for pesticide-use reduction and considerable scientific progress in terms of tactical approaches to controlling pests (e.g. biological control, plant resistance), farming practices – and thus pesticide use – have not changed substantially (Lefebvre et al., 2013). The empirical evidence on the effect of IPM on pesticide use is mixed, even for a given crop. IPM can reduce pesticide use and costs without compromising yield in some circumstances, while in other circumstances IPM has no significant effects on pesticide use; and a few studies even found evidence of increased use (Box 4.3).

Box 4.3. What is the empirical evidence for the benefits of Integrated Pest Management?

Hillocks (2012) argues that loss of triazoles in the United Kingdom could allow *Septoria tritici* to reduce wheat yields 10% to 20% and could cause yield reductions in rapeseed oil due to *Leptosphaeria maculans* and *Pyrenopeziza brassicae*. If *mancozeb* is withdrawn, fungicide resistant deterrent strategies for potatoes and other minor crops could be adversely affected. This would be a great opportunity for the adoption of IPM, at least for selected crops. Of course, some argue that the pesticide regulatory process directly affects the use of individual materials, and influences the types of new pesticides developed, registering new materials, and removing others from the market, but only indirectly affects aggregate quantity (Osteen and Fernandez-Cornejo, 2013).

Velivelli et al. (2014) review the problems and challenges of bacterium-based *bicinchoninic* acid BCA when used as part of an integrated management system. The authors conclude that "in addition to resourcing, the problems and challenges inherent in the identification, performance assessment, and registration of BCAs require significant co-operation from governmental agencies and the academic and industrial sectors to support the development of sustainable agriculture".

An economic evaluation of 61 IPM programmes conducted by Norton and Mullen (1994) reported that adoption of IPM methods resulted in lower pesticide use. Pretty et al. (2006) reported that of 62 international IPM programmes, three-quarters showed declines in pesticide use, although this was criticised by Phalan et al. (2007) for selection bias in the study. More recently, Lechenet et al. (2014) assessed the sustainability of 48 arable cropping systems from two major agricultural regions of ***France***, including conventional, integrated and organic systems, with a wide range of pesticide-use intensities and management (crop rotation, soil tillage, cultivars, fertilisation, etc.). They found that, in comparison with conventional systems, integrated strategies showed a decrease in the use of both pesticides and nitrogen fertilisers; they consumed less energy; and were frequently more energy-efficient. Other studies, however, failed to find significant effects of IPM adoption on pesticide use (Fernandez-Cornejo and Jans, 1996; Wetzstein et al., 1985), while others found evidence of increased use (Yee and Ferguson, 1996).

A study carried out by INRA within the framework of the *EcoPhyto* programme in France, were pesticide use to be reduced by 50% in arable crops, 21% in orchard crops, and 37% in viticulture, found that yield decreases might be 12% in arable crops, 19% in orchards, and 24% in grapes (INRA, 2010). However, Jacquet et al. (2011) demonstrated ways of reducing the use of pesticides for field crops in France without necessarily incurring considerable income losses for the producers. The authors demonstrate that by adopting low-input integrated techniques, the use of pesticides can be reduced by about 10% without significant production loss. A more general adoption of integrated agricultural techniques can further produce a reduction of pesticides by 30%, with a reduction in production that is outweighed by cost savings and thus, no effects on farmers' incomes.

Box 4.3. What is the empirical evidence for the benefits of Integrated Pest Management? (*cont.*)

Pimentel (2009) provides a rough account of the health and environmental costs of pesticide use in United States agriculture. He records that "human pesticide poisonings and illnesses are clearly the highest price paid for all pesticide use. The total number of pesticide poisonings in the United States is estimated to be 300 000 per year. Worldwide, the application of 3 million metric tons of pesticides results in more than 26 million cases of non-fatal pesticide poisonings. Of all the pesticide poisonings, about 3 million cases are hospitalised and there are approximately 220 000 fatalities and about 750 000 chronic illnesses every year". Estimates suggest that human pesticide poisonings and related illnesses in the United States cost about USD 1 billion per year (Pimentel and Greiner, 1997).

There are many reasons underlying the failure of certain IPM programmes to reduce pesticide use. First, studies use different definitions of IPM in different contexts and the results are not directly comparable. For example, as noted above, the definitions of IPM used in the studies vary considerably in the way use of pesticides is considered. Second, side-effects were not always taken into account. For example, IPM adoption may lead to an increase in cultivated areas which will result in higher total farm pesticide use, but lower average use (per hectare use of active ingredient) (Maupin and Norton, 2010). Another important reason is that there are numerous circumstances in standard agricultural practice that may be considered as part of an IPM programme, but which do not really meet IPM guidelines (Epstein, 2014). Finally, it should be noted that scientists are still far from achieving a full understanding all of the longer-term and region-wide agricultural and ecosystem impacts of the use of even the softer pesticides (Bahlai et al., 2010).

Two critical areas which will affect the economic effects of IPM at the farm level are related to the cost for inputs (conventional and IPM related) and the prices for output. Institutional and legislative changes have prohibited the presence of many active substances in pesticides that might affect the cost of pesticides. Furthermore, taxation and other economic regulations, such as quotas may also have an effect on increasing pesticide prices in the very near future. On the other hand, R&D and infrastructure to reduce the cost of monitoring and the early detection of pests reduce the cost of adopting IPM, and more importantly reduces the risk perception of farmers when IPM is adopted.

IPM products command a price premium

The price of IPM products can command a price premium in the market as consumers become more aware of the health risks associated with pesticide residues in food. Research shows that consumers would be willing to pay more for products labelled "IPM Certified" (Anderson et al., 1996; Govindasamy and Italia, 1997; Govindasamy, Italia and Adelaja 2001). A wide range of studies based on surveys indicates that IPM products are closely related to organic products in that those households that are willing to pay a premium for organic products are also willing to consider alternative agriculture, such as IPM. Evidence suggests that consumer preferences for IPM are strongly impacted by the price difference with organic products (Marrone, 2009; Anderson et al., 1996; Magnusson and Cranfield 2005; Cranfield and Magnusson, 2003; Biguzzi et al., 2014).

Positive environmental impacts

The environmental effects of IPM programmes are, in general, positive and stem mainly from the reduction of pesticide use (and, when necessary, use only the most selective pesticides at the lowest required quantity) and incorporation of good agricultural preventive practices which are usually associated with the implementation of IPM practices. Thus, all recorded adverse effects of pesticide use on the abiotic and biotic environment are ameliorated by IPM practices.

As noted above, most IPM assessments confirm a significant reduction in pesticide use, and thus IPM brings about positive environmental effects, but these effects also accrue from the adoption of good farming practices for the prevention of diseases, such as crop rotation and reduced tillage that enhance biodiversity, protect soils and conserve water (conservation tillage and crop rotation form the core of many IPM programmes). Tillage practices affect nutrient availability, soil structure and aggregate

stability, soil strength, soil temperature, the soil-water relationship and finally, the crop residue cover, with profound soil microorganism and ecological effects that may decrease pesticide reliance and use. The same beneficial effects are produced by crop rotation.

Box 4.4. IPM and climate change

There is some discussion that climate change could reduce the effectiveness of current IPM measures. Global warming could have serious consequences for the diversity and abundance of arthropods and the extent of losses due to insect pests (Sharma and Prabhakar, 2014). As such, the components of pest management under IPM, such as host-plant resistance, bio-pesticides, natural enemies, and synthetic chemicals, may become less effective. Therefore, there is a need to take a concerted look at the likely effects of climate change on crop protection and to devise appropriate measures to mitigate the effects of climate change on food security. Sharma and Prabhakar (2014) propose actions to support the adaptation of IPM to possible climate change effects, as follows:

- Map and predict the geographic distribution of insect pests and of their natural enemies, and understand the metabolic alterations in insects in relation to climate change
- Investigate how climatic changes will affect development, incidence, and population dynamics of insect pests
- Refresh the existing economic threshold levels for each crop–pest interaction, as changed feeding habits or increased feeding under high CO_2 will change the economic threshold level for the pest
- Examine changes in levels of resistance to insect pests and identify stable sources of resistance for use in crop improvement
- Understand the effect of global warming on the efficacy of transgenic crops in pest management
- Taking into account the aforementioned, assess the efficacy of various pest management technologies under diverse environmental conditions
- Draw appropriate strategies for pest management to mitigate the effects of climate change.

Gains spread beyond the farm, but the impact on human and social capital is difficult to assess

IPM's economic benefits to society (welfare) are found in the reduction of pesticide use and the consequent prevention of certain human health problems, as well as environmental conservation, but these are not well studied. It is difficult to locate studies dedicated to IPM's impacts on health, which are estimated by assuming that IPM reduces the use of high-risk pesticides and allows or tolerates the use of low-risk, selective and rapidly deteriorating suppression substances.

The impact of pesticides on environmental and human health increase the social cost of pesticides beyond the private cost facing the farmer. If this cost is considerable, it can justify public expenditure for the support of IPM adoption, either in the form of reducing the cost and risk of adoption (monitoring and announcement systems) or in the form of subsidising forgone income.

The literature on the effects of pesticide on human health is long, especially in the area of toxicology,[1] but there is no real body of literature that attempts to measure the economic benefits of IPM adoption on human health and the environment. The results pertain to pesticide use in general and, as such, can be used indirectly in an IPM framework.

The social impacts of IPM refer mainly to impacts on human and social capital, but any assessment faces important attribution issues. Impacts on human capital refer mainly to changes in the knowledge and skills of farmers for decision-making related to pest control. Impacts on social capital refer to changes in organisation, social networks, access to information and collective action for pest control.

IPM is about information provision and building knowledge on new approaches to pest control. Social and human capital changes are embedded in IPM practice and are a pre-requisite to the successful implementation of IPM. With IPM training programmes, farmers acquire knowledge and skills and increase human capital. IPM projects lead to social empowerment and initiate a process of

creation and sharing of IPM knowledge and building of social relations within and between participants. For example, training, and the consequent advancement in human capital resulting from training activities, is an essential condition for the application of IPM. As such, IPM impacts on social and human capital are difficult to disentangle from total IPM impacts. It is, however, difficult to clearly attribute observed productivity or other differences between IPM-practicing farmers and control groups to the practice of IPM per se or to increased human and social capital. More carefully designed studies and monitoring systems are required for such an assessment.

However, the advancement in social and human capital resulting from the implementation of IPM programmes is a stand-alone benefit and as such a distinct positive impact. For example, higher levels of networking achieved because of the implementation of a monitoring activity within an IPM programme can spill over and diffuse information and knowledge not related to IPM. Techniques learned for the prevention of pests in a specific cultivation may trigger the farmer to search for similar techniques for other cultivations.

With IPM training programmes, farmers acquire knowledge and skills on a wide range of issues including knowledge of:

- the origin, biology and behaviour of the pest
- the means of dissemination (ways in which the pest arrives to field or storage)
- control practices
- the principles of controlled practices, that is, farmers learn the reasons for which a specific practice should be implemented at a certain time and place.

And skills to:

- diagnose and identify the presence and severity of an insect or a specific disease that is attacking the crop, and how to monitor the development of the pest
- carry out a specific practice; e.g. in the case where farmers increase their capacity to monitor the presence of pests with pheromone traps which requires skills to install and monitor traps.

Factors influencing the emergence and spread of IPM

The factors influencing the emergence and spread of IPM can be classified into factors pushing farmers out of conventional agriculture and factors pulling farmers into alternative technologies, including IPM. Among the push factors we include all the developments that make the exercise of conventional agriculture more difficult and that are related to IPM. For example, the banning of certain pesticides makes IPM methods an appealing alternative and supports the spread of IPM.

However, many factors attract (pull) farmers to IPM technology. These include many market developments driven by consumers, manufacturers or retailers and scientific and technological developments that either provide IPM cost-efficient solutions to conventional problems or reduce the cost of IPM practices, especially monitoring and announcement. Climate change is also among the push and pull factors in IPM adoption. Finally, agricultural policy instruments can support – but also inhibit – the emergence and spread of IPM and, for this reason, are discussed in their own section.

National policies and international initiatives in force to reduce risks from pesticide use provide a push for IPM

Developments that make the exercise of conventional agriculture more difficult and that are related to IPM could be an important push factor influencing the emergence and spread of IPM. For example, banning of certain pesticides makes IPM methods an appealing alternative and supports the spread of IPM.

In particular, such factors include: international conventions for the restriction of hazardous pesticides and national legislation (especially in Europe, North America and Japan that have banned a number of hazardous pesticides; a pesticide tax that increases pesticide market prices; and the growing-pest resistance to conventional pesticides. There have been two international agreements that have partly limited the use of the riskiest pesticides: the Rotterdam and Stockholm Conventions (Box 4.5).

In many countries, low-toxicity pesticides face different treatment in terms of authorisation, while in other countries they face the same complex authorisation process as conventional pesticides. The United States EPA has adopted a Conventional Reduced Risk Pesticide Program that expedites the review and regulatory decision-making process of conventional pesticides that pose less risk to human health and the environment than existing conventional alternatives. The goal of this programme is to rapidly compile a register of commercially viable alternatives to the riskier conventional pesticides (such as neurotoxins, carcinogens, reproductive and developmental toxicants, and groundwater contaminants). Participants in the programme include the chemical companies and state or federal agencies that submit to the Agency initial registration and amended registration applications for pesticide products (US EPA, 2015). On the other hand, in 2008 the European Union issued a list of low-risk substances for which maximum residue levels are not necessary, although bit did publish a list of low-toxicity conventional pesticides.

The European Union adopted precautionary, principle-based "rules for sustainable use of pesticides to reduce the risks and impacts of pesticide use on people's health and the environment. Acceptable pesticides must be scientifically proven not to harm human health, have no unacceptable effects on the environment, and be effective against the designated pest" (Epstein, 2014).

Sweden, Denmark and Norway have imposed taxes on pesticides. Sweden started pesticide taxation in 1986 and, since 2004, the pesticide tax has been raised to USD 4.7 per kg use of pesticide. Pesticide use was reduced by 67% during 1990s (Peshin et al., 2009).

Box 4.5. International initiatives to restrict the use of hazardous pesticides

The Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade was signed in 1998 and became effective in 2004. It has been signed by 153 nation states and the European Union, but not by the United States. Banned substances include approximately 30 older pesticides, primarily organo-chlorines, organic pollutants and carbamates, fungicides that include captofol and certain formulations of benomyl and thiram. The countries that have signed the Rotterdam Convention may ban importation of the listed compounds and are entitled to receive information about chemical risks and safe handling of the listed compounds.

The Stockholm Convention has more extensive goals in eliminating or restricting the production and use of Persistent Organic Pollutants, which include some of the pesticides included in the Rotterdam Convention. Regarding the pesticides, the 152 nation-states and the European Union, but not the United States, which have signed the Convention agreed to work towards eliminating the production and use of 14 pesticides, with a few exemptions for agricultural use, and to limit the use of DDT to malaria control.

The International Plant Protection Convention (IPPC) addresses the issue of invasive pests, which may also be of significant importance, in view of the impact of climate change on the biogeography of pests. Under the IPPC's Recommendation ICPM-3/2001 concerning Living Modified Organisms (LMOs), Biosecurity and Alien Invasive Species, countries can identify quarantine or regulated pests and define import requirements to prevent pest entry, including pest management practices in exporting countries.

In Denmark, pesticide taxation began in 1992, together with the introduction of incentives to encourage low-pesticide farming. In the case of insecticides, the tax was up to 54% of the retail price, and in the case of herbicides, fungicides and growth regulators a 33% tax was imposed (PAN Europe, 2005). As a result, the pesticide treatment intensity decreased from 3.1 (1990-93) to 2.1 applications (2001-03) and was projected to fall to 1.4 by 2009, while pesticide use decreased by 25% by 1992, and 50% by 1997 (Cannell, 2007). In 2013, Denmark introduced a new tax based on the environmental and human health load caused by pesticides. As such, a basic tax of DKK 50 per kg or litre of pesticide will be complemented by a tax of DKK 107, multiplied by the score of the effect of the pesticide on the environment, its environmental "fate" and human health.

The environmental and human health load of the individual product is divided into the following three groups of factors, which comprise a total of 16 factors. Environmental effects are the effects of the product on non-target organisms (e.g. birds, fish, daphnia, algae and earthworms). The terms "environmental fate and behaviour effect" refer to the degradation and accumulation of the product in the environment. The tax base is determined by the substances' persistence, bioaccumulation and risk of leaching to groundwater. Human health effects concern the risks of the product for users, such as the possibility of causing damage to foetuses, acute toxicity or eye irritations.

Norway started a pesticide reduction programme in 1988, which employed a levied banded tax system based on toxicity at the rate of USD 3.8 per ha. Today, Norway uses an innovative system based on tax rates on pesticides that vary according to actual environmental harm caused rather than quantity sold. This is not as challenging as it seems because Norway has approved only 188 pesticides for use (OECD, 2010).

The counter-argument to taxes comes from the fact that pesticides are price inelastic and thus demand is relatively price insensitive. Skevas et al. (2013) reviewed 27 studies from the United States and the European Union and concluded that, due to the fact that pesticide demand is relatively inelastic in economic terms (meaning that pesticide use is relatively price-insensitive) proposed taxes would be unlikely to have a major effect on pesticide use. For example, in Denmark, the 1996 and 1998 pesticide tax schemes did not deliver pesticide use reductions or reductions in the Treatment Frequency Index (Pedersen and Nielsen, 2012). As the authors argue, it is impossible to deem the tax system of that period either a success or a failure as there were so many concurrent factors influencing pesticide use.

For Norway, Withana et al. (2014) argue that it is difficult to estimate the exact impact of the pesticide tax on the environment due to the multiplicity of variables that can have a potential influence on pesticide sales, as well as statistical data that record pesticide stockpiling in the years before a tax is imposed or raised. However, it seems that the banded tax system in Norway had the effect of encouraging more conservative use of pesticides and provided an incentive to use less harmful products. Skevas et al. (2012) argue that pesticide quotas can be more effective in reducing pesticide use and, consequently, decreasing adverse environmental consequences than taxes, even if they differentiate between high and low toxicity pesticides, price penalties on the environmental effects of pesticides, or subsidies on low-toxicity products.

Pesticides are the predominant control method because they are relatively cheap and – to an extent – efficient, and because supply chains are in place and farmers have the equipment and knowledge needed to apply them (Epstein, 2014). The global pesticide market fluctuates at around USD 33 billion, with herbicides to account for almost half of it and fungicides and insecticides to account for the other half. The EU member states account for roughly one-third of this market. As a percentage of farm production costs, pesticides are relatively inexpensive and account for less than 5% of the intermediate consumption in the European Union and the United States (USDA ERS, 2014). At the same time, the chemicals pesticide industry shows some signs of stagnation. For example, in 2009 only one new chemically active ingredient was registered by the US EPA largely because pesticide development and testing by the crop protection industry, and EPA registration, take an average of nine years to complete and cost pesticide manufacturers USD 152 million to USD 256 million for each crop protection product introduced to market (CropLife, 2014).

In addition to legislative changes and the phase-out of many active substances and residue restrictions, pest resistance is another serious development constraining the use of pesticides and facilitating the use of alternative technologies. Over-application and injudicious preventive use of pesticides have resulted in pest resurgence, secondary pest problems and the development of heritable resistance (Van Emden and Service, 2004). Around the world, almost 500 species of arthropod pests and 200 species of weeds have been reported to present resistance to one or more insecticide or herbicide (Hajek, 2004; Heap, 2010). Weeds have evolved resistance to 21 of the 25 known herbicide sites of action and to 156 different herbicides (Heap, 2014).

Environmental restrictions, especially have related to water quality for human consumption, amenities or nature conservation, have also instigated a range restrictions not only concerning the actual use of pesticides, but also pesticide emissions in soil, water and air. For example, in the Netherlands, a significant push out of the conventional use of pesticides was induced by the adoption of MYCPP to reduce pesticide emissions into soil, surface and groundwater, and air by 50–90% (Wijnands et al., 2014).

Furthermore, and in view of the targets set by the adoption of the EU Water Framework Directive, many National Action Plans for the sustainable use of pesticides in Europe contain specific reference to pesticides emitted to water. For example, the United Kingdom Action Plan states among its priorities that "Residues of some pesticides particularly those in slug pellets applied to autumn sown cereals and oilseed rape crops are detected in water in certain parts of the United Kingdom with a frequency and concentration that may compromise the United Kingdom's ability to meet its obligations under the Water Framework Directive (WFD)". Furthermore, from the nature conservation side, many Natura 2000 protected areas in Europe have attempted to addressing risks posed by pesticides to biodiversity by including restrictions or incentives in their management plans.

Advances in science and technology are key drivers for reducing the perceived risk of low yields in IPM

The perceived risk of low yields is perhaps the most significant barrier to IPM adoption by farmers. Thus, any development in science, technology and policy that reduces this perceived risk will attract farmers to IPM. However, it should be noted that farmers' perception of production risks has not always been identified as a major barrier to adopting integrated farming practices. De Buck et al. (2001), argued that "dealing with production risks, such as weather-dependent problems with weeds, pests and diseases, is considered part of professionalism of both conventional and integrated arable farming systems and hence not a reason for avoiding a specific crop husbandry technique. On the contrary, the authors found that uncertainties emerging from market conditions and environmental policy were more important factors than perceived production risks.

Many developments in science and technology have attempted to provide support and reduce the cost in crucial stages for IPM implementation. IPM is very dependent not only on information collected through monitoring, but also on information regarding *Economic and Action Thresholds*. The information is used in decision making concerning with the need to activate suppression practices or not, selecting which practice to apply and decide on the optimal time to do so. As concerns large-scale monitoring and forecasting, countries have undertaken efforts to improve meteorological data and weather forecasts and warnings of possible pest events to farmers (Box 4.6).

IPM is not a simple farm management practice. Thus, the decision-making process for its adoption is more complex in comparison to packaged technologies. Being a complex technology, IPM requires a well-planned educational effort to facilitate potential users to change their mind and adopt IPM technology. For this reason, IPM is considered to be a knowledge-based technology. Farmers' lack of knowledge about the correct application of IPM technology has been identified as an important constraint to adoption (Olson et al., 2003). To this end, advisory and extension efforts are the most crucial step in encouraging adoption. Conventional extension strategies in developed countries

(e.g. one-on-one farm visits, field demonstrations, training workshops, printed materials, telephone and mass media) have been complemented by developments in information technology (OECD, 2015).

The most important scientific development in the suppression stage of the IPM is the biological control, in general, and of bio-pesticides, in particular. Although there is no commonly accepted definition of bio-pesticides (OECD, 2013), the term that describes them as a "mass-produced agent manufactured from a living microorganism or a natural product and sold for the control of plant pests" encompasses most entities classed as bio-pesticides within the OECD. However, there is no agreement if bio-pesticides include genetically modified organisms (GMOs), growth regulators, or products of natural origin.

Box 4.6. Germany's action thresholds and the United States' *eXtension* initiatives

In Germany, a new forecasting system and simulation models are supported by the National Meteorological Service with 560 weather stations and a radar network (Hommel, et al. 2014). Prognosis models are displayed at nation-wide risk maps using GIS spatial interpolation techniques. These daily risk maps, based on the aforementioned elements, show the infection pressure of different pests in cereals, potatoes, sugar beet, and horticultural crops. Action thresholds – or, in other words, the number of pests above which suppressive action should be taken to block the population from reaching the economic threshold and cause economic injury – are calculated based on the epidemiology of pests and their injury profiles. Thresholds are not available in all regions and crops and, even where they are available, vary between regions and depend on microclimate and agronomic practices. Information about thresholds provided by the plant protection services and via the ISIP online portal has become an important part of independent advice (Hommel et al., 2014). The ISIP is Germany's information system for integrated plant production (*das Informations System Integrierte Pflanzenproduktion*).

eXtension is a USDA-funded extension initiative to gather all the expertise in the United States using the Internet as a collaborative and information-disseminating platform. The *eXtension* site provides useful information about IPM for Extension Agents, as well as farmers and others. In addition, and taking into account the widespread use of Smartphones, the Co-operative Extension Service has started to transmit IPM information using phone applications to help users readily access information.

The best known semio-chemicals are insect sex pheromones, used for monitoring or pest control by mass trapping, lure-and-kill systems and mating disruption. The global market for bio-pesticides was at around USD 1.3 billion in 2011, dominated by North America, which accounted for around 40% of the global bio-pesticide demand in 2011. Europe is expected to be the fastest-growing market in the near future, once certain organisational issues have been resolved.

