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The contribution of precision agriculture technologies to farm productivity and the mitigation of greenhouse gas emissions in the EU

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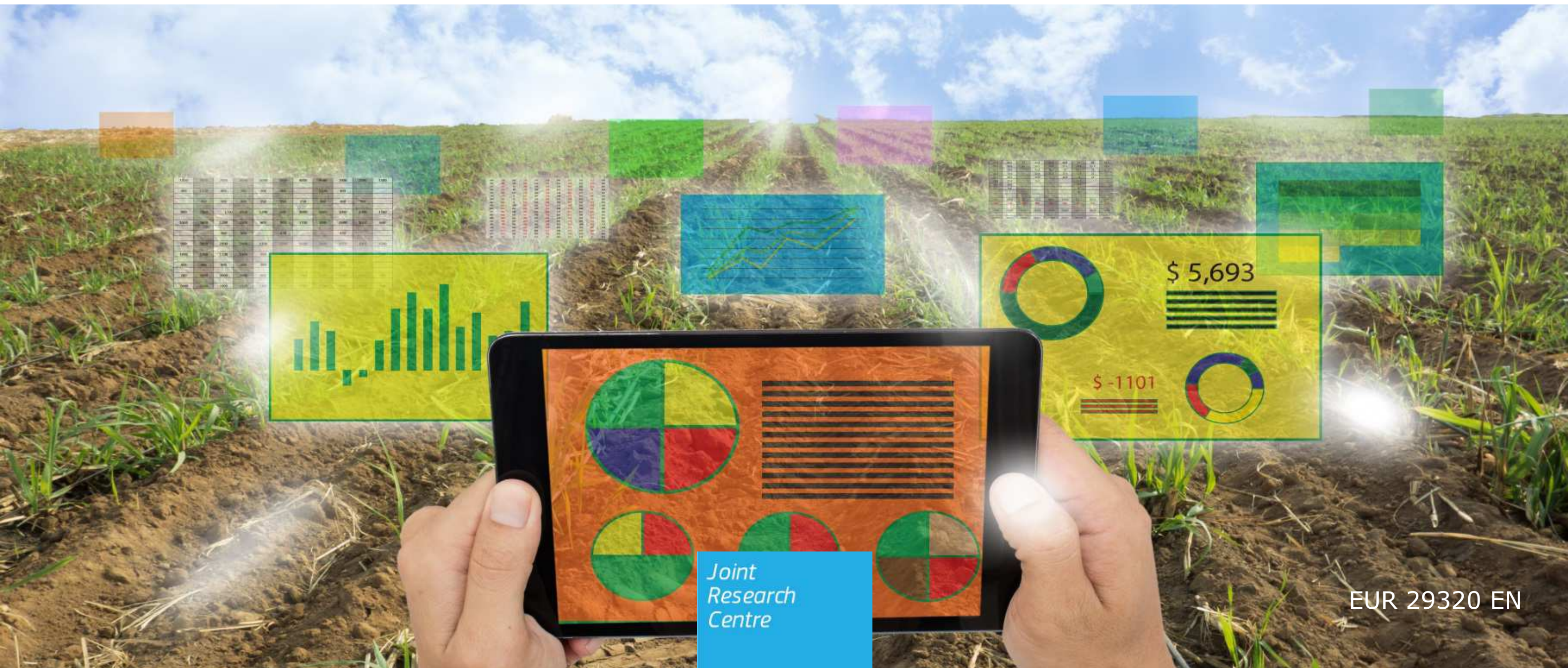

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Abstract

Agriculture in the EU has to cope with global challenges such as climate change mitigation and making farming more efficient. The active management of agricultural practices using appropriate technologies and systems could reduce greenhouse gas (GHG) emissions and increase agricultural productivity and income. However, information on the uptake, use and impacts of precision agriculture technologies (PAT) in the EU is so far sparse and site-specific.