In Europe, efforts have focused on the issue of defining what is not considered as a low-risk substance. Europe has not yet produced a list of low-risk substances that could be supported – something that may take a long time to finalise. As a result, certain bio-pesticides are currently treated as regular chemical insecticides. An example is semi-ochemicals, which are chemicals that mediate interactions between organisms. Semio-chemicals are sub-divided into allelochemicals and pheromones, depending on whether the interactions are interspecific or intraspecific, respectively (Flint and Doane, 2014). EU Regulation 1107/2009 on Plant Protection Products requires that semio-chemicals be subjected to the same regulatory requirements as chemical insecticides – this restriction constitutes a major regulatory barrier for products containing semio-chemicals and has discouraged a number of bio-control firms from putting effort to the European market, while European bio-control firms switch their efforts to North America and other emerging markets with more welcoming legislation (Tasin, 2013).

Marrone (2009) records the major obstacles to the adoption and widespread use of bio-pesticides. She argues that firstly, the market is highly competitive and capital-intensive. Many companies addressing the same market include the large companies (such as Monsanto, Dupont, Syngenta, Bayern, BASF and Dow), the medium ones (including Arysta, Advan, Makhteshim, FMC, Cerexagri, Gowan Valent and others) and the many small ones. This number of companies and products makes it difficult for small bio-pesticides companies to stand out among the others and requires large amounts of capital in order to enter the market, conduct field trials, organise farm demonstrations, and to develop marketing programmes.

The second obstacle to the adoption of bio-pesticides, according to Marrone (2009), is the complex selling channel including distributors, advisors, university and government researchers, etc. Finally, the third serious barrier is risk aversion on the part of farmers, distributors and advisors. Unless a serious problem exists (hazardous pesticide, pest resistance, banning, etc.), growers and their gatekeepers and key influencers (distributors and pest control advisors) have become accustomed to affordable chemicals that generally perform up to expectations. Changing this requires a lot of effort and field trials to persuade farmers and advisors that there is only a low risk of losing the produce if they switch to bio-pesticides.

Problems are also recorded for Biological Control Agents (BCAs) that internationally are becoming harder to source, due to the strict regulation that require impacts of BCA to be assessed. For example, the New Zealand Environmental Protection Authority has approved the use of 19 BCAs since 2000. In addition to resourcing, the problems and challenges inherent in the identification, performance assessment and registration of BCAs require significant co-operation from the stakeholders involved (government, private sector and academia) to support the development of sustainable agriculture (Velivelli et al., 2014). Moreover, marketing a BCA depends on the ability of the provider to illustrate that the product is safe and cost-effective. The economic impacts of BCAs have not yet been the subject of in-depth research (especially in the area of cost effectiveness). This lack of economic assessment can be attributed to three reasons, namely: (a) long period from commencement to full field results; (b) difficulties in assigning monetary values to biodiversity and social impacts; and (c) difficulties in assessing impacts of biological control (McFadyen, 2008).

A final "pull" factor is related to market-driven developments, ranging from consumer concerns over food safety, the retail and manufacturing industry and the institutions regulating the market. As discussed earlier, consumers are gradually becoming aware of IPM technology – however, the level of awareness is not as high as expected or, at least, not as high as the awareness of organic production. To this end, the lack of a clear definition and the lack of harmonisation among IPM policies have contributed to the relatively lower recognition of IPM products in the market.

In the United States, the USDA is developing a national certification scheme for growers adopting organic practices, but there is no similar scheme underway for IPM. Since IPM is a complex pest control process, not merely a series of practices, it is impossible to identify one IPM definition for all foods and all areas of the country. Many individual commodity growers, for such crops as potatoes and strawberries, are working to define what IPM means for their crop and region, and IPM-labelled foods are available in limited areas. The same situation holds for the European Union. In the United States a private IPM labelling scheme was started by Wegmans Food Markets, Inc., a Rochester-based retail grocer, which approached Cornell University in 1994, seeking the means to offer its customers IPM-grown sweet maize. Other private labels include Green Shield Certified, an independent, non-profit certification program that promotes practitioners of effective, prevention-based pest control, while minimising the use of pesticides, the Northeast Eco Apple Project, funded by EPA, Region 1 Strategic Agricultural Initiative and many others.

AvoGreen® is a pest monitoring programme of New Zealand's Avocado Growers' Association and Industry Council with an auditable avocado production system based on the principles of IPM. The programme aims to keep pest populations at levels below those that can cause economic loss and with careful monitoring and trace-back systems provide overall quality and safety assurances to all customers. Beyond food safety, IPM labels can serve as eco-labels, which assure consumers of countryside stewardship and as a guarantee that farming practices have not harmed the environment.

Enabling policy environment necessary to overcome barriers of adoption

Agricultural and other policies related to the environment, food safety and consumer security or even energy, can prohibit or inhibit IPM adoption. Agricultural price support policies or energy policies favouring biofuels can incentivise continuous crop production without rotations because they inflate output prices. This does not favour crop rotation, which is a fundamental practice in IPM programmes.

At the legislative level, certain regulations ban the use of high-risk pesticides and favour bio-controls while, at the same time, many bio-pesticides (e.g. semi-ochemicals) have to undergo the same authorisation procedures as high-risk chemical pesticides.

Other policies have tried to support IPM development. In the United States, in order for growers to collect indemnities for state crop insurance they have to follow "best management practices," which include pesticide applications: Horowitz and Lichtenberg (1993) reported that corn growers in the Midwest who purchased crop insurance spent 21% more on pesticides and treated 63% more acreage with insecticides than those without crop insurance. Even energy policies for biofuel production have prohibited the adoption of IPM in maize cultivation.

In the European Union's rural development policy, IPM is usually treated under the horizontal agri-environmental scheme that offers, on a voluntary basis, farmers with payments for adopting IPM practices such as minimisation of pesticide use and optimisation of input use (fertilisers, irrigation water, etc.). This type of support has been the subject of some criticism, however, on the grounds that they are not targeted and they do not reward best practice. IPM's spread in the European Union has been supported by the Sustainable Use Directive and the Plant Protection Products Directive. In addition, food safety standards and especially the adoption of maximum residue levels have supported IPM adoption worldwide (see Annex 4.A).

More targeted support could be provided for the purchase of inputs (e.g. recognised cultivars and authorised bio-pesticides) to reward specific and costly prevention farming practices, to hire scouting labour or acquire monitoring devises (e.g. light traps) and, more generally, to reduce the high cost of adoption. Furthermore, IPM programmes may consider support to tailor-made insurance packages for IPM participants.

Public policies can improve two critical areas that affect the economic effects of IPM and the probability of IPM adoption at farm level: the cost of inputs (conventional and IPM-related) and the prices for output. Conventional high-risk pesticides may become less available and more expensive due to institutional and legislative changes that prohibit the availability of many active substances and to financial disincentives, such as taxation.

In parallel, IPM practices may also be assisted through the provision of infrastructure for monitoring, early detection of pests and decision making and support to alternative suppression practices including the production of very low-risk pesticides. Such efforts can reduce the cost difference, whenever it exists, between conventional and IPM agriculture and limit the perceived adoption risk for potential IPM adopters. If this is further coupled with an IPM product differentiation rewarded with a market price premium, higher adoption rates can be expected.

Best policy examples include actions initiated by governments in a "top-down" approach that attempt to provide solutions to well-identified barriers to adopt IPM solutions, or actions initiated by the industry itself in a "bottom-up" approach as a response to acute market problems or changing market demands.

Lessons about best-policy practices

Selected examples of successful IPM programmes

In this section some key lessons learned from the application of selective successful IPM programmes and practices are drawn. It is difficult to examine and compare best policies for fostering and promoting IPM because policies comprise several different actions. Of the actions that constitute an IPM policy, some may be more successful than others. In the section below we concentrate on such "case studies" and record the factors that contributed to their success. These cases were initiated from the government in a "top-down" approach where government tried to provide solutions to well identified barriers to adopting IPM solutions or which were initiated by the industry itself in a "bottom up" approach in response to acute problems or market demands.

IPM and wheat production in Canada

Key lessons: Successful IPM programmes are built over a long period of time, based on accumulated knowledge, and include several complementary actions to reduce the cost of IPM adoption (forecast and risk warnings). They also provide alternatives for prevention, monitoring and suppression, as well as support decision-making (Action Thresholds and Decision Support Systems).

Wheat producers in Canada have access to a comprehensive management programme to minimise the economic and ecological impact of *S. mosellana*. This IPM toolkit was developed over a period of 15-20 years, and has been successfully adopted by producers, in large part due to the technology transfer efforts of researchers and provincial entomologists (Dixon et al., 2014). The technology which is available to producers includes: forecasts and risk warnings systems; monitoring tools (e.g. field scouting tool, sticky cards and pheromone traps); cultural control and agronomic practices (e.g. selecting susceptible varieties of spring wheat on planting early); biological control and host plant resistance; Action Threshold Levels (e.g. use of insecticide is only authorised once a specified level of infection has been reached); Decision Support Systems (e.g. accumulated degree-day models to predict the emergence of adult pests throughout the infested areas and to assist producers in the scouting of their fields).

Support bio-control firms in Denmark

Key lesson: Government subsidies can be used to remove barriers to entry in the bio-pesticide industry; increase the number of alternative low-risk pesticides or bio-pesticides available to farmers; potentially reduce their cost; and sustain or attract innovative, high-tech and employment-creating industry.

A subsidy scheme to promote alternative pesticides is in place. The objective is to increase the supply of alternative low-risk pesticides (i.e. those with a better health and environmental profile than traditional synthetic pesticides) by assisting small firms in the bio-control industry to register their products, as the high cost of trial could be a potential entry barrier for small firms. This initiative should be viewed as part of an integrated approach in Denmark to push farmers out of conventional pest control (through taxation, strict regulation, etc.) and pull them into low-risk pest control approaches. It is still too early to report the results of this intervention.

IPM and scientific contributions: The Environmental Impact Quotient

Key lesson: Scientific contributions within a collaborative IPM framework can yield widely applicable and transferable results.

Within the framework of the New York IPM programme, a methodology to assess the environmental impact of pesticides was created (Chandran, 2014). The model, termed the Environmental Impact Quotient (EIQ), considers various factors, such as toxicity and the environmental attributes of pesticides, to produce the risk factor of using a pesticide in a given situation (Kovach et al., 1992). The model was based on a scientific collaboration between Cornell University and the New York State Agricultural Experiment Station. The model has gained US and international acceptance as a credible method to quantify the impact and success of IPM programmes, and has formed the basis for extended-augmented models and for the introduction of more complex pesticide tax systems.

The kiwi and apples industry in New Zealand

Key lessons: Factors contributing to success include: i) a close partnership between researchers, technology transfer experts, and industrial sectors working towards a common goal; ii) strong basic knowledge gained through sustained research programmes, which is shared with the industrial sector when necessary; iii) collaborative activity between scientists and industry personnel in transferring technology; and iv) industries capable of co-ordinating and working towards common commitments.

Kiwi growers in New Zealand traditionally sprayed pests (specifically leaf-roller and scale insects) by the calendar. Early export requirements, required that orchards should be inspected and declared free of pests and diseases, and before 1992, up to eight insecticide applications were made each season (compared with only one in hotter areas, such as Chile and California).

In a collaborative action between the kiwi fruit industry and the scientists from Horticulture and Food Research Institute of New Zealand Limited (HortResearch), large-scale orchard trials were undertaken using IPM in 1991 and 1992. In 1992 an industry trial successfully produced 262 000 trays of fruit under this new management system; 4.7 million trays in 1993; and 6.8 million trays in 1994. Since 1997 100% of kiwi fruit exported from New Zealand (63 million trays) has been produced by growers using this eco-friendly production system known as 'KiwiGreen'. The KiwiGreen IPM label indicates that biocontrol methods are favoured and that chemical sprays are used only when numbers of pests are high. The KiwiGreen programme also considers environmental factors, sustainability, ethical trading practices and hygiene standards.

For apples, which is an important export commodity of New Zealand's agriculture, pesticides and fungicides were used in order to ensure high quality and reduce production loss caused by codling moth and five leafroller species, as well as the key fungal problem caused by black spot (scab) due to the moist New Zealand climate. Pesticides were also used in order to comply with foreign markets' phytosanitary requirements, especially the zero tolerance levels for live codling moth in New Zealand apple exports to Chinese Taipei, the People's Republic of China, Japan, Thailand and India (Gianessi, 2013). The Integrated Fruit Production (IFP) programme started in 1996 and was instigated by the apple industry to introduce major changes to insect and disease management (Stevens, 2011). The programme was rapidly adopted and by late 2010, 91% of the area with apple orchards was under IFP practice. The fungicide loading declined by 45% to 16.9 kg of active ingredient per hectare (Walker et al., 2009) and insecticides use was reduced by 80%, while use of insecticide sprays was reduced by 40-50%.

Agro-environmental partnerships in the Californian wine-grape sector

Key lesson: A dense nexus of pre-existing economic and social relationships amongst local organisations provide a strong basis to successfully develop collaborative scientific support.

Agro-environmental partnerships is a strategy for extending sustainable agriculture in California and consist of an agreement over more than one season among growers, growers' organisations and agricultural scientists to apply agro-ecological principles to farm-scale practices and improve the stewardship of environmental resources. In the wine-grape industry, these partnerships have also involved regulators, and environmental and community leaders and their organisations.

At the state level, in 2001 the Sustainable Winegrowing Program began to promote sustainable practices from "ground to bottle." Practices concerning pest management, water and energy use, labour practices, wine quality, community issues and other topics are outlined in the Code of Sustainable Winegrowing Practices: Self-Assessment Workbook. As Warner (2007) argues, "California wine-grape growers have created more partnerships than any other commodity because they have: strong local organizations; differentiated product quality by varieties that depend on regional environmental conditions; added significant economic value to wines by geographic branding; and recognised the importance of providing educational outreach to their environmentally conscious neighbours". These

factors have prompted the industry to develop what may be the most comprehensive sustainability initiative of any US commodity.

California has more than 40 regional winegrower and vintner associations which provide a pre-existing set of economic and social relationships upon which these partnerships have been built. Many of the practices effectively implement the results of years of University of California research, such as leaf removal and canopy management, use of cover crops, IPM, economic injury thresholds, use of weather data and models for disease-risk forecasting, and genetic resource improvements (Broome and Warner, 2008).

Best-policy practices to address barriers and increase IPM adoption

Best-policy practices aim to confront the factors prohibiting IPM adoption and to support the factors promoting IPM adoption. The latest OECD workshop on IPM (OECD, 2011) contains many recommendations for governments and stakeholders. It should be mentioned that in complex technologies, as is the case for IPM, there is no policy recipe. Policies should be tailor-made to respond to issues and problems created within specific production and environmental frames. Taking this into account, the central issue is how far IPM harmonisation and standardisation may be pursued.

Throughout this chapter, it has been shown that efforts to harmonise IPM definitions and procedures should maintain a delicate balance between expected benefits from harmonisation and possible problems that may be created due to harmonisation. A high degree of harmonisation and standardisation will return benefits related to scale economies of unified markets for IPM products and inputs. This will facilitate the certification and labelling of IPM products and the authorisation of inputs in international markets. It will also allow for improvements in the monitoring and assessment of IPM practices worldwide and for a more efficient design of policy instruments.

At the same time, it may be argued that a strict definition of IPM implies two risks. First, a strict definition of IPM will confine the available IPM practices and thus challenge the very essence of IPM, which depends on the ability of farmers to respond and innovate under different production systems and environmental conditions. In other words, as the degree of harmonisation and standardisation of IPM increases, the diversity of responses and of innovative solutions will decrease and the "integrated" and "environmental" dimensions of IPM will be sacrificed for the sake of economic and managerial efficiency. Second, a strict definition of IPM will bring to the international trade and marketing of agricultural products a level of regulation on top of Sanitary and Phytosanitary requirements. This may create more bureaucracy and give rise to the emergence of yet another non-tariff measure in international trade.

Several policy-relevant recommendations for the adoption of best practices are listed below.

Develop a framework for IPM certification programme

Building on the FAO definition, for example, consumers can be certain that when they purchase an IPM product, three basic concepts prevail in its production: (a) pests are managed in an integrated way with the simultaneous use of different product and place dependent farm practices; (b) there is a decision-making process and a product-place specific decision rule for the use of chemical pesticides as a last resort; and (c) these pesticides are selected and used in such a way as to ensure minimum risks to human health beyond MRLs and that there is minimum damage to the environment, including biodiversity.

Set clearly defined and quantifiable multi-dimensional policy targets

Such targets could, for example, go beyond those focused on cultivated areas under IPM or quantity of pesticides, and take account the quantity of active ingredients or a compound risk indicator. The process of setting up these policy targets may be assisted by life-cycle analysis or other types of

analyses that will measure the sustainability of proposed plant protection practices, taking into account climate change.

Set baseline indicators of IPM adoption according to policy targets

Baseline indicators are the cornerstone of any policy monitoring and evaluation activities, as well as of the cost-effectiveness of policy measures and instruments. Baseline indicators should be extended beyond the policy targets to include indicators related to economic, environmental and social assessment.

Consolidating a strong scientific background and information database on available practices, action thresholds and suppression tactics is a pre-requisite to any IPM programme to be implemented

There is strong and wide scientific knowledge of IPM practices, including Action Thresholds and suppression tactics. This knowledge should be organised under a world-wide, publicly accessible database, to be regularly updated with new research and empirical evidence.

Support innovative IPM training for farmers and assess the effects of these training schemes with sound methodology. Couple training with extension and demonstration

Training schemes have a positive impact on building the human and social capital needed for IPM use on farms. These should be enhanced by providing follow-up schemes for networking, re-training, demonstration projects, visits and meetings.

Reduce farmers' perceived risk of IPM adoption by providing selective support for a pre-defined limited time period

Due to learning curves, a time period is needed for the full range of benefits following the adoption of new IPM practices or technology.[2] During this period, and especially for early adopters, the risk of dropping is high. Therefore, discretionary support may be provided for early adopters (e.g. to be used for the purchase of inputs, such as recognised cultivars and authorised bio-pesticides; to compensate for specific and costly prevention farming practices; support for the hire of scouting labour or the acquisition of monitoring devices, such as light traps; and various other aids that may be judged necessary by the programme to reduce the high initial outlay).

Revise existing insurance subsidy policies that have a negative impact on IPM adoption

Some insurance programmes impede the adoption of IPM. They can be linked to actions that reduce the risk of lower yields and imply the preventive use of conventional pesticides. To counter this, IPM programmes may consider support to tailor-made insurance packages for IPM participants.

Notes

1. There is scientific literature questioning the usefulness of pesticide approval processes because they are based, usually, on the daily intake of the pesticide calculated from the toxicity of the active principle alone (Mesnage et al., 2014).
2. Adoption and implementation on a wide scale of novel tools and tactics by the agricultural community may require up to five years of intensive support (Epstein, et. al. 2002).

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Annex 4A

Integrated Pest Management

Principles, concepts and practices

Integrated Pest Management (IPM) is usually deployed in a number of steps, each of which involving various practices. FAO (2014) suggests the following six main steps as typical for an IPM approach:

- Prevention and/or suppression of harmful organisms
- Monitoring of harmful organisms
- Decision making based on monitoring and with consideration given to individual cases, where pest management might be necessary, with priority given to sustainable, non-chemical methods
- Pesticide application should be considered as a last resort when there are no adequate non-chemical alternatives available and where the use of pesticides is economically justified
- Selection of pesticides which target, as specifically as possible, the problem and which have the least side effects on human health, non-target organisms, and the environment
- Monitoring of the success of the applied pest management measures.

The US EPA (2014) proposes the same strategy, but in a four-step procedure. USDA has put forth the Prevention, Avoidance, Monitoring and Suppression (PAMS) concept, an acronym for prevention, avoidance, monitoring and suppression. In general, the standard procedures include the preventive suppression of potentially harmful organisms, the identification and monitoring of these organisms, a decision-making procedure based on pre-defined action thresholds and information from monitoring and – if and when needed – suppression actions.

There is a wide range of practices applied within IPM strategies due to the fact that IPM is adapted to local geographic conditions and crop needs that vary enormously from region to region even within the same country. For this reason IPM never prescribes ready-to-use recipes or "one-size-fits-all" management practices. For each case, a unique package of practices is proposed and a tailor-made strategy adapted to local requirements is developed. However, in the historical course of developing and applying IPM, certain practices have been found to contribute significantly more than others, and in a wider context of environments.

For the prevention of pests, a combination of the following practices very often provides encouraging results:

- Use of pest resistant/tolerant cultivars and varieties, and use of certified seed and planting material
- Crop rotation, inter-cropping, crop sequences and associations, that minimise the pressure and maximise biological prevention of pests and diseases
- Cultivation practices such as seedbed sanitation, correct selection of sowing dates and densities, under-sowing, conservation tillage, pruning, direct sowing.

It is important to note that most of the preventive IPM practices are also common sense good farm practices for resource (soil and water) conservation, nutrient management and for building resilience to climate change.

Monitoring techniques fall into three types: absolute methods, relative methods, and population indices. In absolute methods, estimates of the density of the pest population are expressed as a level per unit of crop area, or as a percentage of the sampling units affected. In relative monitoring methods the same estimates are expressed per unit of effort, while in population indices methods the estimates are expressed by crop damage or the frequency of pest infestations.

For monitoring harmful organisms field scouting is the primary practice. This is the most important means of obtaining information to make management decisions. Scouting patterns depend upon the pattern of pest infestations which may be uniformly spread over the field, concentrated in particular areas of a field or appear at field edges first. Scouting and visual counts or assessments are frequently supported by traps such as pheromone or light traps.

The decision-making process utilises information from monitoring to address two basic questions. First, whether the natural controls present on the farm capable of keeping the pest population below economic levels. Second, if the cost that may be caused by the pest is higher than the cost of controlling the pest. The decision-making process is assisted by the estimation of the Economic Injury Levels (EIL) and the Economic Threshold (or Action Threshold). Injury is defined as the physical harm or destruction to a valued commodity caused by the presence or activities of a pest. Damage is the monetary value lost to the commodity as a result of injury by the pest. The concept of the EIL goes back to 1959, when Stern et al. (1959) defined it as "the lowest population density of a pest that will cause economic damage; or the amount of pest injury which will justify the cost of control". One way to express EIL mathematically is:

$$EIL = \frac{C * N}{V * I} = \frac{C}{V} * \frac{1}{L}$$

where C is the unit cost of controlling the pest, N is the number of pests injuring the commodity unit, V is the unit value of the commodity and I is the percentage of the commodity unit injured. EIL is expressed as the number of pests per unit area or per sampling unit and L is the loss caused per pest (Pedigo et al., 1986). The EIL is a function of the cost of pest control (C) and the value of the commodity (V). Despite its expression in quantities of pest, the EIL is a break-even point or a cost/benefit ratio that determines the pest control decisions and consequent actions. However, pest managers take account of the time lag between the implementation of a control strategy and its effect on the pest population, and set the so-called Economic or Action Thresholds which set the pest density at which control measures should be implemented to prevent the population from reaching the EIL.

In other words, Action Thresholds point out the pest density at which control operations should begin to prevent the pest from reaching the density at which it will cause economic damage. Graphically speaking, the EIL and the Action Threshold have the relationship shown in Figure A4.1 and Figure A4.2. Figure A4.1 shows how the dynamic of a pest population may reach EIL and cause economic losses. Figure A4.2 sets the Action Thresholds and shows the time at which management activity should be undertaken in order to deter the dynamic movement of the pest population from reaching the EIL. The Action Thresholds and EIL concepts have been criticised. A thorough discussion of these concepts is presented below.

Suppression practices include physical, biological and chemical activities. USDA's manual on IPM records a range of physical suppression practices including cultural practices such as narrow row spacing, or optimised in-row plant populations; alternative tillage approaches, such as no-till or striptill systems; cover crops or mulches, or using crops with allelopathic potential in the rotation; cultivation or mowing for weed control; maximising air circulation in tree or shrub canopies through pruning; baited

or pheromone traps for certain insects; and temperature management or exclusion devices for insect and disease management. Almost all cultural suppression methods are also prevention methods.