This technical report assesses the impact of PAT on GHG emissions and farm economics. To this end, a typology of PAT was created in order to identify those that had the greatest potential to reduce GHG emissions. Secondly, five case studies were selected with the aim of identifying a range of EU countries, precision agriculture techniques and arable crop types that could realise the maximum potential economic and environmental benefits of adopting PAT. A survey was applied to 971 adopters and non-adopters of machine guidance and/or variable-rate nitrogen application technologies on the selected study cases with the aim of assessing the reasons behind uptake and the economic and environmental impacts of different approaches. Finally, economic and environmental impacts were investigated though a partial budgeting analysis and the Miterra-Europe model respectively.

Results indicate that, although most surveyed farmers were aware of PAT, uptake rates are low. High investment costs, farm size and the farmers' age were identified as barriers to the adoption of PAT. The survey reveals that adoption barriers might be overcome by boosting economic incentives that aim to improve economic performance both directly and indirectly. However, non-monetary incentives, such as technical advice or training, also seem to be of interest to the surveyed farmers. The results of the survey also show that information points, such as peer-to-peer learning, attendance at trade fairs, visits to (and by) researchers and industry dealers, have a positive effect on PAT uptake. The results of the partial budget analysis, where capital costs of the technologies are not included, indicate that impacts are highly variable by country, by farm type and size, and by technology. The results of the environmental impact analysis show that the introduction of PAT might have positive effects on the environment, with reductions in GHG emissions from the reduced application of fertiliser, reduced fertiliser production and reduced use of fuels.

1 The role of precision farming in climate change mitigation

Agriculture in the EU has to cope with global challenges that include climate change mitigation, as well as domestic issues such as making farming more efficient and more productive, improving animal welfare, and revitalising the countryside and its rural communities. During the last years, there has been a trend of reducing greenhouse gas (GHG) emissions in the agricultural sector, but more effort in this direction should be made in order to fulfil global climate commitments. In fact, the agriculture sector is still one of the larger contributors to global GHG emissions both directly and indirectly. Agriculture is liable for climate change, as the sector's activities account for nearly 13.5 % of the total global anthropogenic GHG emissions. The major GHGs produced in the agricultural sector are methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) (Montzka et al., 2011).

Carbon dioxide emissions arise from pre-farm and post-farm energy use and from changes to above- and below-ground carbon stocks induced by land use and land use change. Methane is mainly produced from anaerobic decomposition of organic matter during enteric fermentation and manure management, but also from paddy rice cultivation. Methane has a 25 times higher global warming potential (GWP) for a 100-year timescale than CO_2. Nitrous oxide arises from the microbial transformation of nitrogen (N) in soils and manures (during the application of manure and synthetic fertilisers to land) and from urine and dung deposited by grazing animals. Nitrous oxide has a GWP 298 times that of CO_2 for a 100-year timescale.

Agricultural soils contribute about 37 % of the total EU emissions from agriculture, primarily as a result of the addition of synthetic N fertilisers and animal manure to soil (EEA, 2017). The active management of agricultural soils through appropriate agronomic practices and technologies offers a valuable prospective strategy on the mitigation of climate change. The United Nations Framework Convention on Climate Change (UNFCCC, 2008) recognised the importance of the adoption and dissemination of mitigation practices and technologies on the reduction of GHG emissions from agriculture.

A range of agronomic practices has been proposed to reduce GHG emissions of agricultural soils (e.g. Sanz-Cobena et al., 2017; Snyder et al., 2009). The use of nitrification inhibitors and urease inhibitors reduces nitrification rates by hindering the activity of the enzyme responsible for the first step of nitrification. This practice may lead to reductions in N_2O emissions of between 30 % and 50 % (Huérfano et al., 2015). Substituting synthetic fertilisers with organic fertilisers (i.e. manure) in areas where croplands co-exist with livestock farming enables the use of a farm sub-product, thus decreasing the volume of waste that needs to be managed and avoiding the emission of GHG both in the management of such wastes and in the manufacture of new synthetic fertilisers (Sanz-Cobena et al., 2017). The optimisation of irrigation techniques, reducing the amounts of water applied (e.g. through drip irrigation), can generate 'dry' and 'wet' areas in the soil, lowering the overall soil moisture and favouring nitrification over denitrification, thereby reducing N_2O emissions (Sánchez-Martín et al., 2010).

One potential relevant agronomic practice for climate change mitigation purposes is precision agriculture. **Precision agriculture technologies** (PAT) optimise the use of agricultural inputs (e.g. fertilisers, fuel) by accounting for the spatial and temporal variability of the field. They have the potential to reduce GHG emissions from agricultural activities and maintain or improve productivity.

The scientific literature on the agronomic, socioeconomic and environmental impacts of PAT in the EU is highly dispersed and has significant gaps in empirical evidence, with field studies missing in particular. The main aspects of PAT that have been studied focus on the relevant technologies, environmental effects, economic outcomes, adoption rates and the drivers of adoption and non-adoption. However, most of the literature is focused in the United States. Empirical studies for the EU are less comprehensive and do not cover the whole or the most relevant parts of EU agriculture.

Therefore, the objective of this report is to empirically investigate the impact of those PAT that hold the most promise for mitigating GHG emissions while simultaneously being economically attractive to EU farmers (e.g. by increasing or maintaining productivity and being cost-effective). To do so, a comprehensive review of the existing literature has been carried out to firstly characterise PAT and assess the benefits and drawbacks of their adoption (see Annex 1). Secondly, a literature review was undertaken on the economic and environmental impacts of PAT that have greater potential to reduce GHG emissions while maintaining or increasing farm productivity (see Annex 2). Finally, this research has empirically assessed the farmers' perceived economic, agronomic and environmental impacts of two of the PAT that looked more promising in reducing GHG emissions while maintaining farm productivity — variable-rate nitrogen application technology (VRNT) and machine guidance (MG) — through a survey of EU farmers. Analysing the roles these technologies play in both reducing GHG emissions and increasing farm productivity will guide policymakers to assess the relevance of including precision agriculture as part of future agricultural and climate policy instruments.

2 Policy context

In 2008, the European Commission proposed binding legislation to reduce EU GHG emissions by 20 % by 2020 compared with 1990 levels. This 2020 climate and energy package became law in 2009. The reduction target is separated into an EU-wide target for large-scale facilities in the power and industry sectors (and aviation), which is covered by the European Union Emissions Trading Scheme (EU ETS); and a target for emissions in the non-ETS sectors, such as agriculture, buildings, transport and waste. Non-ETS emission reduction obligations are broken down into different individual targets for Member States depending on their emission levels and relative gross domestic product (GDP) per capita[1]. The non-ETS emissions are regulated by the Effort Sharing Decision (ESD), which sets emission reduction targets compared with 2005 levels[2].

The United Nations Framework Convention on Climate Change (UNFCCC) recognised the agricultural sector for its significant mitigation potential in the global efforts to stabilise GHG concentrations in the atmosphere. Moreover, the commitments and responsibilities agreed by the UNFCCC Kyoto Protocol include the development, dissemination and adoption of mitigation technologies that reduce GHG emissions from agriculture (UNFCCC, 2008). Although there are currently no EU-specific measures that oblige the agricultural sector to reach a mitigation target, environmental and agricultural policy measures have contributed significantly to mitigating agricultural emissions in the EU. For example, the ban on stubble burning maintains soil organic matter; and the EU Nitrates Directive[3] has reduced animal manure spreading and mineral fertiliser use, which in turn has reduced the emissions of N_2O from agriculture, over time. Furthermore, since the 2013 reform of the EU's Common Agricultural Policy (CAP), farmers have had to comply with new environmental requirements — often referred to as greening — to receive the full amount of their subsidies (about 30 % of their direct payments[4]). These requirements include measures with a climate change component, such as maintaining permanent grassland; crop diversification; and maintaining an ecological focus area dedicated to ecologically beneficial elements that include, for example, the option to use catch crops and nitrogen-fixing crops. In addition, the agri-environmental-climate measures[5] of the CAP encourage farmers to adopt, on a voluntary basis, environmentally friendly farming techniques that contribute to climate change mitigation and adaptation and are compatible with the protection and improvement of the environment, the landscape, natural resources, soil and genetic diversity.