Figure 4A.1. The concept of economic injury level

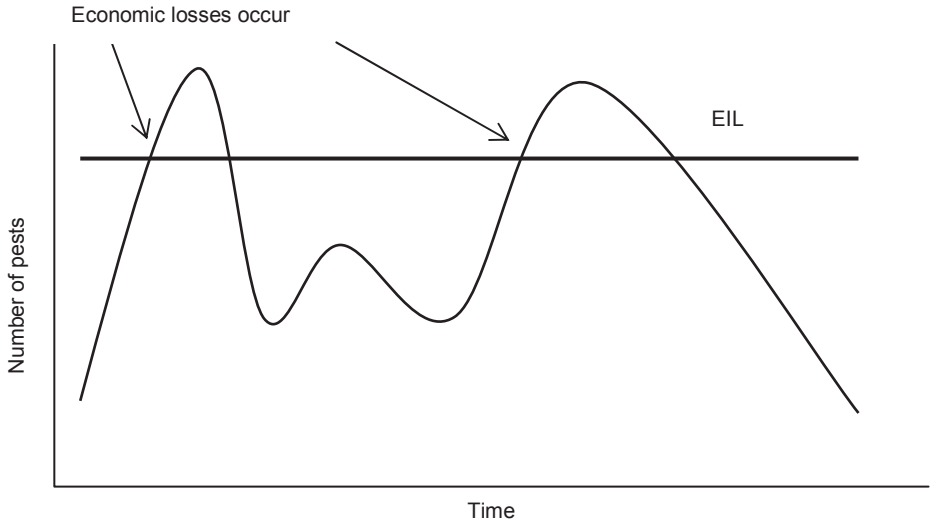
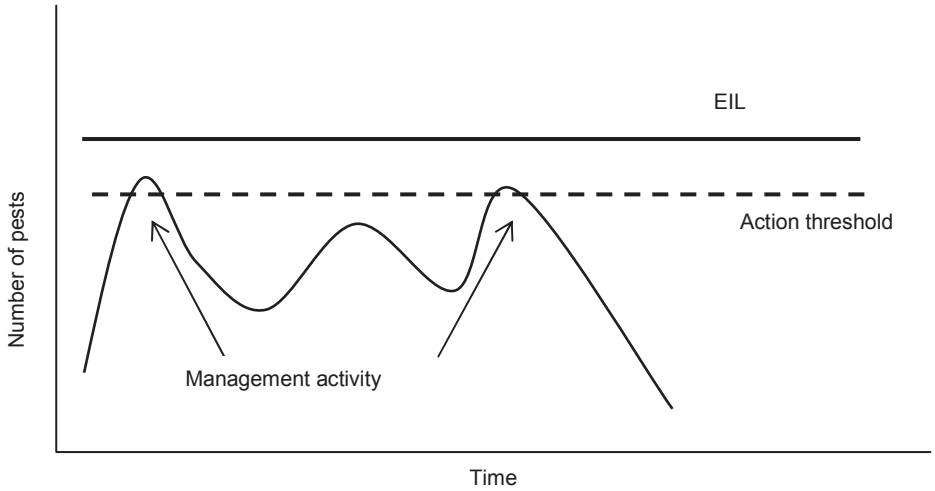


Figure 4A.2. Economic injury level and action (economic) threshold



For insect control, mechanical practices include pinching leafrollers, washing aphids off leaves, pruning out tent caterpillars and fall webworms, and various destructive barriers for slugs and weevils. For weed control, mechanical practices include hand pulling, shallow cultivation or the use of mulches which supress weeds. Physical and mechanical suppression and control practices are more effective when pest populations are low. Biological control practices aim to conserve (protect and enhance) the biological control agents that are already present and to augment or restore a decimated base of beneficial population.

The most important practices of biological control include the selective use of pesticides and the release of predatory agents. Other biological suppression practices include mating disruption for insects, and should be considered as alternatives to conventional pesticides, especially where long-term control of an especially troublesome pest species can be obtained. Chemical suppression methods should be considered only as a last resort, when all other alternatives have been tried. The whole philosophy of

IPM is to consider non-toxic and selective materials first. These materials include horticultural oils, insecticidal soaps and botanically derived pesticides, such as neem seed extracts, pyrethrum, and rotenone. Effective pesticide application (i.e. proper timing and targeted application) may reduce the use of pesticides by as much as 90%.

Adoption of IPM practices across countries

Canada

Canada has been at the forefront of research into reducing the use of chemicals without lowering crop yield or quality since the 1940's. Already in 1968, Canadian researchers had investigated ways to reduce the use of pesticides in apple orchards without increasing damage to the fruit. By 1974, the development of a computerized forecast and early warning system made available pest and weather data to apple-growing areas in Ontario. Initial use and field testing of IPM has generated grower confidence in the programme.

Crops are chosen as candidates for IPM on the basis of three major criteria: crops being treated with large amounts of pesticides; overall value of the crop in the region and/or large crop area and research information available on pest biology; monitoring techniques; and thresholds and control strategies. Today, government support for IPM is provided through two programmes. One is delivered by Agriculture and Agri-Food Canada (AAFC) and the provinces. The Pesticide Risk Reduction Program (RRRP), a joint initiative of AAFC and Health Canada's Pest Management Regulatory Agency (PMRA), aims to reduce the risks from pesticides used in the agriculture and agri-food industry. These include risks to human health, risks to biodiversity resulting from impacts on non-target organisms, and risks to air, water and soil.

The programme creates a framework through which producers develop and implement pesticide risk reduction strategies, targeting priority pest management issues that are determined through stakeholder consultations at a national level. The programme provides project funding and regulatory support for the implementation of developed strategies. The second is the Minor Use Pesticides Program (MUPP), which aims at conducting regulatory data generation trials and submit to PMRA in order to make new pest management product uses available for Canadian growers of small acreage and specialty (i.e. “minor”) crops, thereby expanding the options available to growers (Dixon et al., 2014).

European Union

In the European Union (EU) there is a long history of IPM promotion and adoption which is closely linked to pesticide control. The breakthrough in IPM adoption was the introduction of Directive 2009/128/EC, or the so-called Sustainable Use Directive (SUD). The Directive’s objective is to establish “… 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”.

In article 4 of this Directive, member states were asked to adopt National Action Plans that set up quantitative objectives, targets, measures and timetables to reduce the risks and impacts of pesticide use on human health and the environment, and to encourage the development and introduction of IPM and of alternative approaches or techniques in order to reduce dependency on the use of pesticides. Furthermore, it is obligatory for member states to describe in their National Action Plans how they ensure that the general principles of IPM are implemented by all professional users by 1 January 2014. In this respect, some type of IPM is obligatory across all EU territory. All 28 member states have, by now, submitted their Action Plans. Examination of them reveals that the level and depth of IPM adoption vary significantly across EU member states.

It is argued that, due to the fact that a number of countries have a history of national plans and programmes to reduce pesticide use and risks, the approaches of IPM implementation vary between countries, regarding the main players and stakeholders, and range from the general adoption of the IPM principles; government-driven programmes for demonstration farms; and national IPM projects, to development of crop specific guidelines and scoring systems to evaluate the national IPM performance (Dachbrodt-Saaydeh and Barzman, 2013). Among the most serious critics is the lack of a European Guideline that will harmonise the IPM guidelines at regional/territorial and national level. Non-harmonisation corresponds to a confusing market and an unbalanced competition among the suppliers of different EU member states (Tommasini, 2013).

Other critics argue that, since the SUD was developed and implemented within the DG Environment and DG SANCO, the objectives and indicators relate to environmental protection and food safety – with little consideration given to agricultural productivity, or to farming livelihoods (Hillocks, 2013). Furthermore, it is argued that certain substances which are appropriate to IPM strategies are listed by authorities as active substances, creating adverse consequences for their use in IPM programmes.

IPM and agri-environmental payments in EU member states

Adoption of IPM practices (wholly or partly) is supported in the European Union by payments directed to farmers. These payments are aimed at covering the cost of contracting IPM advisors, the cost of adaptation to the new practices (purchase of machinery and instruments) and to reducing the risk of income foregone when IPM is adopted. The payments were directed to farmers within either the Common Market Organization (CMO) or the Rural Development Plans at regional or national (member state) level. The programmes targeted either specific products or specific environmentally sensitive areas. The following are examples of IPM adoption with financial incentives provided by the Common Agricultural Policy (CAP) and recorded by Christensen (2013):

- Regional Rural Development Programme for Flanders (Belgium) under Axis 2 (Agri-environment Measures): sexual confusion against the codling moth in pipfruit for at least five years and on at least 1 ha, with a subsidy of EUR 250 per hectare;
- Fruit and Vegetables (F&V) Common Market Organization in Emiglia/Romagna, Italy: use of selected pesticides, combined with an integrated production system for F&V, with a subsidy of EUR 100/ha for arable land, EUR 300/ha for vegetables and EUR 550/ha for fruit;
- National Rural Development Programme for Austria (Axis 2): obligation for crop rotations for annual crops, restrictions on fertiliser and pesticide use, training and record-keeping for pesticides, with a subsidy of EUR 150/ha for potatoes and turnips, EUR 250/ha for strawberries, EUR 300/ha for fruit and hops, and up to EUR 400/ha for vines;
- Agri-environmental measures, France: biological control agents, introduction of beneficiaries, sexual confusion, with a subsidy of EUR 105/ha for vegetables, EUR 70/ha for fruit trees and EUR 79/ha for grapes.

Unfortunately, there are no any published assessments (to the best of our knowledge) that examine the rates of IPM adoption once subsidies are phased out. In addition, assessments recording the proportion of farmers who maintain at least some of the IPM practices or who move to organic agriculture or return to conventional agriculture once agri-environment subsidies end, are not available.

In Italy, IPM has a very long history, with its first applications dating back in the mid-1970s (Ciampitti, 2013). IPM began to really take off in 1987 with the nationwide "integrated pest and disease control strategies" and the related first IPM funding of regional action plans (Faraglia et al., 2013). The Action Plan provides for both statutory and voluntary IPM. Statutory IPM includes the application of techniques to prevent and monitor pests, diseases and weeds, the use of biological pest control methods,

recourse to appropriate farming practices and the choice of those plant protection products which entail the least risk for human health and the environment among those available for the same purpose.

Voluntary IPM is a system implemented through crop-specific technical standards and binding plant health instructions (production specifications), including agricultural and plant protection actions and constraints on the choice of plant protection products and on the number of their applications. The Action Plan sets out the actions that should be undertaken by the Ministry of Agricultural, Food and Forestry Policies and by the Regions and Autonomous Provinces to ensure that IPM training and services of forecasting, monitoring and announcement are operational and harmonized and accessible to professional users. The Action Plan also takes account of actions to monitor the presence of pesticides in the aquatic environment and food.

In Germany, IPM is included as Integrated Plant Protection and is embedded in the Plant Protection Act (PflSchG), which states that plant protection may be carried out solely according to good professional practice and in accordance to the Sustainable Use Directive. The German Action Plan also includes a range of quantified targets for the adoption of low-pesticide practices (e.g. the target that any the exceeding of the maximum residue levels must be reduced to below 1% in all product groups for both domestically-produced and imported foods by 2021). Other goals stated in other strategies also form part of the German Action Plan as, for example, the goal in the National Sustainability Strategy, which aims at a 20% share of Utilised Agricultural Area for organic farming.

In France, the National Action Plan is based on the *Ecophyto plan* that pre-existed as a national initiative (Ricci, 2013). *Ecophyto* was adopted in 2008 as a result of wide consultation process among multiple stakeholders. The aim of *Ecophyto* is to reconcile economic and environmental goals in agriculture and to reduce the use of plant protection products, while maintaining a high quantitative and qualitative level of production. The plan was subsequently embedded into the larger goal of "changing the way of cropping", by relying increasingly on the principles of agroecology. The plan is developed in nine axes that include IPM. Many research and demonstration activities are financed under *Ecophyto*. For example, *Ecophyto* has established a pest monitoring network based on observations in 12 000 fields and delivers weekly information bulletins at the regional level. At the same time, *Ecophyto* has selected almost 2 000 demonstration fields with the aim of testing strategies for pesticide-use reduction under alternative cropping systems.

In the United Kingdom, the UK National Action Plan outlines a number of IPM initiatives, but there is no fully developed framework for IPM. Among non-regulatory initiatives and incentives, the Assured Food Standards Schemes require growers to adopt practices which are consistent with the general principles of IPM. Specific standards are set for individual crops and work is underway to develop an IPM self-assessment tool for farmers (an IPM Plan) to encourage the use of IPM tools and techniques, such as decision-support systems and pest and disease monitoring systems. The support to farmers wishing to convert to organic methods of production under the Organic Entry Level Scheme is also considered as an IPM initiative.

Belgium is one of the most advanced member states as concerns adoption of IPM. The Belgian government has adopted a Federal Program for the Reduction of Pesticides (2013-2017) and three regional programmes covering the areas of Walloon, Flemish and Brussels regions. For example, in the Walloon region, a number of initiatives have been adopted, including a blight warning system for potatoes which was adopted in 2011 by 431 farmers representing approximately 10 000 ha, or one-third of the surface area dedicated to potatoes. Other examples include financial incentives for the adoption of IPM, as in the case of subsidies granted to farmers complying with the official specifications for "integrated pest management in pip fruit" adopted in 2011 by 49 farms, representing approximately 70% of pip fruit surface areas in Wallonia. In the Walloon region, the history of IPM dates back to 1988, when arboriculturists founded the GAWI (Groupements d'Arboriculteurs pratiquant en Wallonie les techniques Intégrées – Groupings of arboriculturists applying integrated pest management techniques in Wallonia), who developed and promoted integration production techniques and created the FRUITNET label, which guarantees the minimal impact of production on the environment.

The Dutch crop protection policy has been focussing on the implementation of IPM since 1990. It is claimed that in the 1980s the Netherlands had the highest pesticide use measured in quantity of active ingredient in the world (Wijnands et al., 2014). This created substantial problems for drinking water resources. The Netherlands responded with two long-term programmes. First, the Multi-Year Crop Protection Programme (MYCPP), covering the period 1991-2000 and second, the Sustainable Crop Protection Programme, covering the period 2001-10. During the end of this second period, in 2008-10, national support to develop and promote IPM in practice was realised through the "Farming with Future" initiative. Thus, the Netherlands had accumulated at least 25 years of experience in administering pesticide control policies before launching the "Farming with Future" initiative. The MYCPP achieved a 49% reduction in the volume of active ingredients and a 54-79% reduction in emissions to soil, surface and groundwater, and air. The Sustainable Crop Protection programme achieved an 86% reduction in calculated environmental impacts (Wijnands et al., 2014). Under the "Farming with Future" initiative 100 new IPM methods were tested, 80 were developed into useful, effective and feasible strategies and were subsequently documented, described and demonstrated in hundreds of activities, reaching thousands of farmers (Wijnands and Brinks, 2013). In the Netherlands, the Action Plan ensures that all professional users apply the principles of IPM. It also states that "the industry and government will ensure integrated methods are widely used by putting in place, for instance, financial and fiscal incentives, certification, a link with the Common Agricultural Policy or statutory measures".

United States

The history of IPM adoption in the US is long as, in fact, IPM was born out of early pest control initiatives developed in the 1960s in California. In 1994, the USDA and the EPA announced a joint "IPM Initiative", setting a quantitative goal of IPM adoption on 75% of planted cropland area in the United States by the end of 2000 (Jacobsen, 1996). Such an adoption rate was expected to bring about a reduction in pesticide use on the nation's farms. To measure the level of adoption, USDA put forth the PAMS concept (noted earlier). A farmer was required to utilise at least three of the four PAMS components in order to qualify as an IPM practitioner. In 2001, a survey conducted by the USDA National Agricultural Statistics Service (NASS) found that some level of IPM had been adopted by 71% of farms, as opposed to 51% at the start of the initiative.

However, the anticipated reduction in pesticide use did not occur. According to NASS, pesticide use, as measured by quantity of active ingredient applied, increased about 4% from 1994 to 2000 (i.e. during the period the "IPM Initiative" was in place). In 2000-01, the US General Accounting Office (GAO) conducted a review of the IPM programme, known as the GAO study, to examine the status of IPM adoption in US agriculture. The study concluded that "the implementation rate is a misleading indicator of the progress made toward an original purpose of IPM – reducing chemical pesticide use". The GAO study observed that four elements critical to the successful implementation of the initiative were missing:

- no one was effectively in charge of federal IPM efforts
- coordination of IPM efforts was lacking among federal agencies and with the private sector
- the intended results of IPM efforts were not been clearly articulated or prioritised
- methods for measuring IPM's environmental and economic results were not developed.

In May 2004, the Federal IPM Coordinating Committee adopted The Road Map for the National Integrated Pest Management (IPM) Program after a long period of wide consultation with stakeholders. The Road Map identifies strategic directions for IPM research, implementation and measurement for all pests, in all settings, throughout the nation (Coble and Ortman, 2009). These include pest management for all areas including agricultural, structural, ornamental, turf, museums, public and wildlife health pests, and encompasses terrestrial and aquatic invasive species. Coble and Ortman (2009) state that the

Road Map's overall goal is to improve the economic benefits of adopting IPM practices and to reduce potential risks to human health and the environment caused by the pests themselves or by the use of pest management practices.

The economic benefit of adopting IPM strategies is one dimension of IPM that is rarely mentioned in EU IPM programmes and Action Plans. Evidence from US agriculture show that pesticide expenditures accounted for a growing share of total expenditures of farm production inputs, increasing from 3-4% in the 1950s to 7-8% in the 1990s (Mullen et al., 2003). Coble and Ortman (2009) state that cost–benefit analysis of proposed IPM strategies should not be based solely on the monetary costs, but on four main parameters: monetary; environmental/ecological health and function; aesthetic benefits; and human health.

Currently the Federal IPM programme is managed by the Federal Integrated Pest Management Coordinating Committee (FIPMCC), which was formed in 2003, and is composed of representatives of all federal agencies with IPM research, implementation, or education programmes. As a response to the GAO criticism, the FIPMCC provides inter-agency guidance on IPM policies, programmes and budgets and a forum for communication among federal offices with IPM programmes to ensure efficiency of operations. The committee has been active in defining, prioritising and articulating the goals of the federal IPM effort through the IPM Road Map, making sure that IPM efforts and resources are focused on the goals, and ensuring that appropriate measurements towards progress in attaining the goals are in place.

Chapter 5

How critical is modern agricultural biotechnology in increasing productivity sustainably?

This chapter provides a succinct synthesis of the potential impacts of agricultural biotechnology on resource productivity and efficiency in OECD countries in comparison with conventional agricultural practices and identifies some of the associated main policy issues. Although this chapter touches on the full range of agricultural biotechnology tools and applications, the main focus is on disease-, insect- and pesticide-resistant and drought-tolerant crops.

Key messages

- Modern biotechnology can be potentially applied in several applications in agriculture, but some elements have proved highly controversial in some countries. Commercialisation of biotech crops has been limited to a few crops, mainly feed, and a small number of traits.
- Modern biotechnology can: i) speed up conventional breeding programmes and provide farmers with disease-free planting materials; ii) it can create crops that are resistant to pests and diseases, replacing toxic chemicals; iii) it can provide diagnostic tools and vaccines to help in controlling devastating animal diseases; and iv) value-enhanced or output-oriented products with traits derived from modern biotechnology can address additional and more complex challenges, such as drought tolerance and nitrogen-use efficiency. Empirical evidence shows that, on average, positive economic effects are being generated by first-generation biotech crops, depending on the trait considered, while the effects on biodiversity are ambiguous and context specific.
- Concerns about potential risks to the environment, consumer perceptions and institutional conditions continue to have a critical influence on the adoption of modern agricultural biotechnology and its consequent impacts.

What is biotechnology and how is it used in agriculture?

Innovating through science and technology

This chapter provides a succinct synthesis of the potential impacts of agricultural biotechnology on resource productivity and efficiency in OECD countries in comparison with conventional agricultural practices, and identifies some of the associated main policy issues. It is not intended to provide an exhaustive review of the full range of agricultural biotechnology tools and applications. Genetic engineering, particularly in the crop sector, is the area in which biotechnology has the most direct effect on agriculture in many countries, and has given rise to pressing public concerns and policy issues. Although this chapter touches on the full range of agricultural biotechnology tools and applications, the main focus is on disease-, insect- and pesticide-resistant, and drought-tolerant crops.[1]

Biotechnology comprises a number of related technologies with a wide range of current and potential applications in many sectors and is of significant interest to policy makers. Biotechnology is being used to address problems in all areas of agricultural production and processing and has the potential to contribute to meeting the challenges of green growth. Biotechnology contributes to the development of new varieties of plants and animals, new diagnostic tools, breeding, and veterinary therapeutics and vaccines. Biotechnology can overcome production constraints that are more difficult or intractable under conventional breeding schemes. It can speed up conventional breeding programmes and provide farmers with disease-free planting materials. It can create crops that resist pests and diseases, thus replacing toxic chemicals that harm the environment and human health, and it can provide diagnostic tools and vaccines that help control devastating animal diseases.

Renewed interest in biotechnology has arisen in parallel with the emergence of the notion of the bio-economy – the economic sectors that are based on bioscience and biotechnology innovation (OECD, 2009). For example, the use of renewable resources, which is expected to increase substantially over time, can require specific properties of the plant that can be developed using genetically engineering technologies.

Most of the bio-economy strategies or visions adopted by OECD countries include references to biotechnology. The United States' National Bioeconomy Blueprint, published in 2012 and which recognises the bio-economy as a political priority because of its potential for economic growth and social benefits – considers that biotechnology, including agricultural biotechnology can make an important contribution to the bio-economy through the development of innovative products and

processes, the creation of jobs and growth – the "greening" – of the agricultural sector (www.whitehouse.gov/sites/default/files/microsites/ostp/national_bioeconomy_blueprint_april_2012.pdf).

The OECD study into the bio-economy in 2030 suggests rapid adoption of biotechnology for better diagnostics and improved varieties of farmed plants and animals. But achieving the full promise of the bio-economy by 2030 requires a policy framework that can address technological, economic and institutional challenges (OECD, 2009).

Modern agricultural biotechnology includes a range of tools that scientists employ to understand and modify the genetic make-up of organisms for use in the production or processing of agricultural products: genetically engineered crops, such as insect- and herbicide-resistant plants or transgenic animals, such as pigs that can digest cellulose, or transgenic fish, such as faster-growing salmon. Modern biotechnology in general refers to the combination of life-science with engineering that includes recombinant DNA technology (Tramper and Zhu, 2011). The applications not only include crops and farm animals, but also food products such as cheeses, bakery products, wine, beer, a wide range of pharmaceutical products and other areas of the bio-economy.

The OECD's definition of biotechnology is deliberately broad, covering all modern biotechnology, as well as many traditional or borderline activities. Its defines biotechnology as follows: the application of science and technology to living organisms, as well as parts, products and models thereof, to alter living or non-living materials for the production of knowledge, goods and services (Box 5.1).[2,3]

Box 5.1. OECD definition of biotechnology

Defining biotechnology

The single definition

The provisional single definition of biotechnology is deliberately broad. It covers all modern biotechnology but also many traditional or borderline activities. For this reason, the single definition should always be accompanied by the list-based definition which operationalizes the definition for measurement purposes. The single definition is:

The application of science and technology to living organisms, as well as parts, products and models thereof, to alter living or non-living materials for the production of knowledge, goods and services.

The list-based definition

The following list of biotechnology techniques functions as an interpretative guideline to the single definition. The list is indicative rather than exhaustive and is expected to change over time as data collection and biotechnology activities evolve.

DNA/RNA: Genomics, pharmacogenomics, gene probes, genetic engineering, DNA/RNA sequencing/synthesis/amplification, gene expression profiling, and use of antisense technology.

Proteins and other molecules: Sequencing/synthesis/engineering of proteins and peptides (including large molecule hormones); improved delivery methods for large molecule drugs; proteomics, protein isolation and purification, signaling, identification of cell receptors.

Cell and tissue culture and engineering: Cell/tissue culture, tissue engineering (including tissue scaffolds and biomedical engineering), cell fusion, haploid induction, embryogenesis, vaccine/immune stimulants, embryo manipulation.

Process biotechnology techniques: Fermentation using bioreactors, bioprocessing, bioleaching, biopulping, biobleaching, biodesulphurisation, bioremediation, biofiltration and phytoremediation.

Gene and RNA vectors: Gene therapy, viral vectors.

Bioinformatics: Construction of databases on genomes, protein sequences; modelling complex biological processes, including systems biology.

Nanobiotechnology: Applies the tools and processes of nano/microfabrication to build devices for studying biosystems and applications in drug delivery, diagnostics etc.

Source: www.oecd.org/sti/biotech/statisticaldefinitionofbiotechnology.htm.

Interpreted in this broad sense, the definition of biotechnology covers many of the tools and techniques that are commonplace in agriculture and food production, such as fermentation and brewing.[4] For example, conventional plant breeding has been the method used to develop new varieties of crops for hundreds of years. The most controversial of the improved biotechnologies are transgenic crops also called genetically engineered or genetically modified organisms, commonly known as GMOs.[5] Genetic engineering is a tool for "precision breeding," enabling the insertion of genes with desirable traits even from different species. The genetic diversity of agricultural crops is a crucial factor in the ability of agriculture to adapt to climate change, to maintain increase the resistance of crops to pests and diseases and to meet changing consumer preferences. There is concern that current crop breeding does not utilise sufficient genetic diversity (van Heerwaarden et al., 2013).

It should be emphasised, however, that modern agricultural biotechnology is more than genetic engineering. The most significant breakthroughs in agricultural biotechnology, for example, are coming from research into the structure of genomes and the genetic mechanisms behind economically important traits. The rapidly progressing discipline of genomics, revolutionising understanding of the ways in which genes, cells, organisms and ecosystems function, is opening new horizons for marker-assisted breeding and genetic resource management: it provides information on the identity, location, impact and function of genes affecting such traits – knowledge that may increasingly drive the application of biotechnology in all agricultural sectors (Boxes 5.2 and 5.3).

Box 5.2. Genomics: The new revolution

Genomics, the study of all the genetic material in an organism, is leading to tremendous advances in biotechnology. Genomics is both generating new tools and techniques and producing huge amounts of biological data for scientists to analyse. As a result of genomics, genes for desirable traits can be rapidly identified and used to create new biotechnology products.

It should be stressed that genomics does not necessarily involve genetic modification or synthetic biology. Rather, genomics technologies can be applied to animal and plant breeding to greatly improve the efficiency of selection of traits. In the case of trees, this is especially important given the long timescales needed for growth and trait expression. Genomics can address several challenges facing sustainable agriculture. For example, the combination of drought/heat tolerant traits with the ability of a plant to make its own fertilisers addresses several vitally important challenges, including water security, food security, resource depletion and climate change.

Box 5.3. Bio-fortification: Creating *Golden Rice*

Bio-fortification – the creation of plants that make or accumulate micronutrients – aims to increase the nutritional quality of staple crops through breeding and is used for the production of functional foods. The breeding can either be through conventional or traditional ways or through genetic engineering methods. Crops produced through bio-fortification tend to be rich in nutrients such as iron, zinc, and Vitamin A. Bio-fortification differs from ordinary fortification because it focuses on making plant foods more nutritious as the plants are growing, rather than having nutrients added to the foods when they are being processed. *Golden Rice* is a good example of a bio-fortified crop. In this specific case, bio-fortification was obtained by genetic modification of the rice plant to produce and accumulate pro-vitamin A in the grain, a trait not found in nature. Initially developed in Switzerland and Germany in the late 1990s, *Golden Rice* has now spread to other places – although its critics point out that dealing with Vitamin A deficiencies may not best be achieved through the engineering of a rice cultivar (Scoones, 2002).

Source: Hall and Dorai (2010), "What have been the farm-level economic impacts of the global cultivation of GM crops? Systematic review", www.environmentalevidence.org/wp-content/uploads/2014/07/CEE11-002.pdf.

Genetic engineering in agriculture is in its infancy

Genetically engineered commodities have been classified into one of three generations. Input-oriented traits, such as pest resistance and herbicide tolerance to improve yields and/or reduce costs of production, represent the first generation. The second-generation focuses on value-enhanced or output-oriented traits, such as nutritional features and processing characteristics (e.g. extra vitamins that might make the food more attractive to consumers; nutrient-enhanced seeds for feed). Third-generation crops

include traits that produce pharmaceuticals, improve the processing of bio-based fuels, or produce products beyond food and fibre (Fernandez-Cornejo, et al., 2014). Today, commercially available transgenic crops are only of the first-generation type, although all three generations are in various stages of research and development.

In the case of plants, agricultural biotechnology encompasses a range of modern plant breeding techniques. The best known technique is genetic modification, although the term also covers such techniques as Marker Assisted Breeding, which increases the effectiveness of conventional breeding without involving the transformation of isolated genetic material into the genomes of plants. The main goals of biotechnology include: i) agronomic traits to improve yields and provide resistance to stress, such as heat, cold, drought or salinity; ii) herbicide tolerance, to allow plants to resist the effects of specific herbicides; iii) pest resistance to improve the ability of the plant to resist harmful insects, viruses, bacteria, fungi or nematodes; and iv) product quality characteristics, such as modified colour, or flavour, modified starch or oil composition to improve nutritional value or processing characteristics, and the production of medical and industrial compounds.

For livestock, biotechnology has three main applications: breeding, propagation and health. Diagnostics can be used to identify serious inherited diseases, so as to remove afflicted animals from the breeding population. The largest commercial application of biotechnology in animal breeding is the use of Marker Assisted Selection (MAS) to improve the accuracy and speed of conventional breeding programmes, by employing biological markers to identify certain traits. MAS is widely used in both OECD and non-OECD countries.

However, whether the traits selected through biotechnology are in support of a green growth agenda depends very much on the goals of crop improvement efforts. While breeding approaches to develop drought-tolerant, pest-resistant varieties could have a benign effect on green growth, the same techniques could be used to address traits, such as responsiveness to chemical fertilisers, which are not intrinsically sustainable.

Adoption of first generation biotech crops has been rapid, but narrowly based

The use of biotech (transgenic) crops has increased steadily since the first commercial plantings in North America in 1996. Over the 1996-2014 period, the global area planted with biotech crops increased by more than 100-fold – from 1.7 million hectares in 1996 to 181.5 million hectares. This represents just over 12% of the world's arable land, and is largely constituted of soybeans, maize, cotton and oilseed rape (canola) (James, 2015).

A significant development in 2014 was the over fivefold increase in the adoption of the first biotech drought-tolerant maize (which uses less water per hectare) planted in the United States in 2013 (from 50 000 ha in 2013 to 275 000 ha in 2014).

Although 28 countries worldwide are growing biotech crops, adoption has been uneven across countries and commercialisation has involved only a few crops and traits. Five countries (United States, Brazil, Argentina, Canada and India) accounted for almost 90% of the global area planted in biotech crops in 2014, and two crops (soybeans and maize) and two traits (insect resistance and herbicide tolerance) accounted for more than 70% of the global area planted in biotech crops (Figure A5.1, Table A5.1).

Worldwide, for nearly half of the biotech crop area herbicide tolerance is the dominant trait introduced, followed by insect resistance. Stacked traits is an important and growing feature of biotech crops (28% of the global 181 million hectares), with 13 countries having planted biotech crops with two or more traits in 2014. Herbicide tolerance soybean is the most dominant transgenic crop grown commercially (48% of the global area devoted to biotech crop total, mainly in Brazil, the United States and Argentina), followed by Bt maize (33% – mainly in the United States) and Bt cotton (14% – mainly in India, the China, the United States and Pakistan) and herbicide tolerance canola (mainly in Canada and the United States (James, 2015).

Box 5.4. Biotech crops in the United States

Biotech seed suppliers and technology providers

The number of field releases for the testing of biotech varieties approved by USDA's Animal and Plant Health Inspection Service (APHIS), which is an important indicator of R&D activities in agricultural biotechnology, grew from 4 in 1985 to 1 194 in 2002 and averaged around 800 per year thereafter. Also, releases of biotech varieties with agronomic properties (like drought resistance) jumped from 1 043 in 2005 to 5 190 in 2013. As of September 2013, about 7 800 releases were approved for biotech maize, more than 2 200 for biotech soybeans, more than 1 100 for biotech cotton and about 900 for biotech potatoes. Releases were approved for biotech varieties with HT (6 772 releases), IR (4 809), product quality such as flavour or nutrition (4 896), agronomic properties like drought resistance (5 190) and virus/fungal resistance (2 616). The institutions with the most authorised field releases include Monsanto (6 782), Pioneer/DuPont (1 405), Syngenta (565) and USDA's Agricultural Research Service (370). As of September 2013, APHIS had received 145 petitions for deregulation (allowing biotech seeds to be sold) and had approved 96 petitions: 30 for maize; 15 for cotton; 11 for tomatoes; 12 for soybeans; 8 for rapeseed/canola; 5 for potatoes; 3 for sugar beets; 2 each for papaya, rice, and squash; and 1 each for alfalfa, plum, rose, tobacco, flax, and chicory.

Farmers

Three crops (maize, cotton and soybeans) make up the bulk of the area planted to biotech crops. In 2013, about 169 million acres of these biotech crops were planted, or about half of total land used to grow crops. In 2013, the area of HT crops planted accounted for 93% of soybean acreages, 85% of maize acreage and 82% of cotton acreage. Farmers planted insect-resistant (Bt) cotton to control pests on 75% of cotton acreage and Bt maize was planted on 76% of maize acreage in 2013.

The adoption of Bt crops increases yields by mitigating yield losses from insects. However, empirical evidence regarding the effect of HT crops on yields is mixed. Generally, stacked seeds (seeds with more than one biotech trait) tend to have higher yields than conventional seeds, or seeds with only one biotech trait. Biotech maize with stacked traits grew from 1% of maize acres in 2000 to 71% in 2013. Stacked seed varieties also accounted for 67% of cotton acres in 2013.

Planting Bt cotton and Bt maize seed is associated with higher net returns when pest pressure is high. The extent to which HT adoption affects net returns is mixed and depends primarily on the extent to which weed control costs are reduced and seed costs are increased. HT soybean adoption is associated with an increase in total household income because HT soybeans require less management and enable farmers to generate income via off-farm activities or by expanding their operations.

Insecticide use has decreased with the adoption of insect-resistant crops. Farmers generally use less insecticide when they plant Bt maize and Bt cotton. Maize insecticide use by both genetically engineered seed adopters and non-adopters has decreased – only 9% of all US maize farmers used insecticides in 2010. Insecticide use on maize farms declined from 0.21 pound per planted acre in 1995 to 0.02 pound in 2010. The establishment of minimum refuge requirements (planting sufficient acres of the non-Bt crop near the Bt crop) has helped delay the evolution of Bt resistance. However, there are some indications that insect resistance is developing to some Bt traits in certain areas.

The adoption of HT crops has enabled farmers to substitute glyphosate for more toxic and persistent herbicides. However, an overreliance on glyphosate and a reduction in the diversity of weed management practices adopted by crop producers have contributed to the evolution of glyphosate resistance in 14 weed species and biotypes in the United States. Although the herbicide glyphosate is more environmentally benign than the herbicides that it replaces, weed resistance may lead to higher management costs, reduced yields and profits, and increased use of less environmentally benign herbicides. Best management practices (BMPs) to control weeds may help delay the evolution of resistance and sustain the efficacy of HT crops. BMPs include applying multiple herbicides with different modes of action, rotating crops, planting weed-free seed, scouting fields routinely, cleaning equipment to reduce the transmission of weeds to other fields, and maintaining field borders.

The price of biotech soybean and maize seeds grew by about 50% in real terms (adjusted for inflation) between 2001 and 2010. The price of genetically engineered cotton seed grew even faster. The yield advantage of Bt maize and Bt cotton over conventional seed has become larger in recent years as new Bt traits have been incorporated and stacked traits have become available. Planting Bt cotton and Bt corn continues to be more profitable, as measured by net returns, than planting conventional seeds.

Source: Fernandez-Cornejo, J., S. Wechsler, M. Livingston and L. Mitchell (2014), *Genetically Engineered Crops in the United States*, USDA, Economic Research Service Economic Research Report Number 162, www.ers.usda.gov/media/1282246/err162.pdf

Data on adoption patterns show: i) adoption rates and speed of herbicide tolerant plants which are higher than for insect resistant plants; ii) herbicide tolerant soybean worldwide being the crop with the highest adoption rate; iii) herbicide tolerant sugar beet in the United States being the crop with the

highest speed of adoption; and iv) biotech maize being the crop where adoption substantially increased with a combination of traits.

The differences in adoption pattern can be explained by the differences in the cultivation problems addressed. For example, the dominance of herbicide-resistant transgenic varieties is linked to the use of the large area where it can be applied. Glyphosate and other broadband herbicides control almost all plants, and can be applied under different agro-climatic conditions and the technology is easy to apply. Moreover, their use can encourage the use of no-till, by removing the need for mechanic weeding (e.g. soybeans and canola).

Public policies also play a key in explaining the narrow geographical development of biotech crop use. Although several OECD countries have granted regulatory approvals to biotech crops for use as food, feed or environmental release since 1996, biotech crops are planted in only nine OECD countries – United States, Canada, Mexico, Australia, Spain, Portugal, Czech Republic, Slovakia and Chile for seeds (Table A5.1). In terms of food or feed approval, the OECD country with the highest number of approved events for biotech crops is Japan, followed by the United States, Canada and Mexico (James, 2015).[67] The information presented in Table A5.1 clearly shows that currently the United States (with 70.1 million hectares and with an average of around 90% adoption across all crops) and Canada are the two OECD countries where biotech crops are of main importance.

In the European Union, only one biotech crops is currently authorised for cultivation – insect-resistant Bt maize (MON810).[8] Commercial planting of this crop is grown on relatively small areas. The Bt maize (MON810) aims to protect the crop against a harmful pest – the European corn borer. In 2014, Bt maize – which aims to protect the crop against a harmful pest (the European corn borer) was cultivated in five EU member states (Spain, Portugal, Czech Republic, Slovakia and Romania), with a total area planted of 143 016 hectares (of which 131 538 hectares planted in Spain). It represents 1.6% of the 9.6 million hectares of maize cultivated in the European Union (or 30% of maize cultivated in Spain). New GM traits, genes and crops that have been tested in field trials, but are not authorised for commercial planting, include crop varieties which provide different nutritional or industrial qualities (such as easier conversion to biofuel), or increased tolerance to environmental stresses such as freezing, drought or salinity.

Box 5.5. EU legislative framework covering GMOs

Authorisation for the import, cultivation and processing of GMOs in the EU requires, *a priori*, authorisation at the EU level, based on a scientific risk safety assessment on health and the environment conducted by the European Food Safety Authority (EFSA). The risk assessment for GMO plants that are used for non-food or non-feed purposes include, *inter alia*, assessments of persistence, invasiveness and selective advantage or disadvantage. While cultivation of GMOs is recognised to be an issue with strong national or local dimensions, EU legislation offered limited possibilities to member states to adopt GMO cultivation on their territory. Member states could only restrict or ban the cultivation of GMOs by adopting safeguard clauses where new serious risks to human health, animal health and the environment have been identified, following cultivation of the GMO. In 2009, 13 member states requested the European Commission to grant more flexibility in this area.

In March 2015, an amendment was adopted which aims at giving EU member states enhanced flexibility by broadening the criteria for refusing to permission to cultivate GMO on their territory. In particular, during the authorisation procedure of a GMO, EU member states may demand that the geographical scope of the authorisation be adjusted to exclude all or part of their territory. In addition, the amendment permits that EU member states to "opt-out" of the EU authorisation (i.e. be able to restrict or prohibit cultivation of GMOs that have been authorised at the EU-level on "compelling grounds" related to, *inter alia*, environmental policy objectives, town and country planning, land use, socio-economic impacts, agricultural policy objectives and public policy). However, the amendment does not allow Member states to ban a GMO on the grounds of risk to health or the environment: this will remain the domain of EU's food safety body, EFSA and of the safeguard clauses.

Source: http://ec.europa.eu/food/plant/gmo/legislation/future_rules_en.htm

In the European Union, there are considerable differences in the attitudes of member states towards the use of biotech crops, including a wide range of views on the impacts of these crops on biodiversity (EC, 2011). A number of EU countries have chosen to adopt the precautionary principle, with nine of them implementing national ban on GM crop cultivation (Austria, France, Germany, Greece, Hungary, Italy, Poland, Luxembourg and Bulgaria). Anyone who wants to release a GM organism or market a GM product has to get formal authorisation before doing so. Applications for approval to market a product (including crop seeds for cultivation, food or feed) are assessed and decided upon at EU level, while applications to release a GM organism for R&D purposes are considered at national level (Box 5.5).

Profitability expectations are mainly based on yields and relative costs

Positive but varied farm-level economic impacts

Like any farm management practice, biotechnology will have economic impacts on farmers' wellbeing. Productivity gains encompass higher returns on all factors of production or lower input requirements per unit of production. This could lead to higher crop yields (due to the presence of fewer insects or pests), lower pesticide and fertiliser applications, less demanding production techniques, higher product quality, better storage and easier processing. These gains should be assessed in comparison with conventionally produced crops, produced under the same production system. Ultimately, higher productivity may result in lower producer and consumer prices.

Enhanced economic return will be one of the primary incentives for farmers to grow a biotech crops. The potential income-related impacts for farmers include changes in the use of inputs; associated costs; output (quantity and quality); and gross income. The overall economic impacts of biotechnology will depend on a wide range of factors including (among others) the impact of the technology on farming practices and yields, consumers' willingness to buy biotech products and regulatory requirements and associated costs. In the longer term, other factors, such as industry concentration on the production and marketing of biotechnology crop technology, may also influence the level and distribution of economic benefits.

Farmers who adopt the new technology, especially those who adopt early, may reap benefits in terms of lower production costs and/or higher output.[9] Other farmers could be placed at a competitive disadvantage depending on how consumer preferences and regulatory regimes evolve. If the attitude of consumers is generally accepting of biotech crops and if regulatory requirements are not too onerous, adopting farmers would gain and non-adopting farmers would lose (this is usually the case with biotech cotton). If consumer opinion is negative, however, non-adopting farmers could turn this into a competitive advantage and command a price premium for non-biotech products.[10] Another consideration to be taken into account is that biotechnology is mainly controlled by a few large companies, which can raise issues of competition.

Biotech-adopter farmers could also directly influence the economic benefits of non-biotech adopter farmers. For example, non-adopters of herbicide tolerant crops might also benefit from an induced effect on cost savings. On the other hand, if there is inadvertent gene flow from biotech adopter to non-biotech adopter fields then such eventuality may create problems for non-biotech adopter farmers willing to sell their products in specific markets (e.g. organic certified markets).

Thus, the net economic impact of biotech on farms can be a complex and dynamic concept that is not easily measured. Although, in the first instance, biotech will only be widely adopted if it provides economic benefits for farmers, a number of economic and institutional factors affect the farm-level profitability of biotech crops in addition to their purely agronomic characteristics.[11]

Overall, the farm-level profitability of biotech crops is likely to be influenced by key variables such as differences in yield, reductions in insecticide or weed management costs, differences in seed prices, and differences in the price received by the farmer between the biotech crop and its conventional

counterpart. Moreover, a combination of underlying factors, such as local socio-economic and cultural factors, are also important drivers.

There is a voluminous and ever increasing body of literature concerning the potential economic effects of biotech crops, which has found positive economic impacts, although the impacts vary between and within countries, across years and between different crop or trait combinations (Annex 5.A). It appears that the more heterogeneous the growing environment, pest pressures, farmer practices and social context, the more variable are any benefits likely to be. Thus, the extent of economic benefit associated with different crop-trait combinations is likely to vary widely.

For example, a study by Klumper and Qaim (2014), which performed a meta-analysis approach – on 147 published biotech crop studies conducted during 1995-2014 worldwide – found that, on average, biotech technology has reduced chemical pesticide use by 37%; increased crop yields by 22%; and increased farmer profits by 68%. One of the key findings of the Hall et al. (2013) study, who performed a *systematic literature review* approach[12], is that planting GM crops as opposed to a non-GM equivalent, resulted in a positive farm-level economic impact.

The methodological difficulties in measuring the impacts of biotech crops should not be underestimated and a degree of caution should be exercised in analysing and utilising the results. For example, several studies only compare farm-level and short-term profitability and results are very sensitive to changes in the price of seeds, agro-chemical inputs and commodity prices. In addition, in several profitability studies, prices for biotech crops and conventional crops are assumed to be the same. Other conceptual limitations, particularly in early studies, include the use of gross rather than net margins (i.e. they do not take into account land and labour costs) and very small data samples, and a bias associated with the self-selection of farmers growing biotech crops (Smale, 2012).

Increased seed costs but lower chemical costs

Generally, studies have found that certain categories of costs are lower following adoption of biotech crops (notably chemical costs), while others are consistently higher (specifically, seed costs). Cost categories that are particularly high for biotech crops when compared to non-biotech crops include seed costs and technology fees (value of biotech technology) (the latter are an entirely additional cost not incurred with conventional crops), while chemical costs are generally lower.

Changes in farm costs have been shown to vary through time, but the results are inconclusive as to why. It appears that the greatest benefits have been recorded by the earliest studies (profits were highest and cost increases were lowest) and that the benefits from cultivating biotech crops have declined since then.

Improved yields for insect tolerant and cost savings for herbicide tolerant biotech crops

Overall, available empirical evidence suggests that farmers who have adopted biotech crops obtained higher yields in many cases because of more cost-effective weed control and reduced losses from insect pests, although there is significant variation by crop, trait, location and year. While yield effects of herbicide-tolerant crops are generally minor as farm level benefits are mainly on the cost side, the yield gains of Bt crops can be significant. The largest yield increases have been observed in Bt cotton, followed by Bt maize. The yield effects in herbicide-tolerant crops are, on average, moderate, as they mainly facilitate simplified crop management, particularly weed control and encourage no till.

Unsurprisingly, the yield gains reported for soybeans are smaller than those for cotton and maize, as biotech soybean varieties are mainly herbicide-resistant and the yield effect there is small. As noted earlier, the primary impact of biotech herbicide-resistant technology has been mainly to provide cost savings and easier weed control rather than improving yields. The studies also show a wide range of yield effects, which can be explained by differences in environmental (e.g. different pest pressures, seasonal variations), economic and surrounding policy conditions between countries. The introduction of an insect-resistant variety results in a larger yield gain in countries where farmers do not use

insecticides to control plant pests (e.g. many developing countries) compared with countries where crop protection is commonly practiced (Bennett et al., 2013).

Positive impacts of employment and labour productivity are mainly evident in non-OECD countries

Insect-resistant and herbicide-tolerant crops can reduce on-farm labour demand as they reduce the number of pesticide applications, increase flexibility and simplify crop management. According to Marra and Piggott (2006), farmers in the United States highly value the simplified weed control offered by herbicide-tolerant crops. The non-pecuniary benefits have been estimated to be about USD 10 to USD 25 per hectare. In countries with a high use of insecticides for pest control, insect-resistant crops not only reduce labour demand, but also provide labour benefits via reduced health costs.

While the effects of labour productivity will be more pronounced in non-OECD countries, such as the China and India, major employment effects are expected in the up- and down-stream sectors of OECD countries. As modern biotechnology is a key technology for the emerging bio-economy, additional employment opportunities can be expected in the bio-economy sector (OECD, 2009).

Potential to maximise environmental benefits and to reduce risks are enhanced through sustainable pest management

Adoption of herbicide-tolerant crops could help improve soil and water quality

Biotechnology can support green growth by improving the environmental performance of primary production and industrial processing and by helping repair degraded soil and water. Examples include: i) the use of bioremediation – using micro-organisms to reduce, eliminate, contain or transform into benign products the contaminants present in soil, sediments, water or air; ii) improved crop varieties that require less tillage (reducing soil erosion and compaction) or fewer pesticides and fertilisers (reducing water pollution); and iii) industrial biotechnology applications to reduce greenhouse gas emissions from chemical production (e.g. biotechnological processes to produce chemicals and plastics) (OECD, 2009).