The 21st Conference of the Parties (COP21) resulted in the Paris Agreement on climate change, which established a process to reach zero emissions globally (GHG

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[1] Commission Decision of 26 March 2013 on determining Member States' annual emissions allocations for the period from 2013 to 2020 pursuant to Decision No 406/2009/EC of the European Parliament and of the Council (2013/162/EU) (OJ L 90, 28.3.2013, p. 106-110)

[2] Decision No 406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020 (OJ L 140, 5.6.2009, p. 136-148)

[3] Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (OJ L 375, 31.12.1991, p. 1-8)

[4] Regulation (EU) No 1307/2013 of the European Parliament and of the Council of 17 December 2013 establishing rules for direct payments to farmers under support schemes within the framework of the common agricultural policy and repealing Council Regulation (EC) No 637/2008 and Council Regulation (EC) No 73/2009 (OJ L 347, 20.12.2013, p. 608-670)

[5] Regulation (EU) No 1305/2013 of the European Parliament and of the Council of 17 December 2013 on support for rural development by the European Agricultural Fund for Rural Development (EAFRD) and repealing Council Regulation (EC) No 1698/2005

emission neutrality) during the second half of the century. This first-ever universal and legally binding global climate agreement set out the objective of keeping global warming below 2°C and covers the period from 2020 onwards. The Paris Agreement entered into force on 4 November 2016 after 55 countries that contribute at least 55 % of global emissions have ratified it. Before and during the conference, countries submitted their Intended Nationally Determined Contributions (INDCs) for the new global climate agreement. The EU was the first major economy to submit its INDC to the new agreement, in March 2015, and it is already working on its commitment to reduce GHG emissions by at least 40 % by 2030, compared with 1990 levels. All Member States will have to modernise their economies and ensure successful transitions to low-carbon economies by stimulating investment and innovation in new technologies and maintaining EU leadership in markets for related goods and services, such as low-emission vehicles and energy efficiency[6].

The submission of the EU's INDC is based on the EU 2030 Climate and Energy Framework[7], which includes the commitment to reduce GHG emissions from the non-ETS sectors by 30 % by 2030, compared with 2005 levels. Details of the policy framework are still under discussion, but the European Commission's proposal also includes new flexibilities to reach the targets such as

i) the option for eligible Member States to reach national targets by covering some emissions in the non-ETS sectors with EU ETS allowances (i.e. up to 100 million tonnes of CO_2 over the period 2021-2030 for the whole EU); and

ii) the option to access credits from the land use sector to be used for national targets for all Member States, specifically granting higher access to those Member States with larger agricultural emissions (i.e. up to 280 million tonnes of CO_2 over the period 2021-2030).

In addition, the formal compliance check will be organised every 5 years rather than annually to allow the inclusion of land use mitigation and reduce the administrative burden[8].