There may also be other types of beneficial environmental impacts associated with biotech crops. Biotech crops change farming practices and contribute to savings in energy and air emissions or reductions in soil erosion relative to conventional crop equivalents, due to less frequent operations in the field. Herbicide-tolerant crops may lead to environmental benefits by letting farmers use herbicides that do need not to be incorporated with the soil, thereby encouraging a shift to no-till and conservation tillage practices, and reducing associated GHG emissions.[13]

In contrast to crops requiring conventional chemical applications, herbicide-tolerant crops may reduce wind and water sediment damages by allowing for reductions in ploughing. These techniques also facilitate the use of winter cover crops, thereby limiting nutrient leaching (e.g. nitrates). Certain biotech crops in the pipeline could also increase removal of toxic heavy metals from the soil, either by incorporating them in the cells or transforming them into less toxic substances. The scientific evidence concerning these environmental impacts of biotech crops is still emerging.

Due to higher yields, biotechnology crops might reduce pressure on land resources and diminish the need for clearing the land or for land preservation, thereby reducing pressure on natural habitats from agricultural land-use. Drought-tolerant biotech crops have become available (thereby saving water). Salinity-resistance of the soil could contribute towards the continuation of agriculture in regions affected by this phenomenon, which is primarily linked to irrigation.

The development of biotech crops that can be grown in adverse conditions (high salt, drought susceptible conditions, etc.) and utilise water and nutrients more efficiently, reduces the dependency on non-sustainable intensive high input agriculture. This is particularly important where such adverse conditions exist and where water is in short supply.

Several studies have attempted to assess the environmental impacts of first-generation biotech crops, but the complexity of ecological systems presents considerable challenges for experiments to rigorously assess the benefits and risks of these technologies. In aggregate, the conclusion from the literature is that there is no validated evidence to associate these crops with higher risks to the environment compared with conventional varieties of the same crop (EC, 2010). Studies also highlight that the nature and magnitude of impacts can vary spatially, temporally and according to the trait and cultivar modified (FAO, 2003; Wolfenbarger and Phifer, 2000).

Reduction in chemical use will benefit the environment

As noted earlier, energy use is lower under biotech cropping systems compared to the conventional crop equivalents. Reduction in pesticide use associated with the production of biotech crops have been considered to have potential benefits for human health and the environment.[14] In comparison with conventional agricultural practices, cultivation of biotech crops could lead to a reduction in the use of environmentally harmful chemicals to control weeds and pests because certain pesticides are no longer used, the frequency of treatments is reduced, or the area treated is reduced. Studies have also found that, as a result of the rapid adoption of herbicide-tolerant crops, there has been a marked shift away from the more toxic herbicides towards less toxic forms (Brookes and Barfoot, 2013). Moreover, insect-resistant varieties may lead to reduced pest pressure, and this could have positive regional spin-off beneficial effects to non-adopters.

The scientific consensus appears to be that the use of transgenic insect-resistant Bt crops is reducing the volume and frequency of insecticide use on maize, cotton and soybean (see Annex 5A. These results have been especially significant for cotton in Australia, China, Mexico, South Africa and the United States.

The environmental benefits include less contamination of water supplies and less damage to non-target insects. Reduced pesticide use suggests that Bt crops could be beneficial to in-crop biodiversity in comparison with conventional crops that receive regular, broad-spectrum pesticide applications. However, as noted earlier, in some regions where biotech herbicide-tolerant crops have been widely grown, farmers have overly relied on the use of single herbicide, such as glyphosate to manage weeds and this has contributed to the development of weed resistance (Box 5.4).

While, *a priori*, a considerable reduction in the overall quantity of pesticides used could be expected, one survey conducted in the United States finds that an initial reduction in the quantity of herbicide used on a farm in the first three years following the introduction of herbicide-tolerant crops of biotech soybeans, maize and cotton, followed by a subsequent increase (Benbrook, 2012). This resulted from an increase in resistant weed species and a reduction in the price of competing herbicides. However, the amount of insecticide used decreased over the nine-year period of the survey. Changes in pesticide use depend on a number of factors, including rates of use on existing conventional crops, price relativity of pesticide products, value of the crop, climatic conditions in individual years, relative toxicity of pesticide products and build-up of resistant weed species.

Fertiliser use efficiency uncertain

The contribution of first-generation biotechnology crops to improvements in nitrogen-use efficiency (NUE) is indirect via yield-improving traits (pest and/or herbicide resistance) (e.g. reduced damage to the root system of biotechnology-maize resistant to maize rootworm can lead to greater nitrogen uptake). In contrast, the adoption of herbicide-tolerant soybean crops increases the use of glyphosate, which is toxic to the nitrogen-fixing symbiont *Bradyrhizobium japonicum* – important for supplying soybeans with nitrogen. Further, concerns exist about the impacts of biotechnology crops on soil microbes and hence nutrient cycling, but empirical evidence is lacking.

The net effect of biotechnology crops on NUE is still uncertain and needs further investigation. Rosegrant et al. (2014) found that NUE in new crop varieties have strong yield impacts and reduces negative environmental impacts from fertilisation. Studies investigating the effects of biotech crops

consider biotechnology to be neutral in terms of fertiliser use (see, for example, Qaim and Traxler, 2005).

Impacts on biodiversity can vary spatially, temporally and according to the trait and cultivar modified

Innovations are not inherently more sustainable or biodiversity-friendly than conventional practices. The changes associated with biotech crop production practices can have positive or negative effects on biodiversity, and the overall impact can vary according to the precise management practices, environment and landscape context, and may only be noticeable after a number of years (Box 5.6).

As is the case of conventional farming systems, the main impacts of current biotech crops on biodiversity are mostly related to the changes in management practices involved, particularly changes in herbicide or insecticide use, reduced till and zero-till practices, and altered crop-rotation practices. The scale and direction of these impacts depends very much on how farmers manage biotech crops, the regulatory restrictions imposed on biotech crop management, and on how the biotech crop system is compared with conventional crop management practices.

Changes in insecticide use on biotech insect-resistant crops can be associated with benefits for biodiversity if insecticide or fungicide use decreases in frequency and toxicity, particularly if biotech crops are used with Integrated Pest Management (IPM). Changes in management of biotech herbicide-tolerant crops can influence biodiversity through: i) the change in herbicide application and timing; ii) the change in the type(s) of herbicide applied; and iii) associated changes in farming practices, including reduced or no-tillage and alterations in crop rotations or monoculture.

Scientists acknowledge that there is insufficient evidence to predict what the long-term impacts of transgenic herbicide-tolerant crops will be on weed populations and associated in-crop biodiversity. Biotech herbicide-tolerant crops change the types of herbicides used (usually glyphosate combined with a pre-emergence herbicide). The altered herbicide use associated with herbicide-tolerant biotech crops may reduce weed populations, resulting in reduced populations of weed-associated wildlife, such as seed-eating birds. But changes in herbicide use could also be beneficial for biodiversity if the frequency and toxicity of herbicide use are decreased and if weed populations continue to provide habitat and food resources for wildlife.

Biotech herbicide-tolerant crops enable greater flexibility of herbicide use and this can be implemented in a way that either increases in-field biodiversity or that significantly decreases it, depending on the timing and frequency of herbicide applications. Some evidence shows that growing biotech herbicide-tolerant crops in the United States has not resulted in decreasing the quantity of herbicide used on crops, but has produced a large-scale adoption of herbicides with a lower environmental toxicity rating than the previously used treatments, because glyphosate is a relatively quick-acting, readily degradable herbicide.[15] There is concern, however, that greater use of herbicides – even less toxic ones – will further erode habitats for farmland birds and other species.

As mentioned earlier, biotech herbicide-tolerant crops facilitate the greater uptake of reduced tillage or zero-till farming systems, which are beneficial to biodiversity. However, a lack of weed resistance management could result in the proliferation of herbicide-resistance weeds.[16]

Biotech herbicide-tolerant crops systems have led to a greater use of monocultures and the corresponding reduction in crop rotations, with adverse impacts on farmland biodiversity. This has given rise to concerns that the expansion of biotech herbicide-tolerant crops has contributed to a reduction in biodiversity, particularly in Latin America. However, while the expansion of agriculture may have reduced biodiversity, to link this expansion with biotechnology is questionable, as the agricultural expansion may have happened with or without the technology and increased productivity through biotech crops may have reduced the amount of land needed for the same amount of product. For instance, the expansion of soybean production has largely been driven by the increase in demand for protein feeds (Backus et al., 2009). Soybean traders, together with other stakeholders, have organised a

Soybean Moratorium, which has been in place since 2006, under which is undertaken not to "purchase soy from lands that have been deforested in the Amazon biome from this date." (Cargill, 2014)

Box 5.6. Possible impacts of biotech crops on biodiversity: What does the scientific evidence show?

Risks or benefits with a measureable impact on a biodiversity assessment endpoint

- Impacts of changed management of biotech herbicide-tolerant crops
- Biotech Bt crops have few direct impacts on natural biological control
- Biotech Bt maize affects soil processes compared to conventional maize, but to no greater degree than between crop types, tillage and pesticide use systems
- Biotech Bt crops may have some effect on non-target Lepidoptera, but have not been found to have significant effects on bees or other non-target organisms

Risks or benefits that are likely to occur, but have not been associated with a clear negative effect on a biodiversity assessment endpoint

- Impacts of changed management of biotech insect-resistant Bt crops
- Risk management specifications for biotech insect-resistant crops are mandatory, but not for herbicide-tolerant crops
- Gene flow occurs, but it is often difficult to clarify or achieve consensus on the actual harm to biodiversity
- Secondary pest problems occur on biotech Bt crops, but the biodiversity consequences are not clear

GM cropping is associated with indirect land-use change, but the biodiversity implications are disputed

Risks to biodiversity extrapolated from small-scale test results

- There is evidence from small-scale tests of non-target impacts of protease inhibitor genes

Risks demonstrated in experiments but very difficult to prove in the field

- Horizontal gene transfer has been demonstrated in experiments but is very difficult to detect in the field

Source: Underwood, E. (2013), "The kinds of possible impacts of GM crops on biodiversity and current evidence on impacts", Annex to Chapter 6(b) in Underwood, et al. (2013), *Technology options for feeding 10 billion people. Climate change and agriculture; biodiversity and agriculture*..

Other environmental and economic concerns

Despite the rapid adoption of biotech crops by farmers in many countries, controversies about this technology continue. Concerns about economic and environmental impacts of biotech crop are one reason for widespread public suspicion.

Economic concerns

While the production of biotech crops may give rise to certain direct economic return in the form of increased yield, improved quality due to control of pests or reduced input costs, concern has been expressed that any such economic return will be more than offset by a reduction in market value of the produce of biotech crops. In addition, concern has been expressed that the cultivation biotech crops in a region may lead to a reduction in the value and competitiveness of conventional and organic crop produce from that region. The ability of non-biotech crop growers from a biotech crop-growing region to market their produce may also be diminished due to a reduction in the number of market outlets available. In addition, there may be possible implications for the following crops in the rotation. The economic loss is potentially greater for higher value crops such as organic produce and the loss may extend to following crops over a period of time. Such issues relating to economic loss necessitate the

requirement to determine liability, assess the level of loss incurred and establish possible measures to redress such loss.

The possibility that biotech farms could contaminate non-GM farms via unintentional, inadvertent gene flow constitutes a challenge for the coexistence of biotech farming and non-GM agriculture, including in particular organic certified agricultural systems. Organic farmers are not allowed to use seed or plants with any transgenic content. For example, the EU Regulation for organic farming (EC No. 2092/91) forbids the use of living modified organisms (LMOs).

Organic farmers are not allowed to use seed or plants with any transgenic content. In July 2003, the European Commission published guidelines for the development of strategies and best practices to ensure the co-existence of LMO crops with conventional and organic farming, with the intention of helping EU member states to develop workable measures for co-existence in conformity with EU legislation. The guidelines set out the general principles and the technical and procedural aspects to be taken into account: approaches to co-existence should be developed in a transparent way, based on scientific evidence and in co-operation with all concerned; and measures should be specific to different types of crop and regional and local aspects should be fully taken into account.

The way contracts for the use of biotech crops were drafted – with concerns that contracts were too binding for farmers – also raised much controversy. Biotechnology has led to increased concentration on the seeds sector and farmers are becoming increasingly dependent on a limited number of suppliers. In addition, farmers who adopt biotechnology are confronted with several constraints: biotech seeds are often sold with contracts which generally preclude seed-saving by farmers; biotech firms have developed technologies that render biotech crops sterile in order to protect the research-value of biotech seeds and to limit gene flow into the environment; and biotech companies often charge a "technological fee", which has to be taken into consideration with property and patenting rights. The technological fee and the restriction on seed-saving imply increased seed costs, and oblige farmers to comply with the requirements of the biotechnology firms.

Another issue is that the "first generation" of genetically engineered products has focussed on agronomic traits which have not been perceived as delivering significant benefits to consumers compared to conventional varieties. But the modification of agronomic traits is only the beginning of the contribution of genetic engineering in modifying the food chain. The envisioned benefits of output trait biotech crops could bring substantial benefits to consumers in both developed and developing countries. The choice of which innovations will go forward is likely to be determined in part by the private sector's expected profitability estimates and the legal framework, which permits countries to appropriate the return to their research. Intellectual Property Rights or patent rights allow the patent holder to exclude all others from making, using, offering for sale, selling or importing the claimed invention for a limited time period (20 years).

Environmental concerns

Environmental concerns centre around the possible effects – direct or indirect – of biotech crops on non-target organisms and on the transfer of biotechnology traits to populations of wild plants (FAO, 2003). The potential transfer of herbicide-resistant and insect-resistant traits to weedy species and the persistence of feral crop plants carrying these traits raise issues about possible impacts on the environment. Other concerns relate to whether biotech crops will give rise to the development of resistance in pests and diseases, which would then prove difficult to control, using conventional methods. The question has also been raised as to whether biotech plants will be poisonous to non-target species including herbivores, pollinators, soil-inhabiting organisms and biological predators. Finally, it is important to bear in mind that modern plant breeding has the potential to produce biologically novel crops and cropping systems without the use of transgenesis.

Moving forward: Policy priorities to boost the beneficial impacts of modern agricultural biotechnology

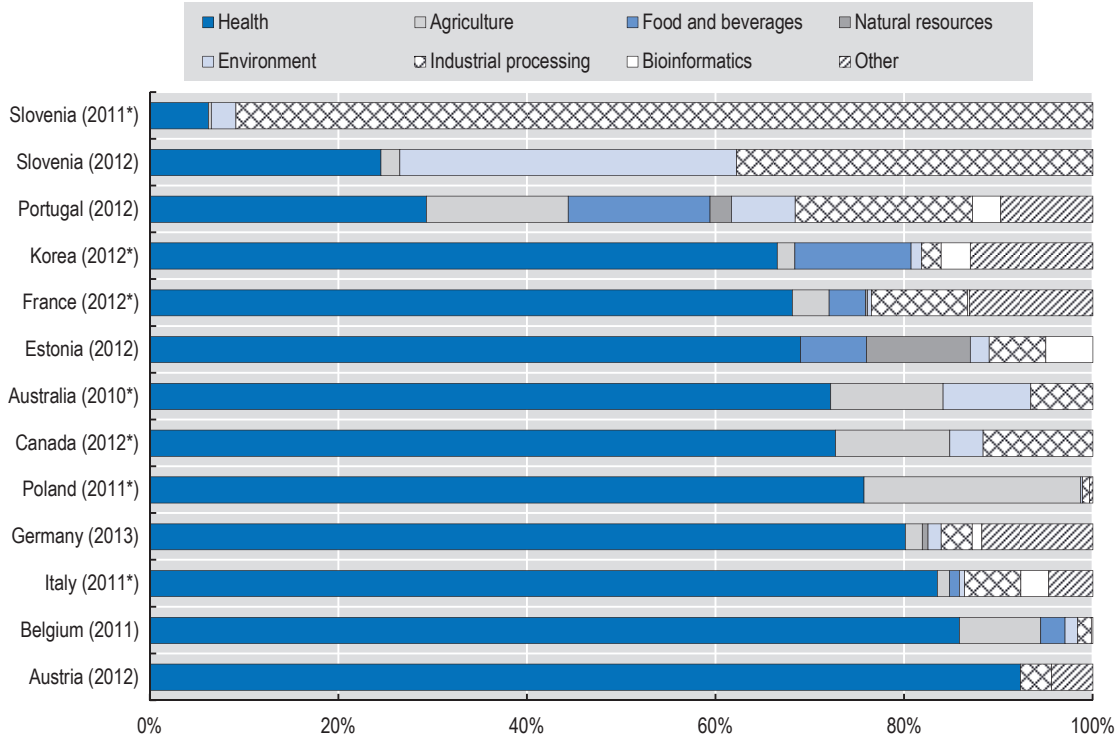
Public R&D investment an important factor in enhancing availability and accessibility of new biotechnologies

If modern agricultural biotechnology is to be perceived and used as one of the solutions for fostering green growth in agriculture, policy will have to play a significant role, in investing in research, establishing the regulatory frameworks necessary to ensure that biotech applications meet acceptable bio-safety and environmental standards and in increasing public awareness of the potential benefits (as well as risks) (OECD, 2009).

Despite growing awareness of the importance of innovation for increasing agricultural productivity sustainably, and even though government funding for R&D is permitted under international trade agreements, public spending on agricultural R&D accounts for only a small share of total support to agriculture – around 2% in the OECD area.

OECD data on business enterprise expenditures on R&D (BERD) for biotechnology provide a direct measure of research effort. According to OECD data, the United States devotes almost 10% of total US BERD to biotechnology and accounts for about 66% of total biotechnology BERD expenditures in the 28 countries for which data are available. On average, biotechnology accounted for 5.9% of total BERD in the countries with data available in 2011. However, the share of BERD on biotechnology for agriculture is rather small for all these countries (Figure 5.1).

Figure 5.1. Percentage of biotechnology R&D by application, latest available year



Notes. Results are limited to dedicated biotechnology firms, except for biotechnology R&D firms for Australia, Estonia, Italy and Slovenia, and biotechnology firms for Korea. Australia: reported results are for agricultural biotechnology; environmental biotechnology; industrial biotechnology and medical biotechnology. Canada: reported results are for agricultural biotechnology; environmental biotechnology; industrial biotechnology and medical biotechnology. France: data, which are provisional, reflect firms' activity related to research, rather than their principal activity. Italy: results are by primary application. Korea: "Agriculture" includes "Natural resources". Poland: results are by primary application. "Industrial processing" includes "Food and beverages". Slovenia: "Industrial biotechnology" instead of "Industrial processing".

Source: OECD, *Key Biotechnology Indicators*, http://oe.cd/kbi, October 2014.

Public-sector investment on R&D has contributed to the basic science underpinning agricultural biotechnology. But in contrast to the green revolution – which was driven by the public sector – most applied research in agricultural biotechnology and almost all commercial development are performed by the private sector. Biotechnologies are controlled mainly by a small group of multinational companies and the cost of obtaining material transfer agreements and licenses could slow public R&D. Establishing and maintaining national agricultural research capacity is therefore a critical determinant factor of the availability and accessibility of new biotechnologies which are suitable to the particular agro-ecological environment.

Modern agricultural biotechnology is cross-sectoral and interdisciplinary. Genetic engineering in crops, for example, cannot proceed without knowledge derived from genomics and is of little practical use in the absence of an effective plant-breeding programme. Agricultural biotechnology should therefore be part of a wider agricultural knowledge and innovation strategy that brings about interactions between multiple stakeholders.

Assuring safety at reasonable cost indispensable for the development of modern agricultural biotechnology over time

All OECD member countries, as well as many non-members, have a system for performing environmental assessments of genetically engineered plants used in the production of foods and feeds. In the majority of countries, these systems have been in place for a number of years. National approaches to biosafety have been enhanced by successful multilateral activities aimed at developing a common approach to both the principles and practice of risk/safety assessment. Much of this common understanding was developed through work at the OECD, where biosafety projects, addressing, *inter alia*, transgenic crops, have been in place since approximately.

The main objectives of the OECD work on biosafety, which dates back to 1986, are to: promote harmonisation in the sharing of information and risk assessment practices; assist countries in ensuring a high standard of safety; aid in the mutual understanding of the regulatory systems among countries; and avoid non-tariff barriers to trade. There are two aspects to the OECD's work on biosafety. First, the OECD's Working Group on the Harmonisation of Regulatory Oversight in Biotechnology primarily addresses the environmental risk/safety assessment of transgenic organisms. Second, the Task Force for the Safety of Novel Foods and Feeds specialises mainly in the safety assessment of foods and feed derived from transgenic organisms.

The main outputs related to environmental risk/safety assessment include the series of 'biosafety consensus documents' which compile information regarded as relevant by countries to risk and safety assessment (e.g. the use of the crop or trait in agricultural practice; its taxonomy; characteristics of its reproductive system; knowledge of its wild relatives including those with which it can hybridise; its centre of origin and diversity; and its weediness).

A separate but complementary series of documents has also been published, which address the safety assessment of novel foods and feeds, especially those derived from transgenic varieties. Once again, they are intended for use in regulatory safety assessment.

It is important to note another significant multilateral effort, the Cartagena Protocol on Biosafety, which is a key international instrument dealing with "living modified organisms" (LMOs) in transboundary movements. The objective of this Protocol is to contribute to ensuring an adequate level of protection in the field of the safe transfer, handling and use of LMOs resulting from modern biotechnology that may have adverse effects on the conservation and sustainable use of biological diversity. The Protocol has established an advance informed agreement (AIA) procedure to ensure that countries are provided with the information necessary to make informed decisions before agreeing to the import of such organisms into their territory. The Protocol has also established a Biosafety Clearing-House (BCH) to facilitate the exchange of information on, *inter alia,* LMOs used for Foods Feeds or Processing. The BCH also assists countries in the implementation of the Protocol.

Box 5.7. The Gene Technology Act in Australia

The development and use of GMOs in Australia is regulated through an integrated legislative framework which includes the Gene Technology Regulator and a number of other regulatory authorities, with complementary responsibilities and expertise. This arrangement both enhances co-ordinated decision-making and avoids duplication.

The Gene Technology Act 2000 and the Gene Technology Regulator 2001, which administers the Act, in conjunction with corresponding State and Territory legislation, underpin the framework. Implementation of the framework is overseen by the Gene Technology Ministerial Council, which comprises representation from all Australian jurisdictions. Its object is to protect human health and safety, and to protect the environment, by identifying risks posed by, or resulting from, gene technology, and by managing those risks.

Transparency is built into the regulatory system through requirements in the gene technology legislation for the Regulator to: maintain a publicly accessible record of GMO and GM product dealings; provide quarterly and annual reports to the Australian parliament; and conduct extensive consultation with the public and a wide range of experts, agencies and authorities on applications for dealings involving the intentional release of GMOs into the environment.

The inter-governmental Gene Technology Agreement 2001 (GTA) sets out the understanding between Commonwealth, State and Territory Governments regarding the establishment of a nationally consistent regulatory system for gene technology. The GTA requires an independent review of the Act every five years. The first review was completed in 2006. The 2006 review found that the Act and the national regulatory scheme had worked well over the previous five years (2000-05), and that no major changes were required. The review panel recommended a number of changes intended to improve the operation of the Act. In particular, the 2006 review recommended that the Act be reviewed in five years (2011) to ensure that it continues to accommodate emerging trends. The 2011 review was limited to issues within the scope of the object of the Act (i.e. health and safety of people and the environment). The review also considered the findings from the 2006 review.

Source. Office of the Gene Technology Regulator, www.ogtr.gov.au/internet/ogtr/publishing.nsf/Content/home-1; Australian Government, Department of Health, www.health.gov.au/internet/main/publishing.nsf/Content/gene-techact-review

Governments need to listen to public concerns and inform them of the risks

Confidence in the decisions that governments make on behalf of the public is a precondition for public acceptance and adoption of agricultural biotechnology products. A well-defined biosafety regulatory system is a prerequisite for realising the benefits that modern agricultural biotechnology can provide to foster green growth, as weak regulatory systems could fuel public distrust and trigger opposition to modern agricultural biotechnology.

In addition to assessments based on scientific evidence, public perception of risk is also important in ensuring acceptance. There are distinct national and regional differences to acceptability of modern agricultural biotechnology. Continuing concerns about possible food safety and environmental risks have slowed or even stalled commercialisation in many countries. Public attitudes to biotechnology, including consumers' perceptions on the "naturalness" of biotech foods will play an important role in determining how widely genetic engineering techniques will be adopted in food and agriculture (Van Haperen, 2012; Van den Heuvel et al., 2008).

As noted earlier, genetically engineered technologies have been mainly applied to four crops: soybean, cotton, maize and oilseed rape. Genetically engineered sugar beet, alfalfa and potato are additional crops gaining in importance. Innovations are also expected for wheat, barley, rice and many other species (Stein and Rodriguez-Cerezo, 2009). The main application of biotechnology for crops has been for animal feed crops and for crops used in food processing; neither of which produce agricultural products for direct human consumption.

New value-enhanced traits (second generation) are likely to be developed among field crops. However, to succeed these products should not only be able to deliver improved quality, but also good agronomic performance. In contrast with the first generation genetically engineered crops where farmers expected a direct benefit on their use of pesticides and herbicides (in order to minimise their input costs), the adoption rate of the new generation may proceed more slowly. In addition, some of the value enhanced genetically engineered crops might be limited to niche markets (EC, 2001).

One of the stumbling blocks to the commercialisation of biotech crops has been the reluctance of the downstream sector such as millers, brewers, soft drink companies, and fast food chains to use GMOs (Gruère and Sengupta, 2009; Venus et al., 2012). This has recently changed in the United States and Canada for potato (e.g. Johnson, 2014), sugar beet (Dillen et al., 2012), and wheat (e.g. Arnason, 2013). Overall, this adoption difficulty can be traced back to consumer concern about food products derived from biotech crops.

Overall, products based on biotech crops have been successful in those parts of the world where the technology is accepted. Restrictive regulatory systems have arisen, also as a result of negative public perceptions that have little to do with scientific evidence and objective risk assessments (Miller, 2007). Greater consumer acceptance of this technology is a necessary precursor to regulatory reform.

Consumer acceptance of foods with biotech ingredients varies with product characteristics, geography, and the information that the public is exposed to. Most studies in OECD countries find that consumers are willing to pay a premium for foods that do not contain biotech ingredients: willingness-to-pay for non-biotech foods is highest in the European Union, where some retailers have policies limiting the use of biotech ingredients. Non-biotech foods are available in the United States, but there is evidence that such foods represent a small share of retail food markets.

Social factors play a key role in the debate of biotech crops. Some farmers may reject biotech crops for ethical, cultural and other reasons (although available empirical studies about adoption or rejection do not indicate that ethical reasons are an important factor among farmers). One important factor that has been identified for the European Union is the view of neighbours, friends, and local communities. Some farmers who were considering cultivating biotech crops observed their families being threatened (Venus et al., 2012), while others reported social pressure from organic farmers (Binimelis, 2008).

Notes

1. For more information on OECD's work on biotechnology, see the OECD biotechnology at: www.oecd.org/sti/biotech/.
2. For this reason, the OECD recommends that it should always be accompanied by a list-based definition based on seven categories that serves as an interpretative guideline. The categories are: DNA/RNA, Proteins and other molecules, Cell and tissue culture and engineering, Process biotechnology techniques, Gene and RNA vectors, Bioinformatics and Nanobiotechnology. In addition, respondents are usually given write-in option for new biotechnologies that do not fit any of the categories. A firm that reports activity in one or more of the categories is defined as a biotechnology firm.
3. The Convention on Biological Diversity (CBD) defines biotechnology as: “any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use" (Secretariat of the Convention on Biological Diversity, 1992). This definition includes medical and industrial applications as well as many of the tools and techniques that are commonplace in agriculture and food production. The Cartagena Protocol on Biosafety defines “modern biotechnology” more narrowly as the application of: (a) In vitro nucleic acid techniques, including recombinant deoxyribonucleic acid (DNA) and direct injection of nucleic acid into cells or organelles, or (b) Fusion of cells beyond the taxonomic family, that overcome natural physiological reproductive or recombination barriers and that are not techniques used in traditional breeding and selection (Secretariat of the Convention on Biological Diversity, 2000).

4. For example, micro-organisms have been used for decades as living factories for the production of life-saving antibiotics including penicillin, from the fungus *Penicillium*, and streptomycin from the bacterium *Streptomyces*. Modern detergents rely on enzymes produced via biotechnology, hard cheese production largely relies on rennet produced by biotech yeast and human insulin for diabetics is now produced using biotechnology.

5. Different countries have different preferences for terms which describe products of modern biotechnology. This document uses the term "transgenic crops" or "transgenic organisms". For the purposes of this text, the term transgenic organisms is equivalent to the terms "genetically modified organisms" (GMOs), "genetically engineered organisms " or "living modified organisms (LMOs)". For convenience, applications of these terms for crops are referred to as biotech crops.

6. Data on GE events are also available in the OECD Biotrack Product Database, regularly updated on a voluntary basis by national authorities, see www2.oecd.org/biotech/.

7. Among the biotech crop events, the herbicide-tolerant soybean event GTS-40-3-2 has the most number of approvals, followed by the herbicide-tolerant maize event NK603, insect resistance maise MON810 and insect resistant maize Bt11 (James, 2015).

8. The Amflora potato, which was authorised in 2010 for cultivation and industrial processing, is no longer cultivated since 2011.

9. Early adopters of any agricultural technology tend to benefit more than later adopters because they achieve a cost advantage over other farmers, earning a premium for their innovation. As more farmers adopt the technology, the cost reduction eventually translates into a price decline for the product that means, while consumers continue to benefit, the gains to farmers decline.

10. This is the case of certain animal products labelled as free from GM in Europe, and a large number of GM free products from the United States. However, multiple countries produce GM and non-GM so there is an economic benefit trade-off. Some large farms in North America do both, depending on price expectations.

11. Smallholder farmers, for example, may be entrepreneurial in spirit but they often lack the security to take risks and in order to create and maintain a favourable environment for entrepreneurship a range of barriers outside the control of the farmer must be addressed, such as poor or absent infrastructure, unsupportive laws and regulations, lack of investment capital, social barriers, lack of training facilities for farmers, support services and extension staff and constrained access to markets (poor communications, marketing facilities, lack of reliable and timely market information) (Kahan, 2012).

12. A systematic review (also systematic literature review or structured literature review) is a literature review focused on a research question that tries to identify, appraise, select and synthesize all high quality research evidence relevant to that question. It is an approach which synthesises and critically appraises the evidence.

13. The two most common herbicides are Roundup Ready, with the effective chemical glyphosate and BASTA, with the effective chemical glufosinate (Wolfenbarger and Phifer, 2000).

14. See for example, Royal Society, 1998; Ervin, et al., 2000; Fernandez-Cornejo and McBride, 2002; Wolfenbarger and Phifer, 2000; Kleter and Kuiper, 2005.

15. However, there is also recent evidence that suggests that glyphosate may actually have a higher environmental toxicity than previously considered and that its environmental risk rating should be revised (FoEE, 2013; Helander et al., 2012).

16. Risk management specifications are mandatory for biotech insect-resistant crops, but not for herbicide-tolerant crops. As a result, rigorous resistance management measures and monitoring have been required for insect-resistant biotech crops (particularly Bt maize and Bt cotton) since the

first approvals. In contrast, the evolution of herbicide-resistant weeds is now posing problems for biotech herbicide-resistant crops in the United States, Argentina, Paraguay and Brazil. The consequences for biodiversity derive from the increased use of herbicides to control resistant weeds that are more toxic and/or more persistent in the environment than glyphosate, such as 2,4-D or dicamba, and/or increases in glyphosate applications (Brookes and Barfoot, 2013).

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Annex 5.A

Types of transgenic traits in commercial cultivation

Currently, there are three main types of traits used in commercial cultivation: herbicide tolerance; insect resistance; and virus resistance. Insect resistant transgenic crops are used as a way of controlling specific pests. Insect resistant crops have been developed by integrating genes derived from various strains of a bacterium Bacillus thuringiensis (Bt), which produces toxins that kill certain insect pests, for example, the European maize borer and the South-western maize borer. Insect resistance genes have been introduced in maize and cotton.

For herbicide-tolerant traits, the insertion of a herbicide tolerance (HT) gene into a plant enables farmers to spray wide-spectrum herbicides on their fields to control weeds without harming the crop. Herbicide-tolerant crops include soybean, maize, rapeseed, cotton, sugar beets and alfalfa. Virus resistance genes have been introduced in tobacco, potatoes, papaya and squash. Transgenic crops, which involve two or more traits (e.g. stacked events), have also been developed. The most common stacked events at present are combinations of HT and insect resistance (e.g. Bt).

In addition to this relatively small number of biotech crops which have been commercialised so far, it is important to note that there is an impressive range of crops and traits in R&D, many of which have already been in field trials. Many of these are likely to be commercialised in the near future. It takes around a decade for a new transgenic crop variety to be developed from the field trial stage to commercialization.[1] New genetically modified traits include improved plant nutrient use, altered crop metabolism for industrial products, abiotic stress tolerance including, freezing-tolerance and salinity-tolerance, disease resistance traits; nitrogen use efficiency, and bioremediation capacity. In particular, crops in the pipeline include soybeans with improved animal nutritional qualities through increase protein and amino acid content; crops with modified oils, fats and starches to improve processing and digestibility, such as high stearate canola, and low phytate or low phytic acid maize. The OECD's Product Database (www2.oecd.org/biotech/) contains information on most transgenic crops which have been approved for commercial use (planting, and/or food and feed use) in OECD countries.

Empirical evidence of the effects of biotech crops

Economic effects

A study by Klumper and Qaim (2014) performed a meta-analysis approach – on 147 published biotech crop studies conducted during 1995-2014 worldwide – in order to evaluate the impacts of biotech crops (soybean, maize or cotton) on yields, pesticide use, and farmer profits. The study found that, on average, GM technology has reduced chemical pesticide use by 37%; increased crop yields by 22%; and increased farmer profits by 68%. Impacts vary, especially by modified crop trait and geographic region. Yield gains and pesticide reductions are larger for insect resistant crops than for herbicide-tolerant crops. Yield and farmer profit gains are higher in developing countries than in developed countries.

Hall et al. (2013) performed *a systematic literature review approach* to review and analyse the available literature published between 2006-10 on the costs and profits of genetically modified (GM) crops in agriculture in comparison with conventional agriculture. One of the key findings from the

1. Actual commercialisation depends on the time for and outcome of the biosafety regulatory approval.

review is that, in every case, planting GM crops as opposed to a non-GM equivalent, resulted in a farm-level economic impact. This was particularly notable for certain economic variables, namely gross profit and seed costs, but less significant for other economic variables such as price and energy costs. In some cases the economic impact was positive for farmers and in other cases it was negative. Generally, the change in gross profit, revenue and net profit was positive, while the change in seed costs, labour costs and total variable costs was negative. As price was generally not differentiated, the profit and revenue increases are probably largely due to increased yield (decreased losses). Economic impact was shown to vary by crop/trait combination, indicating that treating "GM crops" as one homogenous technology is an unhelpful approach, and that the impact of each crop/trait combination should be examined individually. Economic impact was also shown to vary by development status of the country, suggesting that the baseline state of agricultural production at the time of commercialisation is a key factor influencing economic impact. The change in farm level profit was least positive in the most developed countries, where net profits were 66% higher for GM crops, while seed costs were 97% and total variable costs 23% higher for GM crops.

Qaim (2009) found that on average (when reviewing 19 studies) the gross margin gains were higher for Bt cotton than Bt maize, suggesting that farm-level economic impacts from cultivating GM cotton were likely to be more positive for farmers than cultivating GM maize. Important productivity gains are also reported by Brookes and Barfoot (2013), while Barrows, Sexton and Zilberman (2015) estimate the land use savings of GM cotton, maize and soybean at about 13 million hectares over the period 2000-10.

Carpenter (2010), when reviewing 49 previous studies, found evidence of a negative economic impact, resulting from cultivation of GM cotton in a range of countries, including Australia, China, Colombia, India and South Africa. Similarly, Wang et al. (2008) found that those farmers who had planted Bt cotton in certain Chinese villages made less money than the farmers who planted conventional cotton.

The collective study of INRA/CNRS experts (Beckert, et al. 2011), reaches a more cautious conclusion, pointing out that although yields of GMO herbicide resistant crops could be increased in the early years of adoption, they could be decreased after five years. This is partly due to the emergence of resistance as farmers are obliged to use more toxic herbicides and pay higher prices for seeds than for conventional seeds. For Bt crops, the yield does not increase. The Union of Concerned Scientists (2009) study concludes that the overall impact of genetically engineered crops on yields is modest, with no yield increase for herbicide-tolerant soybeans (the most widely planted biotech crop).

Review studies of farm-level impacts have noted considerable variation in both the nature and scale of impact. For example, the scale of increase in gross margins from cultivating Bt and Ht crops has been found to vary enormously between countries, from USD 12 per ha in the United States (for maize) to USD 470 per ha in China (for cotton) (Qaim, 2009). Further inter-country variability has been demonstrated for GM cotton, with a 12% increase in profits recorded in Mexico, and a 340% increase in profit recorded in China (Pehu and Ragasa, 2007). Large variability from year to year and region to region has also been noted by some studies. The more heterogeneous the growing environment, pest pressures, farmer practices and social context, the more variable are any benefits likely to be.

The National Center for Food and Agricultural Policy, which estimated the impacts of nine transgenic crops in the EU, found that, collectively, these nine transgenic crops have the potential to increase yields by 8.5 million tonnes per year, increase grower net income by USD 1.6 billion per year and reduce pesticide use by 0.014 million tonnes per year. Transgenic tomatoes would offer the greatest yield and grower income increase, while herbicide-tolerant maize would result in the largest reduction in pesticide use. The largest increase in yields is estimated for transgenic sugarbeet, whereas for glyphosate tolerant maize, wheat and rice yields would remain unchanged (Gianessi, Sankula and Reigner, 2003).

Traxler (2004) found that yields of glyphosate-tolerant soybeans are not significantly different from yields of conventional soybeans in either the United States or Argentina. A study by USDA

(1999a) reports that while glyphosate-tolerant soybeans appear to have low yields, in some US Midwest regions, farmers planting Bt maize produced yields that were 26% higher than conventional, non-modified crops. Brookes et al. (2003) found that the effect of Bt insect-resistant maize yield in Spain varies depending, inter alia, on location, climatic factors, timing of planting and on whether insecticides are used, with a country average yield benefit of 6.3%. In Australia, the yield advantage offered by GM rapeseed over non-GM varieties is estimated to be 12.7% (Foster, 2003), while in Canada it is estimated at 10% (Serecon et al., 2001).

In the United States, it was estimated that through the use of biotechnology-enabled control of maize rootworm, 10 million acres of farmland produced USD 231 million in additional annual revenue from crop yield gains, reduced insecticide use by 5.5 million pounds annually, and eliminated 5.5 million gallons of water annually from the farming process (NCRC, 2010). The report also notes that yield gains from herbicide tolerant and insect resistance maize were higher in places where pest pressure is high and the pest/weed control methods prior to adoption had a relatively low efficiency.

Environmental effects

Knox et al. (2012) carried out *a systematic literature approach* to analyse the available literature published between 2006-10 on the environmental impacts of commercial biotech crops. The database analysis undertaken indicated that adoption of biotech crops caused a significant increase in the ratio of environmental change with biotech crops as compared to conventional farming. However, due to the limitations and diversity of the environmental indicators extracted from the articles, it cannot be ascertained whether this shift represents a beneficial or detrimental environmental change.

Brookes and Barfoot (2013), applying the Environmental Impact Quotient (EIQ) indicator – which includes the impact of pesticides on the environment, farm workers and consumers – to biotech crops, found that biotech traits have contributed to a significant reduction in the environmental impacts associated with insecticide and herbicide use on the areas devoted to biotech crops: the use of pesticides on the biotech crop area was reduced, on average, by 8.9% and the EIQ by 18.3% over the 1996-2011 period. In absolute terms, the largest decline in pesticide use was associated with biotech herbicide-tolerant maize, followed by biotech-insect resistant cotton, while the largest environmental impact has been associated with the adoption of biotech insect resistant maize, followed by biotech insect resistant cotton and biotech herbicide-tolerant canola. Overall, the environmental impacts associated with herbicide use were larger than the decline in their absolute volumes, suggesting a switch to more environmentally benign herbicides from those generally used on conventional crops. Applying the EIQ to herbicide-tolerant soybean varieties indicates an overall positive environmental impact compared with non-herbicide tolerant soybean varieties. The study also estimated that biotech crops have led to reduction in GHG emissions of 14.6 million tonnes of carbon dioxide over the 1996-2011 period, arising from reduced tractor fuel use and additional soil carbon sequestration.

Kleter et al. (2007) calculated that for pesticide applications on conventional versus biotech rapeseeds in the United States, applications of pesticide active ingredients, total ecological impact per hectare, ecological impact, and farmer impact were 30, 42, 39, and 54% lower, respectively.

Gusta et al. (2011) and Smyth et al. (2011a, 2011b) show that the adoption of herbicide-torelant canola has changed weed control practices in Canada, where shifts from soil-incorporated- to foliar-applied post-emergent herbicides have taken place. As a result, the environmental impact of canola production – based on a modified EIQ – dropped by 59% between 1995 and 2006.

Studies published so far on the effects of transgenic plants on agricultural biodiversity indicate that there is a lack of consensus of the consequences of gene flow and conclude that more data and new models are needed to analyse the possible long-term unexpected effects of transgenes (Ervin and Welsh, 2005).

The US National Research Council has concluded that GM crops in the United States have brought environmental benefits but "excessive reliance on a single technology combined with a lack of diverse farming practices could undermine the economic and environmental gains" (NRC, 2010).

Wolfenbarger et al. (2008) conducted a meta-analysis on the effects of Bt crops on functional guilds of non-target arthropods. They could not find uniform negative or positive effects when comparing Bt crops with their non-GM counterparts, treated without any additional insecticides. Some species-specific effects have been identified, but when the non-GM counterpart has been controlled with insecticides, Bt crops exhibited a higher abundance of non-target arthropods. The effect of Bt-maize pollen on non-target Lepidopetera in Europe has been estimated to be extremely low.

Perry et al. (2010) calculated mortality rates in the worst-case scenario of less than one individual per 1 572 (one per 5 000 at the median) for butterflies and less than one individual per 392 (one per 4 366 at the median) for moths. Comparing this with alternative cultivation practices, they conclude that no negative environmental impacts of Cry1Ab expressing Bt corn have so far been reported. Álvarez-Alfageme et al. (2011) point out previous results showing the toxic effect of Cry1Ab and Cry3Bb on ladybirds feeding on maize; these were not replicable.

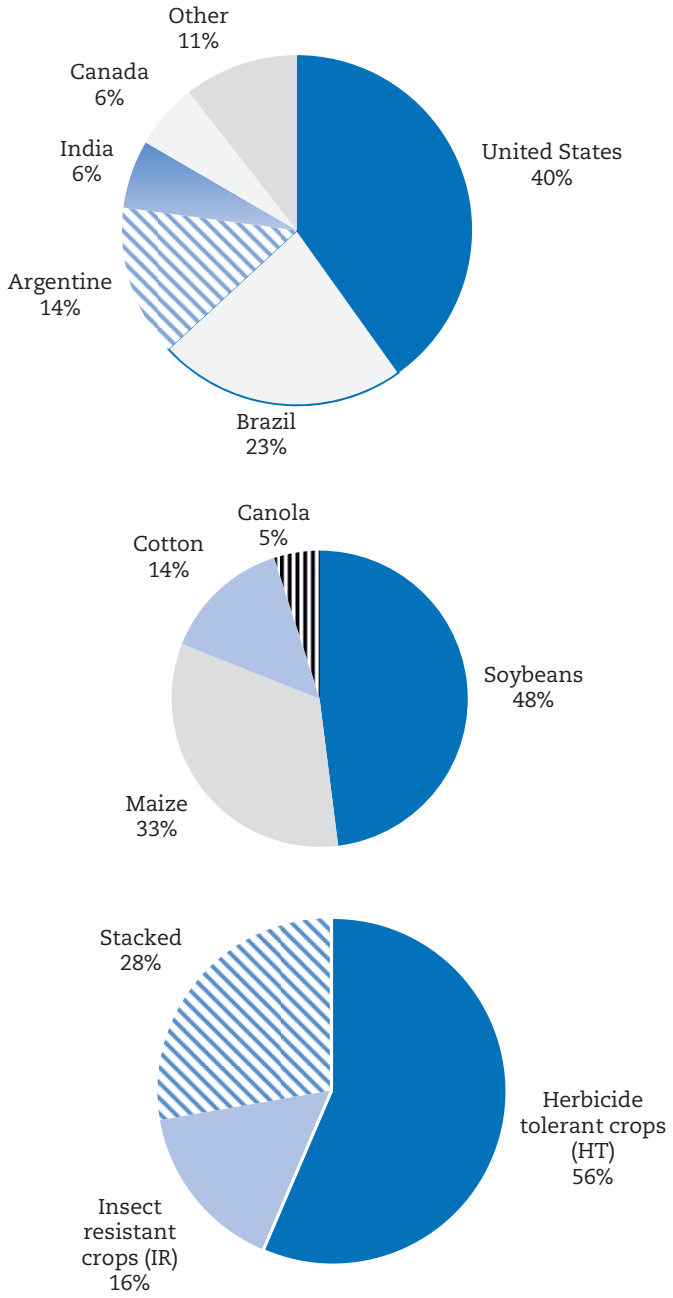
The Farm-Scale Evaluation study initiated by the government of the United Kingdom compared biodiversity in fields of glyphosate-tolerant sugarbeet, maize and rapeseed with that in comparable plots of equivalent non-transgenic varieties in adjoining fields (DEFRA, 2003). The findings showed that there were differences in the abundance of wildlife between genetically modified herbicide-tolerant crop fields and conventional crop fields. However, the study stressed that the differences found arose not because the crops had been genetically modified, but because the GM herbicide-tolerant crops gave farmers new options for weed control. The differences on which herbicides were used and how they were applied.

The Royal Society has published the results of extensive farm-scale evaluations of the impacts of transgenic herbicide-tolerant maize, spring oilseed rape (canola) and sugarbeet on biodiversity in the United Kingdom. These studies found that the main effect of these crops compared with conventional cropping practices was on weed vegetation, with consequent effects on the herbivores, pollinators and other populations that feed on it. These groups were negatively affected in the case of transgenic herbicide-tolerant sugarbeet, positively affected in the case of maize and showed no effects on spring oilseed rape. The studies concluded that commercialisation of these crops would have a range of impacts on farmland biodiversity, depending on the relative efficacy of transgenic and conventional herbicide regimes and the degree of buffering provided by surrounding fields.

In the United Kingdom, a large-farm scale evaluation of four biotech herbicide-tolerant cropping systems concluded that GMO herbicide-tolerant rapeseed and sugar beet (but not biotech herbicide-tolerant maize) reduced the abundance of weeds and associated wildlife compared to the conventional management at that time (Brooks et al., 2003; Brooks et al., 2005; Firbank et al., 2006; Haughton et al., 2003; Hawes et al., 2003; Heard et al., 2003). The negative effect on weeds was considered sufficiently important to conclude that, on balance, the biotech herbicide-tolerant crops would reduce biodiversity (UK ACRE, 2004a; 2004b; 2005). In contrast, research in the United States, Canada and South America has come to the opposite conclusion (i.e. that biotech herbicide-tolerant crops have increased weed diversity) (Gulden et al., 2009; Gulden et al., 2010; Puricelli and Tuesca, 2005; Scursoni et al., 2006; Young et al., 2013). The authors conclude that this is because glyphosate has allowed more broad-leaved weeds to survive and causes greater species richness and evenness than the conventional weed control used in comparable US farming systems.

There is also evidence to suggest that changes in pesticide use rates have been variable (van den Bergh and Holley, 2001). For example, USDA studies found that, in the aggregate, as more farmers adopted transgenic crops, insecticidal treatments have been reduced on maize, whereas the use of glyphosate, such as Roundup ®, on maize and soybeans has increased (USDA, 1999a and 1999b). However, the use of more toxic chemicals has decreased. The situation varies by production method and by region.

Figure A5.1. Global area of biotech crops, by country, crop and trait, 2014 (%)



Source: James (2015), *Global status of commercialized biotech/GM crops: 2014*, ISAA Brief 49-2015.

Table 5A.1. Global area of biotech crops in 2014, by country

Rank	Country	Area	Biotech crops
		(million hectares)	
1	United States	73.1	Maize, soybean, cotton, canola, sugarbeet, alfalfa, papaya, squash
2	Brazil	42.2	Soybean, maize, cotton
3	Argentina	24.3	Soybean, maize, cotton
4	India	11.6	Cotton
5	Canada	11.6	Canola, maize, soybean, sugar beet
6	China	3.9	Cotton, papaya, poplar, tomato, sweet pepper
7	Paraguay	3.9	Soybean, maize, cotton
8	Pakistan	2.9	Cotton
9	South Africa	2.7	Maize, soybean, cotton
10	Uruguay	1.6	Soybean, maize
11	Bolivia	1	Soybean
12	Philippines	0.8	Maize
13	Australia	0.5	Cotton, canola
14	Burkina Faso	0.5	Cotton
15	Myanmar	0.3	Cotton
16	Mexico	0.2	Cotton, soybean
17	Spain	0.1	Maize
18	Colombia	0.1	Cotton, maize
19	Sudan	0.1	Cotton
20	Honduras	<0.05	Maize
21	Chile	<0.05	Maize, soybean, canola
22	Portugal	<0.05	Maize
23	Cuba	<0.05	Maize
24	Czech Republic	<0.05	Maize
25	Romania	<0.05	Maize
26	Slovak Republic	<0.05	Maize
27	Costa Rica	<0.05	Cotton, soybean
28	Bangladesh	<0.05	Brinjal/Eggplant
	Total	**181.5**	

Chapter 6

Is precision agriculture the start of a new revolution?

Precision agriculture is a whole-farm management approach with the objective of optimising returns on inputs, while improving agriculture's environmental footprint. Precision farming is a relatively new management practice which has been made possible by the development of information technology and remote sensing. A wide range of technologies is available, but the most widely adopted precision farming technologies are knowledge-intensive. Information on precision agriculture adoption is based on sporadic and geographically dispersed surveys as countries do not regularly collect data. Although the main focus of precision agriculture has been on arable crop production, precision farming technologies are also applicable to the entire agro-food production system (i.e. animal industries, fisheries, forestry). This chapter examines the concept and use of precision farming in OECD countries, the key impediments to nurturing its green growth potential, and its impact on resource efficiency and productivity.

Key messages

- Data on farmers' use of precision-agriculture technology are sparse as countries do not usually collect such data.
- Adoption of precision-agriculture technologies is limited to only a few countries and sectors (mainly arable crops).
- The most widely adopted precision farming technologies are GPS guidance.
- Significant efficiency and resource productivity gains can be achieved on arable crops, particularly where intra-field variability in yield is high.
- Knowledge and technical gaps, high start-up costs with a risk of insufficient return on investment, and structural and institutional constraints are key obstacles to the adoption of precision agriculture by farmers.
- Precision agriculture has a substantial role to play in fostering green growth in agriculture in OECD countries, but the prevalence of small-size farms in several countries makes widespread adoption problematic.

Applying the right treatment in the right place at the right time

Precision farming is a relatively new management practice which has been made possible by the development of information technology and remote sensing. Precision agriculture entails the application of technologies and agronomic principles to manage the spatial and temporal variability associated with all aspects of agricultural production – both crops and livestock (Box 6.1).

In particular, precision farming, defined as a systems approach to optimise crop yields through systematic gathering and handling of information about the crop and the field, has the potential to contribute to nutrient management by tailoring input use and application more closely to ideal plant growth and management needs.

Understanding of the precision agriculture concept is often limited to variable rate technologies, which enable a site-specific supply of agricultural inputs. But technological possibilities associated with precision farming cover a great range – from automatic data acquisition and documentation over site-specific fertilisation, to optimised fleet management (Auernhammer, 2001). The term encompasses many technologies providing more precise information about the managed resources and at the same time allowing the farmer to respond to in-field variations by allocating inputs, such as fertiliser and irrigation, in a targeted manner, rather than coming out indiscriminate field-level operations, with sub-optimal efficiency.

Crop management and aspects of animal rearing can be optimised, through the use of information collected from sensors mounted on-board agricultural machinery (soil properties, leaf area, animal health), or derived from high-resolution, remotely sensed data (plant physiological status). Over the years, emphasis has changed from simply "farming by soil", through variable-rate technologies, to vehicle guidance systems and will evolve to product quality and environmental management. The definition of precision agriculture is still evolving as technology changes and our understanding of what is achievable grows (McBratney et al., 2005).

Although the main focus of precision agriculture up to date has been on arable crop production, precision farming technologies are also applicable to the entire agro-food production system (i.e. animal industries, fisheries, forestry). The use of precision agriculture techniques on arable land is the most widely used and most advanced amongst farmers. Precision agriculture is most advanced amongst arable farmers – particularly those with large farm sizes – in the main arable-crop growing areas of

Europe, the United States and Australia, who have well developed business models to maximise profitability.

Perhaps the most successful example of precision farming, on arable land is the use of Controlled Traffic Farming (CTF) technology – a whole-farm approach that aims at avoiding unnecessary crop damage and soil compaction by heavy machinery caused by standard methods, thereby reducing costs.[1] In particular, farmers in Australia and the United Kingdom have been able to reduce machinery and input costs up to 75% in some cases, while at the same time increasing crop yields (Tulberg et al., 2007; Bowman, 2008).

Precision-agriculture technologies are applied to a wide range of field and horticultural crops, such as: maize, soybean, potato, wheat, sugar beet, sugarcane, barley, sorghum, cotton, oat, rice, wine grape, citrus, bananas, tea, date palm, tobacco, olive, tomato and kiwifruit (Bramley, 2009). The development and adoption of precision-agriculture technologies and methodologies in viticulture are more recent than has been the case for arable land. Precision-livestock farming focuses on: the automatic monitoring of individual animal, milk and egg production; the early detection of diseases; and monitors animal behaviour, productivity and the physical environment (such as the thermal micro-environment and emissions of gaseous pollutants).

The precision agriculture management approach currently relies almost entirely on the private sector, which offers services, devices and products to the farmers. Public-sector involvement is generally very limited, notwithstanding the growing policy interest in the role of innovations for increasing productivity sustainability. An example of a recent public initiative aimed at the "mainstreaming of precision farming" is the creation of a focus group in the European Union under the European Innovation Partnership on Agricultural Productivity and Sustainability. The initial priorities of the group are to look at data capture and processing, but it is envisaged that the process will be expanded to encompass evidence-based benchmarking of precision-agriculture performance and impact evaluation.

Available data on adoption rates are fragmented and often dated because countries do not regularly collect data on the use of precision agriculture, while manufacturers and precision agriculture dealers rarely revealing their sales data. Evidence on the use of precision agriculture relies mainly on information from sporadic and geographically dispersed surveys; an accurate measurement of the rate of adoption and the various technological practices is thus problematic.

Box 6.1. What is precision agriculture?

Precision agriculture is a broad term. For some, it means using the auto-steer capability in their tractor and for others it means applying site-specific herbicide using a pre-programmed map. Over the years, the emphasis has moved from variable-rate technologies to vehicle guidance systems to yield mapping. The term first came into popular use with the introduction of Global Positioning Systems (GPS) and Global Navigation Satellite Systems (GNSS), and other methods of remote sensing, which allowed farm operators to create precision maps of their fields that provide detailed information on their exact location while in-field. Five main groups of technologies used in precision agriculture can be distinguished:

- Geographical Information Systems (GIS): software to manage spatial data.
- Global Positioning Systems (GPS): which provide the topographic information of the positions used in GIS although for in-field accuracy differential, GPS is needed.
- Sensors to make measurements of soil properties, pests, crop health, etc. in order to vary management operations accordingly. They are either placed on the field and their signal picked up by hand-held devices or devices placed on tractors, or are part of remote sensors, which take aerial or satellite photographs.
- Yield Monitoring: measures the crop yield during harvest, providing a yield map with information on production and variability.
- Variable Rate Technology: this combines a variable-rate control system in order to apply inputs at a precise location. This is the approach used to achieve site-specific application rates of inputs.

Source. Adapted from Zarco-Tejada et al. (2014), *Precision Agriculture: An opportunity for EU farmers – potential support with the Cap 2014-200*, www.europarl.europa.eu/RegData/etudes/note/join/2014/529049/IPOL-AGRI_NT(2014)529049_EN.pdf.

In summary, the results of analysed adoption studies show similar tendencies for selected OECD countries:

- Adoption rates of precision agriculture technologies have not been as rapid as previously envisaged
- Adoption rates of auto guidance systems are higher compared with variable rate technologies
- The percentage of farmers who have adopted data collection (diagnostic) techniques is higher than the percentage of farmers who are actually using this information for site-specific management.

The overall conclusion of the available studies is that farm-level adoption of precision agricultural technologies has been low, uneven – both geographically and temporally – and often lags behind the initial expectation (e.g. Bramley, 2009; Evans et al., 2013; Lamb et al., 2008; Reichardt and Jürgens, 2009; Griffin et al., 2010; Mandel et al., 2011).

Notwithstanding the low adoption rate, the number of farmers using precision agriculture technologies has been growing steadily over the last decade: in Germany, from 2001 to 2006 the proportion of farmers using precision agriculture grew from 7% to 11%, while the rate of un-informed farmers dropped from 46% to 28% (Reichardt et al., 2009); among the grain growers of Australia, it increased from 5% in 2006 to 20% in 2012 (Robertson et al., 2012), and a survey in Ohio (United States) showed that by 2010 39% of all farms and 48% of farmers with gross sales over USD 100 000 had already adopted precision agriculture (Diekmann and Batte, 2010).

In the European Union, uptake remains modest, and is mostly concentrated on the large and more business-oriented farms in the main grain growing areas of the EU (Zarco-Tejada et al., 2014). Use of nitrogen sensors for fertiliser application is very high, probably because it helps farmers to comply with the EU nitrate regulation and also because it receives government support. There is growing interest in GPS guidance, especially in areas with relatively large farms, such as eastern Germany and farmers are also becoming aware of the possibilities of CTF technology on arable land.[2] Adoption of precision

agriculture for fruits and vegetables and viticulture is more recent than for arable farming, with a rapid increase in the adoption of machine vision methods.[3] In high-value fruit and vegetable crops, precision irrigation methods are being developed in order to save water, increase yields and improve quality, while automatic monitoring of individual animals is used for animal growth, milk and egg production and the detection of diseases, as well as for monitoring animal's behaviour and physical environment.

The basic patterns observed so far in the adoption of precision agriculture technologies are likely to continue into the foreseeable future: adoption is likely to expand faster in those places where input use in agriculture is already relatively efficient and in labour-scarce, land-abundant countries (e.g. Australia, the United States, Canada), with rates of adoption accelerating when commodity prices are high and interest rates low: adoption is likely to expand more slowly in land-scarce, but labour- and capital-abundant countries (e.g. Europe) (Swinton and Lowenberg-DeBoer, 2001).

The following paragraphs present examples of the rates of adoption for selected OECD countries (Australia, the United States, United Kingdom and Germany) and an attempt will be made to identify country specific trends in terms of adopted technologies and crops, respectively.

Australia: A leader of GPS guidance technology

A survey by Robertson et al. (2012) finds that 20% of Australian grain growers have implemented precision agriculture technologies to manage variable inputs. Jochinke et al. (2007) surveyed farmers from the Wimmera Conservation Farming Association in 2006 and found that 42% of members had adopted precision agriculture technologies. Detailed results of the survey are listed in Table 6.1. As shown in this table, steering and auto-guidance systems belong to the most important implemented precision agriculture technologies. Jochinke et al. (2007) mention that their results are comparable to the situation in other regions in Australia.

As noted earlier, Australia has led the way in use of GPS guidance (the CTF approach). The use of the Control Traffic Farming (CTF) has been reported to reduce fuel consumption by a further 50% from Zero-Till systems (Tullberg, 2009). Yet, data available from an Australian Bureau of Statistics survey indicates that CTF is now being implemented by only about 25% of farms.[4]

Table 6.1. Precision agriculture tools used by Wimmera Conservation Farming Association members in 2006

Precision agriculture tool		All respondents (%) (N=146)
Steering/guidance		
Auto-steer	2 cm	16
Auto-steer	10 cm	13
Auto-steer	< 100 cm	2
Visual guidance-sub 1 m, including light bars		27
Marker arms		1
Other		
Yield maps		14
Aerial photos		3
Electromagnetic 38 or Gamma radiometric soil surveys		3
Sowing equipment with variable rate technology		2
Auto depth on sowing equipment		<1

Source: Adapted from Jochinke, D.C., B.J. Noonon, N.G. Wachsmann and R.M. Norton (2007), "The adoption of precision agriculture in an Australian broadacre cropping system—Challenges and opportunities", *Field Crops Research*.

There is public sector research in precision agriculture for viticulture, as well as an interest in precision agriculture for sugar, which is being driven by economic and environmental concerns. Tullberg et al. (2007) have described the high adoption rates of this technology in Australian cropping systems.

United States: Increasing adoption of yield monitoring technology

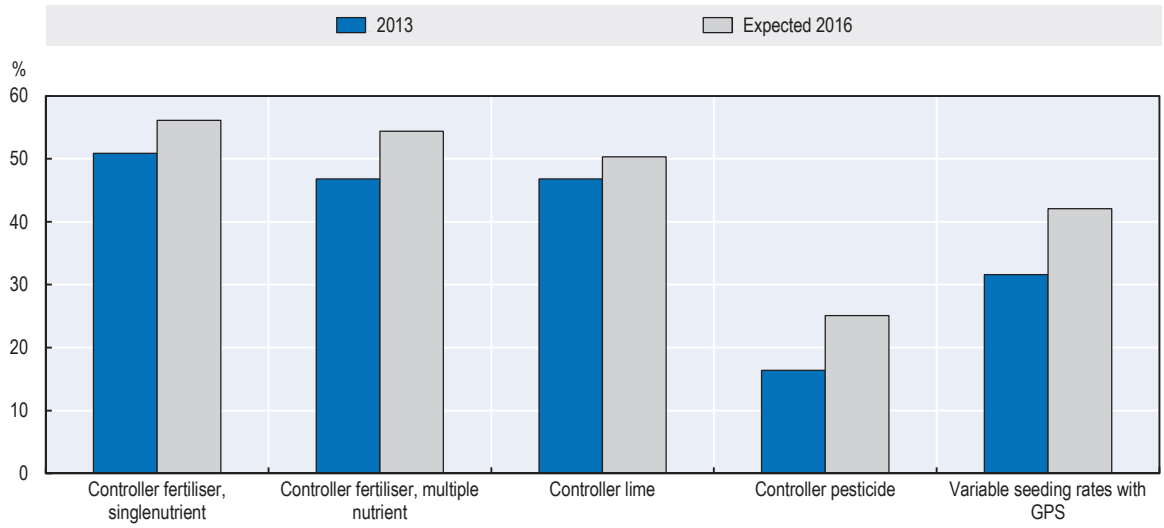
Using Agricultural Resource Management Survey (ARMS) data collected over the past 10 years, an USDA/ERS report found that adoption by farmers of the main precision information technologies – yield monitors, variable-rate applicators and GPS maps – has been mixed (Schimmelpfenning and Ebel, 2011). While yield monitoring – often a first step in the utilisation of precision technology for grain crop producers – has grown most rapidly (being used on over 40% of grain crop area), farmers have mostly chosen not to complement this yield information with the use of detailed GPS maps or variable-rate input applicators that capitalise on the detailed yield information. Farm operator education, technical sophistication and farm management acumen are among the factors cited in the report that could be contributing factor in this adoption lag.

The study reports that yield monitors are being adopted more quickly by farmers who practice conservation tillage. Adoption of guidance systems, which notify farm equipment operators as to their exact field position, is showing a strong upward trend, with 35% of wheat producers using it by 2009. Farmers who adopted of yield monitors achieved higher maize and soybean yields than non-adopters. Even though the adoption of GPS mapping is less prevalent than yield monitors, both maize and soybean farmers achieved higher yields nationwide when GPS was used. Likewise, when variable-rate technology was used to apply fertiliser, higher yields were obtained for both crops. Average fuel expenses, per area planted, for both maize and soybean are lower for farmers who use yield monitors. Variable-rate technology for fertiliser application is associated with lower fuel expenses for both maize and soybeans.

The precision agriculture services dealership survey, conducted biennially, provides an extensive data source on the use of precision agriculture technologies and offers of related services by US dealerships (Holland et al., 2013). Figure 6.1 illustrates that in 2013 more than 50% of surveyed crop input dealers in the US offered variable rate application services for single nutrients. For multi-nutrient applications, dealerships reported slightly lower adoption rates. The projections for 2016, made by survey participants, show expectations of increased demand in areas of variable rate seeding and variable rate pesticide use.

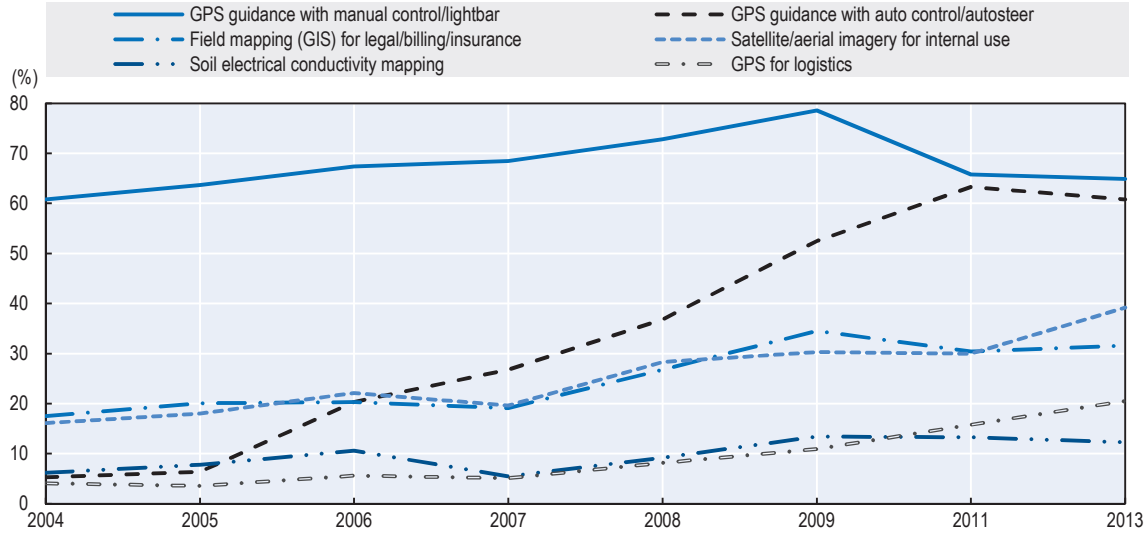
Figure 6.2 shows the adoption of precision technologies by service providers from 2004-13. GPS guidance with auto control (auto-steer) shows the highest positive changes in terms of adoption rates over time. Other technologies, like field-mapping or GPS for logistics, show increasing adoption rates, albeit, on a much lower level compared to GPS guidance with auto control (auto-steer).

Figure 6.1. Variable rate application of precision technology



Note: 171 survey respondents in 34 states.
Source: Adapted from Holland, J.K., B. Erickson and D.A. Widmar (2013), *2013 Precision Agricultural Services Dealership Survey Results*.

Figure 6.2. Adoption of precision agriculture technology over time by service providers



Note. 171 survey respondents in 34 states.
Source: Figure 20 in Holland, J.K., B. Erickson and D.A. Widmar (2013), *2013 Precision Agricultural Services Dealership Survey Results*.

Germany: Increasing adoption by farmers

Reichardt and Jürgens (2009) provide the most current and comprehensive data regarding the adoption of precision agriculture technologies by German farmers. Their study showed that the percentage of precision farmers increased from about 7% in 2001 to more than 10% in 2007. The study found that most farmers who have adopted precision farming technologies are more active in terms of data collection techniques compared to variable rate application techniques.

United Kingdom: Increasing adoption by farmers

In England, GPS technologies, particularly auto-steering and auto-guidance systems, were adopted by 22% of surveyed farms in 2012. Adoption of other precision agriculture applications (soil sampling technologies, variable rate application techniques or yield mapping) increased between 2009 and 2012 (Table 6.2).

The two most common reasons for adopting precision farming techniques were to improve accuracy in farming operations (76% of farms in 2012) and to reduce input costs (63% of farms in 2012). Almost half of the farmers in the 2012 survey who did not use any technique claimed that they were not cost effective and/or the initial setup costs were too high; 28% said they were not suitable or appropriate for the type or size of farm concerned; and a similar 27% said that they were too complicated.

Table 6.2. Proportions of farms using precision farming techniques

Technique	2009	2012
	% of holdings	
GPS (Global Positioning System)*	14	22
Soil mapping	14	20
Variable rate application	13	16
Yield mapping	7	11
Telemetry	1	2

Note. Based on responses from a minimum of 1392 farms in 2009 and 2731 in 2012.

Source: Adapted from Department for Environment, Food and Rural Affairs (DEFRA) (2013), *Farm Practices Survey Autumn 2012- England*, www.gov.uk/government/uploads/system/uploads/attachment_data/file/181719/defra-stats-foodfarm-environ-fps-statsrelease-autumn2012edition-130328.pdf (last accessed 4 February 2014).

Important efficiency and resource productivity gains

Farmers who have already adopted precision agriculture technologies or are planning to adopt it have done so mainly because of the expected higher profitability (Diekmann and Batte, 2010; Reichardt et al., 2009). The use of precision agriculture technologies contributes to enhanced technical and allocative efficiency, incorporating advanced information sources and techniques for more efficient management. Precision agriculture inherently increases resource productivity by using natural resources more efficiently.

As noted earlier, precision agriculture is an information-based, decision-making approach to farm management, designed to improve the agricultural process by precisely managing each step. In this manner, precision agriculture can provide a management approach, optimising both agricultural production and profitability, and reducing the use of inputs (machinery, labour, fertiliser, chemicals, seeds, water, energy, etc.), leading to improvements in productivity, the management and quality of the work, and also environmental benefits.

Precision agriculture aims to use either less inputs to generate similar crop yields, or the same amount of inputs resulting in higher crop yields due to more efficient input use. Typically, precision agriculture is associated with investments allocated to land use. The costs associated with precision agriculture implementation are information costs, expenses involving data processing, software and hardware, and learning costs for the farmer to develop management schemes and calibrate the machinery. On the other hand, fuel and fertiliser expenses might be expected to decline with adoption of precision technologies, as compared with conventional farming. The various technologies contribute to the technical and allocative efficiency in different ways and profitability may vary tremendously.

Controlled Traffic Farming (CTF) and auto-guiding systems are the most successful applications on arable land, showing clear benefits in nearly all cases. For variable rate technology methods, such as optimising fertiliser or pesticide use to areas of need, the success varies greatly according to the specific factors of the application.

Several studies have reported no appreciable economic benefit resulting from the use of variable rate technology for fertiliser application. The economic benefits of the adoption of variable rate application methods varies, depending upon the type of crop, the geographic area, the field size and type of agriculture, whether it is water- or nutrient-limited, and upon the actual inputs used. Experimental studies have led to different economic effects depending on the element considered (i.e. variable-rate nitrogen application, phosphorus and potassium).

A mixed picture can be drawn from experiences with variable rate applications of nitrogen in the United States, Australia and Denmark, as such applications may not necessarily result in lower fertiliser application rates (Box 6.2). A different picture is given with the challenge of a site-specific supply of phosphorus and potassium. From an agronomic point of view, in arable systems, phosphorus and potassium fertiliser can be applied every few years, according to the nutrient status of the soil, and it is often unnecessary to adjust the fertiliser supply to the actual needs of the current crop.

Thus, precision agriculture concepts for phosphorus and potassium are generally more related to the status of the soil. Especially for bigger fields, service providers can offer mapping of soil nutrient status, which can be used as a recommendation for phosphorus and potassium fertiliser application.

A similar situation arises with site-specific application of lime. Soil pH is an important agronomic parameter, which can vary substantially across fields. The soil pH directly influences nutrient availability for plants because nutrients in the soil become soluble only within a certain pH range. An imbalanced pH leads to economic losses and environmental problems. Thus, variable rate application of lime can optimise nutrient availability for all parts of the field. Soil mapping or on-the-go soil pH sensing systems can be used to map the spatial distribution of pH in the field and prescribe the appropriate lime application rates (Bongiovanni and Lowenberg-DeBoer, 2000; Wang et al., 2003).

Precision weed and pest management can contribute to a drastic reduction the application of pesticides and thus contribute to increased efficiency of their use. Automatic guidance systems are well known to increase input efficiency by avoiding application overlaps. The economic advantages are well documented and contribute to the success of precision agriculture technology (Knight et al., 2009).

For example, the investments required for the implementation of automatic guidance systems are generally lower than other precision agriculture technologies, the risk is lower, and the results obtained are more convincing for the farmer. Additionally, automatic guiding systems are easy to use and they do not require agronomic experience, producing benefits, such as profitability, by reducing input costs (seeds, fertiliser, chemicals, fuel and labour) and increasing yields, work simplification and speed, work comfort and ability to extend the working hours on the field.

Nevertheless, precision agriculture technologies are designed for optimal input use rather than increased output per ha. Also, production functions are mostly unaffected by precision agriculture technologies, with the exception of precision irrigation, which generally enables higher crop yields.

Box 6.2. Economic impacts: What does the empirical evidence show?

A review of 234 studies published from 1988 to 2005 showed that precision agriculture was found to be profitable in an average of 68% of cases (Griffin and Lowenberg-DeBoer, 2005). The USDA/ERS report found that in the United States: i) corn and soybean yields were significantly higher for yield monitor adopters than for non-adopters nationally; ii) corn and soybean farmers using yield monitors had lower per-acre fuel expenses; iii) average per-acre fertiliser expenses were slightly higher for corn farmers who adopted yield monitors, but were lower for soybean farmers; iv) average fuel expenses were lower, per acre, for farmers using variable-rate technologies for corn and soybean fertiliser application, as were soybean fuel expenses for guidance systems adopters; v) adopters of GPS mapping and variable-rate fertiliser equipment had higher yields for both corn and soybeans (Schimmelpfenning and Ebel, 2011). Godwin et al. (2003) showed that in 2001 low-cost precision farming technology could be profitable on farms of 80 ha farm size or over, while the breakeven area for integrated systems was 250 ha. As cereal and N fertiliser prices have doubled since then, while the cost of the technology has remained stable, the breakeven area has decreased and the profitability of precision farming on medium-sized farms has improved. This trend is likely to continue. The assumption that uptake is going to increase in the future is also supported by the findings that precision farming adopters are more likely to be younger (Diekmann and Batte, 2010) and to have college or university degrees (Diekmann and Batte, 2010, Reichardt et al., 2009) – the general trend is towards an increasing level of education and younger generations are going to be more familiar with information technology.

Variable rate technologies

Thöle and Ehlert (2010) analysed a mechanical crop biomass sensor ("crop meter"). They found that the use of the sensor could improve N efficiency by 10-15%, reducing N fertiliser applications without impacting crop yield. A German provider for precision farming technologies reported a 5% higher crop yield in winter wheat with the same amount of fertiliser applied and a 5% increase in crop yield, with 12% reduction of fertiliser applied.[1] Dillon and Kusunose (2013) illustrate that, with theoretical considerations for fertilising maize in the United States, a variable rate approach may not necessarily result in lower fertiliser application rates. A similar mixed picture can be drawn from experiences with variable rate applications of nitrogen in Australia, Denmark and elsewhere (Lawes and Robertson, 2011, Biermacher et al., 2009, Boyer et al., 2011; Berentsen et al., 2002, cited in Oleson et al., 2004).

Studies by Anselin et al. (2004) and Meyer-Aurich et al. (2008, 2010) concluded that the economic gross advantage of site-specific management of nitrogen fertiliser in Germany ranges between EUR 10 per ha and EUR 25 per ha, depending on the type of sensor used and size of the field, with improvements on N efficiency by 10-15%, by reducing the application without impact on crop yield. In such cases, the economic assessment concluded that the size of the field needed to be greater than 250 ha to obtain financial benefits. Other studies claim that economic and statistical analyses over a period of ten years showed no statistically significant economic advantage in sensor-based fertiliser application (Boyer et al., 2011). This conclusion is consistent with earlier observations (Liu, Swinton and Miller, 2006; Anselin et al., 2004), who calculated profitability below EUR 8 per ha, which hardly covers the costs of application. Studies in Denmark showed no economic effect from sensor based fertiliser redistribution in the field according to high- and low-yield zones (work by Berentsen, cited in Oleson et al., 2004).

Automatic guidance systems

The economic benefits of guiding systems in the United Kingdom were estimated for a 500 ha farm to be, at least, at EUR 2.2 per ha (Knight et al., 2009), but the benefits grow if other more complex systems are adopted, such as controlled traffic farming (2-5%), which would lead to additional returns of EUR 18-45 per ha for winter wheat cultivation. In Germany, economic benefits due to savings of inputs were assessed at EUR 27 per ha for the case of winter wheat.

1. www.agricon.de/nc/de/produkte-leistungen/sensoren-agronomie/effekte-im-getreide?cid=2743&did=1718&sechash=fb130ca9

The positive effects of precision agriculture on the natural resource base can be further achieved with precision pest management. Another positive effect of precision agriculture can be expected from controlled traffic farming, where less driving is needed, which releases the land allotted to driving tracks for crops in a more resource efficient way, and with less soil compaction from heavy farm machines.

The use of precision agriculture technologies needs to result in higher revenues to cover the costs of the technologies. However, even if precision information is accurate, poorly timing the application of inputs can negatively impact the environment. For example, Morari et al. (2013) have indicated that high quality standards for wheat grains may create incentives to fertilise wheat at very high rates in order to capture economically attractive premiums for high quality wheat.

Precision agriculture technologies could be used to secure this economic potential. Meyer-Aurich et al. (2010) showed incorrect fertiliser decisions can be costly if quality of the output, in addition to yield, is influenced by the application rate. Considering quality enhances the opportunity for site-specific management to be profitable, as the benefits of variable rate technology compared to uniform management increases with the degree of heterogeneity. In this case, it is only with the availability of precision agriculture technologies that it becomes possible to achieve a higher quality.

Positive employment effect in the up- and down-stream sectors, but variable for the on-farm sector

There is limited information available on the effect of precision agriculture on employment or farm labour. However, CropLife's 2013 survey provides indirect trends of precision agriculture on labour off the farm (Holland et al., 2013). It can be supposed that equipment manufacturers, dealers, retailers or input suppliers have a growing demand for employees with a precision agriculture background.

There is anecdotal evidence that precision agriculture technologies require more office time, compared with conventional farming (Möbius, 2012). Meyer-Aurich et al. (2008) provide an economic analysis of precision farming technologies at the farm level and find, depending on farm size and structure, that the implementation of precision agriculture technologies can reduce labour requirements due to the automation potential of variable rate technologies.

This is confirmed by Pedersen et al. (2006), who conclude that autonomous systems are capital-intensive, but less labour-intensive, as they are more flexible than conventional systems and may significantly reduce labour costs and restrictions on the number of daily working hours. Kingwell and Fuchsbichler (2011) showed that under Australian conditions labour input, and therefore cost, could be reduced through CTF compared with conventional farming systems. However, Maheswari et al. (2008) found that labour cost per ha (for vegetable production) may increase significantly with the adoption of precision agriculture compared with conventional farming.

The adoption of precision farming practices has impacts on the management and organisation of the farming system. This includes the implementation of on-farm IT systems and processes. Depending on the approach, this could include services from precision agriculture service suppliers and extension services. Precision agriculture practices, such as guidance systems, may increase the availability of labour, which has an indirect effect on other farming practices. Furthermore, the adoption of precision agriculture technologies may have impact on the farming practices of neighbouring farmers through land or technology leasing (Batte, 2003).

In summary, it can be presumed from the available information that precision agriculture technologies have a positive employment effect in the up- and down-stream sectors, whereas the on-farm effects may be negative due to the automation potential of precision agriculture technology. Nonetheless, it can be expected that precision agriculture technologies will increase on-farm workforce productivity. Give the limited research results in this area, research will need to analyse the employment effects of precision agriculture in more detail.

Improved environmental footprint of agriculture

Although the possible use of precision technologies to manage the environmental side effects of farming and to reduce pollution is appealing, little assessment has been made on the benefits provided to the environment and no quantified figures are available.

Some research has shown that site specific management of inputs such as fertilisers and chemicals that are required by precision agriculture technologies can reduce the environmental footprint of agriculture. For example, by providing an opportunity to reduce physical overlap between machinery passes, precision farming reduces GHG emissions and lowers diffuse water pollution from fertilisers, agro-chemicals and fuel. GPS mapping and guidance systems can reduce the need for over-spraying by precisely defining the borders of previously sprayed areas.

Other examples include nitrate leaching in cropping systems, demonstrating that variable rate application methods were successful in reducing groundwater contamination and that precision agriculture methods may reduce erosion when precise tillage is conducted. A literature review on the environmental effects for whole field or conservation tillage with precision agricultural practices is provided by Bongiovanni and Lowenberg-Deboer (2004).

Impediments to nurturing the green growth potential

Precision agriculture remains in the early stages of adoption and the suite of information technologies are not expected to be adopted universally across and within countries. The high cost and complexity of the technology, farm-operator education and farm management acumen, as well as failure to deliver the expected economic benefits in some instances, are among the main factors which have hindered wider adoption as cited in several studies (Khanna et al., 1999; Griffin et al., 2004; Reichardt and Jürgens, 2009; Robertson et al., 2012; Rutt, 2011). More widespread adoption would largely depend on the extent to which precision agriculture technologies become less expensive, and/or easier to install and maintain.

Farm structural characteristics are critical drivers of adoption

Precision agriculture is effectively a suite of methods, approaches and instrumentation that farmers should examine in detail to decide which is the most suitable for their business. Farm-level factors such as farm size, field size, field geometry, and soil heterogeneity play a prominent role in the adoption of precision agriculture technologies and therefore strongly influence its growth potential. Since one of the goals of variable rate technology is to manage in-field soil heterogeneity, it is clear that a reasonable amount of observable soil heterogeneity is a prerequisite. However, if precision farming technology results in low to moderate changes in input levels at a given location within a field, there is a high probability that improved profits will be very low.[5]

Regarding farm size, economies of scale are an important issue when calculating the economic benefit and discussing the adoption of cost-intensive precision agriculture technologies, as cost/benefit estimations require a minimum farm size in order to depreciate the investment over the entire farm (Kingwell and Fuchsbichler, 2011). In the European Union, studies demonstrate that auto-guidance systems are profitable when they are implemented on fields of 100-300 ha (Frank et al., 2008; Lawes and Robertson, 2011).[6]

Another important aspect for successful adoption is the suitability of the fields for the implementation of precision agriculture methods. Where field size is small, or when the farmer does not own the technology, specialist contractors, sharing of farming methods and co-operative approaches may be suitable ways to introduce precision farming technologies.

Wagner (2009) provided cost estimations for three different technological approaches for site-specific nitrogen fertilisation (Table 6.3). Annual costs of a sensor system decreased from EUR 21.38 per ha, assuming a cropping area of 250 ha, to only EUR 5.35 per ha for a cropping area of 1 000 ha. As a consequence, many reports show that increasing farm size has a positive effect on the probability that precision agriculture technologies are adopted (e.g. Roberts et al., 2004; McBride and Daberkow, 2003).

Table 6.3. Estimated costs for three site-specific fertilisation strategies

	Map	Sensor	Net
Hardware/ software	Terminal with GPS (EUR 4 800), yield monitor for the harvest combine (EUR 8 500), GIS- Software (EUR 1 500)	Yara-N-Sensor® with terminal and installation (EUR 22 350)	Yara-N-Sensor® with terminal and installation (EUR 22 350), yield monitor for the harvest combine (EUR 8 500)
Annual costs*	**EUR 3 010**	**EUR 4 545**	**EUR 6 274**
Additional information	-	-	Electrical conductivitiy measurements (EUR 5, once within 6 years)
Annual costs per ha*	**-**	**-**	**EUR 1.02**
Service provider	Map preparation (EUR 2/ha)	Annual system check (EUR 800)	Data processing, decision rules preparation (EUR 2/ha) annual system check (EUR 800)
Annual costs*	**EUR 2/ha**	**EUR 800 p.a.**	**EUR 2/ha + EUR 800 p.a.**
Cost/ha (area 250 ha)	EUR 14.04	EUR 21.38	EUR 31.31
Cost/ha (area 500 ha)	EUR 8.02	EUR 10.69	EUR 17.17
Cost/ha (area 1000 ha)**	EUR 5.01	EUR 5.35	EUR 10.09

* Calculated according to the annuity method, depreciation time six years for hardware and software, interest rate 6%.
** The second combine necessary for 1 000 ha is not equipped with a yield monitor.

Source: Wagner, P. (2009), "The economic potential of Precision Farming – An interim report with regard to nitrogen fertilization", in E.J. van Henten et al. (2009), *Precision Agriculture '09*.

High level of farmer expertise is required

Precision farming is an agricultural system approach that demands a high level of expertise due to its information-intensive and embodied-knowledge features. The concept of precision farming is primarily based on data collection, data processing and variable rate application of inputs. The challenge in using precision agriculture technology to its fullest potential is in incorporating all the data into a workable plan for an individual field. With the overwhelming amount of data that can be collected from seeding through which harvest, translating this data into useable information may require more time than some farmers are willing to invest.

Low awareness, time requirements to get used to the technology, lack of technical knowledge, incompatibility of machines from different manufacturers, the high cost of the technology and the difficulty in quantifying the benefits of precision farming are among the main barriers mentioned most frequently by farmers in the United States, Europe and Australia (Diekmann and Batte, 2010; Reichardt et al., 2009; Reichardt and Jurgens, 2009).

Farmers using this technology can be overburdened by its complexity. An enabling policy environment can play an important role in facilitating farmers' uptake of precision agriculture by providing support and advice to farmers within the wider agricultural knowledge and innovation system (AKIS) of the country, where multiple stakeholders interact. Acquisition and transfer of precision farming knowledge should be as simple as possible. Several studies of precision farming conducted in the United States, the United Kingdom, Denmark and Germany identified the high costs involved and the time-consuming learning process required as the primary factors behind the slow dissemination of precision-farming knowledge.

For farm information technologies, Fernandez-Cornejo et al. (2001) find that farm operators who study beyond high school have a 15% greater likelihood of adopting precision technologies. Griffin et al. (2004) consider the adoption of precision agriculture to be "human capital intensive". These observations could be related to an element of technology adoption that has been noted in other agricultural settings: learning-by-doing. Aversion to risk has been shown to have a large negative

impact on the adoption of information technologies, contributing more than all other factors combined (Fernandez-Cornejo, et al 2001).

Factors that slow adoption in some regions are related to social capital and the strength of information networks. Kutter et al. (2011) analysed social factors, such as the role of communication and co-operation with regard to the adoption of precision farming technologies. In terms of communication, they studied various information sources and communication channels and their impact on adopting precision agriculture technologies. Additionally, joint investments, agricultural contracting and data out-sourcing were investigated as possible forms of co-operation.

Based on qualitative interviews, Kutter et al. (2011) came to the conclusion that professional literature, field days, and exhibitions played a key role as communication instruments. Furthermore, they concluded that co-operation between contractors, farmers and industry was important to advance the adoption process.

These conclusions are in line with Aubert et al. (2012), who also pointed out the importance to co-ordinate all stakeholders (farmers, input suppliers, equipment manufacturers and dealers) in order to improve adoption of the technology. Such co-ordination could be organised by co-operatives or farmers associations (Aubert et al., 2012). McBride and Daberkow (2003) observed that personalised technical support (e.g. from crop consultants/input suppliers) was extremely important in terms of the probability that precision farming technologies would be adopted at the farm level (see also Bramley and Trengove, 2013).

Aubert et al. (2012) recognised training programmes as important in the adoption process of precision agriculture technologies. Zhang et al. (2002) also found that educational programmes involving various stakeholders (researchers, industry, extension specialists and consultants) were needed to speed up the implementation of precision agriculture technologies. Reichardt et al. (2009) came to similar conclusions, underlining the importance of teaching precision farming at vocational and technical schools in order to improve implementation.

Further relevant social and socio-economic factors discussed in the literature were farmers' education and age (see Adrian et al., 2005; Aubert et al., 2012; Walton et al., 2008). McBride and Daberkow (2003) showed that the probability of precision agriculture adoption declined with age. However, Aubert et al. (2012) found no correlation between the age of farmers and adoption rates.

With regard to education, higher levels of education influence the probability of adoption (Aubert et al., 2012; Reichardt and Jürgens, 2009; McBride and Daberkow, 2003), since the technology is sophisticated and often complicated to use. However, Pannell et al. (2006) argued that participation in technology-relevant training courses may be more important than the level of education, when predicting adoption.

High start-up costs hinder adoption

The relative advantage of precision agriculture technologies compared to conventional agriculture (e.g. uniform input management) is an important factor influencing adoption (Aubert et al., 2012), and, therefore, the growth potential of the technology. The relative advantage can have economic, social, or environmental dimensions (Pannell et al., 2006).

In terms of economic relative advantage, it can be stated that for most variable rate technologies, farm level economics currently shows mixed results, resulting from: high technology and learning costs, the complexity of the technology, missing compatibility of technology components, sub-optimal or missing decision algorithms, and the limiting effect of flat pay-off functions. For instance, according to the method of managing nitrogen fertiliser used, the site-specific, annual technology costs (not including the learning cost) vary between EUR 3 010 and EUR 6 274 (Table 5.3). This is a large capital investment to make, in order to achieve more precisely managed nitrogen fertiliser application.

An early review of 108 studies provided by Lambert and Lowenberg-DeBoer (2000) shows that 63% of the analysed studies reported positive net returns from precision agriculture approaches. However, 11% of the studies showed negative returns, and 26% indicated mixed results (Lambert and Lowenberg-DeBoer, 2000). Although this review is now 14 years old, it still reflects the economic situation of precision agriculture (Table A6.1).

Another important factor influencing the relative advantage and therefore the growth potential of precision agriculture applications is the availability of appropriate decision algorithms. These algorithms make collected site-specific data relevant in terms of site-specific management. Without decision algorithms, farmers are unable to transfer collected site-specific information into site-specific management. There is a complex interaction of agronomic, disease, and soil moisture factors in site-specific management. For example, soil agronomy can impact soil moisture movement and the prevalence of disease on a fine scale within any individual field.

The algorithms mentioned above can be set to meet different criteria. For instance, yield maximisation may not be the goal on all sections of a field. Programs for field operations are being developed to minimize costs on pre-determined sites that are known to be lower yielding within a farmer's fields. McBride and Daberkow (2003) and Reichardt and Jürgens (2009) provided empirical evidence for this argument. They showed that the percentage of farmers who adopted data collection (diagnostic) techniques was much higher than the percentage of farmers who actually used this information for site-specific management. Wagner (2009) highlighted the importance of decision rules for the economics of precision farming. Gandorfer et al. (2011) also stated that the development of decision algorithms with economic objectives was a major determinant for the future of precision agriculture applications.

Finally, Aubert et al. (2012) clearly showed that most of the factors discussed above were very important for the adoption decision. To a large extent, these findings are also confirmed by survey results from Reichardt and Jürgens (2009), presented in Table 6.4.

Overall, the circumstances described above lead to the low adoption levels of many variable rate technologies. In contrast, the more discernible relative economic and social advantage of auto guidance systems or automatic section control of sprayers leads to much higher levels of adoption.

From an environmental point of view, it could be suggested that precision agriculture technologies provide relative advantages if underlying decision algorithms follow or include environmental considerations. However, the relative advantage in environmental terms does not seem to be (at least currently) a main driver for adoption (Reichardt and Jürgens, 2009).

Table 6.4. Reasons why farmers hesitate to implement precision farming (more than one possible answer)

Answers	2001* (N=126)	2003 (N=137)	2005 (N=167)	2006 (N=47)
Machinery is still too expensive	42.1	44.1	62.9	63.8
The techniques of precision farming are very complicated	6.3	5.1	11.4	8.5
The benefit of PF-techniques is not yet proved	11.1	9.6	9	4.4
Waiting until PF is no longer problematic	28.6	20.6	24	25.5
I will use PF but I have no time	15.4	9.6	13.2	6.4
My fields are too small	15.4	18.4	17.4	46.8

Values are expressed in %.
* Surveys were conducted from 2001 to 2005 at the Agritechnica fair and in 2006 at the DLG field days.

Source: Adapted from Reichardt, M. and C. Jürgens (2009), "Adoption and future perspective of precision farming in Germany: Results of several surveys among different agricultural target groups", *Precision Agriculture*.

Notes

1. CTF methods involve confining all field vehicles to the minimal area of permanent traffic lanes with the aid of GNSS technology and decision support systems.
2. The growing interest in Europe in the CTF technology is reflected in the creation of an European association aiming at fostering its development (www.controlledtrafficfarming.com).
3. An example is PA methods in viticulture, where grape quality assessment and yield maps obtained from remote sensing and field instruments avoid mixing grapes of different potential quality during harvest.
4. Data source is the ABS ARMS survey, *Number of agricultural businesses using controlled traffic farming*.
5. This means that even quite large deviations from optimal management decisions of inputs (e.g. nitrogen) may make little absolute difference to the expected payoff. In other words, the payoff function is flat near the optimum, often over quite a wide range (Pannel, 2006).
6. Regarding resource efficiency and individual treatment of land areas, plants or animals, it is important to gain awareness of variation within the field or animal herd. On small farms, simple applications based on, for example, mobile phones and identification tags are often adequate to create awareness about the site or animal specific variation, and these applications can guide the user in decision-making (e.g. Cunha et al. 2010; Delgado et al., 2013; So-In. et al., 2014). Treatments may include manual control when seen necessary if automated solutions are too expensive.

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Annex 6.A

The economic benefits of precision agriculture

Table 6A.1. Economic benefits of precision agriculture technologies

Precision agriculture technology	Crop	Location	Economic effect	Source
Variable Rate Nitrogen	Winter wheat, canola	Germany	Net profit increase of EUR 16/ha for the Yara N-sensor compared to uniform management, net profit loss of EUR 11/ha for a mapping approach compared to uniform management, technology cost not included	Schneider and Wagner (2008)
Variable Rate Nitrogen	Winter wheat	United States (Oklahoma)	Net profit increase (including capital costs for sensing and application) of USD 15 with a variable top-dress sensed nitrogen application system, based on experiments over nine sites and nine years.	Biermacher et al. (2009)
Variable Rate Nitrogen	Wheat	United States (Oklahoma)	No profit increase with variable rate nitrogen application, the uniform 90 kg N/ha top-dress N strategy showed on average highest net returns	Boyer et al. 2011
Variable Rate Nitrogen	Maize	South Africa	Variable rate nitrogen application is slightly more profitable compared to conventional management	Maine et al. 2010

Table 6A.1. Economic benefits of precision agriculture technologies (*continued*)

Variable Rate Nitrogen and Lime	Soybean/corn	United States/Canada	Increase of annual return by up to USD 20/ha	Bongiovanni and Lowenberg-DeBoer (2000)
Variable Rate Nitrogen and Phosphorus	Cereals	Australia	Positive economic potentials in six out of 20 investigated fields with an additional economic payoff of 15 AUD/ha excluding costs for information gathering and variable rate application	Lawes and Robertson (2011)
Variable Rate Pesticide	Winter wheat	Germany	Initial costs for investments for sensor based fungicide spraying technology are around EUR 13 000 and could be covered within approximately 2 years on a 1 000 ha farm with 60% cereal cultivation	Dammer (2005)
Variable Rate Irrigation	Corn	United States (Iowa)	Precision irrigation was economically in one out of 28 analysed cases	DeJonge et al. (2007)
Auto-guidance	Cereals and oilseeds	England	Economic benefits of guiding systems were estimated for a 500 ha farm at least at GBP 2 /ha	Knight et al. (2009)
Auto-guidance	Peanuts	United States (Georgia)	Economic benefits of using auto-steer compared to conventional steering is approximately USD 34/ha	Vellidis et al. (2013)
Automatic section control	Corn/soybean	United States (Kentucky)	Economic advantages of up to USD 36/ha due to input savings	Shockley et al. (2012)
Controlled Traffic Farming	Winter wheat	England	Additional returns of GBP 16-40/ha	Knight et al. (2009)
Controlled Traffic Farming	Various crop rotations	Australia	Approximately 50% profit ncrease (farm level)	Kingwell and Fuchbichler (2011)

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OECD PUBLISHING, 2, rue André-Pascal, 75775 PARIS CEDEX 16
(51 2015 16 1 P) ISBN 978-92-64-23864-0 – 2016

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Farm Management Practices to Foster Green Growth

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ISBN 978-92-64-23864-0
51 2015 16 1 P