The proposal to integrate the land use sector into the EU 2030 Climate and Energy Framework sets out a binding commitment for each Member State and sets out the standardised accounting rules to determine compliance and carbon storage from forestry and agriculture. Land use and forestry include the use of soils, trees, shrubs, plants, biomass and timber. Farmers will be supported by the adoption of climate-smart agriculture practices, and foresters and forest-based industries will be supported by promoting the use of wood products that have a longer lifetime and soil organic carbon capacity, while avoiding fire risk. The 'no-debit' commitment for land use establishes that every accounted emission needs to be entirely compensated for by an equivalent emission removal from actions taken in the same sector. The aim of this commitment is to incentivise the adoption of measures that increase soil organic

[6] Communication from the Commission to the European Parliament and the Council, The Road from Paris: assessing the implications of the Paris Agreement and accompanying the proposal for a Council decision on the signing, on behalf of the European Union, of the Paris agreement adopted under the United Nations Framework Convention on Climate Change. COM/2016/0110 final. http://europa.eu/!rH84nx

[7] Conclusions on 2030 Climate and Energy Policy Framework. European Council (23 and 24 October 2014) [SN 79/14]

[8] Proposal for a regulation of the European Parliament and the Council on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 for a resilient Energy Union and to meet commitments under the Paris Agreement and amending Regulation No 525/2013 of the European Parliament and the Council on a mechanism for monitoring and reporting greenhouse gas emissions and other information relevant to climate change. COM/2016/482 final. http://europa.eu/!Gr87bX

carbon sequestration (e.g. emissions derived from deforestation should be compensated for by planting new trees or improving the sustainable management of existing forest, croplands and grasslands). Flexibilities are also included in the proposal to meet the 'no-debit' commitment. For example, when net CO_2 removals are higher than net emissions they can be banked for the next compliance period, and Member States are able to buy and sell net removals between them[9].

The 2030 commitments for the non-ETS sectors to reduce GHG emissions by 30 % will require significant efforts at national scale and, in turn, a robust and comprehensive framework for climate policies, including guidelines on how to achieve emission reductions from the agriculture and LULUCF sectors. In this context, technical and management-based mitigation options, such as precision agriculture, may contribute and facilitate the mitigation of GHG emissions in the agricultural sector (Pérez Domínguez et al., 2016).

There are different EU legislative instruments that could frame and enhance the use of precision farming technologies (STOA, 2016). For example, Regulation (EU) No 1305/2013 of the European Parliament and of the Council of 17 December 2013 on support for rural development by the European Agricultural Fund for Rural Development (EAFRD) provides incentives for agri-environment-climate commitments, motivating farmers to adopt environmentally friendly farming techniques. This instrument also supports investment in physical assets towards farm modernisation and intensification, which could support investment in PAT. The legislation includes services for the delivery of best agronomic practices and integrated pest management, linked to the economic and environmental performance of the agricultural holding; PAT users could benefit from them.

Additionally, the latest Common agricultural policy (CAP) legislative proposal[10] stresses the need to contribute to climate change mitigation and adaptation by increasing the ambition level of environmental and climate actions. Although the implementation details are not specified, the proposal reflects actions aiming at promoting and incentivising farmers to implement agricultural practices beneficial for the climate and the environment.

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[9] European Commission — Fact Sheet: Proposal to integrate the land use sector into the EU 2030 Climate and Energy Framework. Brussels, 20 July 2016. http://europa.eu/!gx39Yq

[10] Proposal for a regulation of the European Parliament and of the Council establishing rules on support for strategic plans to be drawn up by Member States under the common agricultural policy (CAP Strategic Plans) and financed by the European Agricultural Guarantee Fund (EAGF) and by the European Agricultural Fund for Rural Development (EAFRD) and repealing Regulation (EU) No 1305/2013 of the European Parliament and of the Council and Regulation (EU) No 1307/2013 of the European Parliament and of the Council. COM/2018/ 392 final.

3 Methodology

Different methods have been integrated in this study (Figure 1). Firstly, a comprehensive literature review was carried out to characterise the different existing PAT and to understand the economic, social and environmental impacts of the adoption of those PAT (see Annex 1). This literature contains information on around 11 technologies or devices. Based on this literature review and on experts' opinions, the PAT categorised were screened to end up with a set of PAT that have the potential to reduce GHG emissions while maintaining or even increasing crop productivity (see Annex 2).

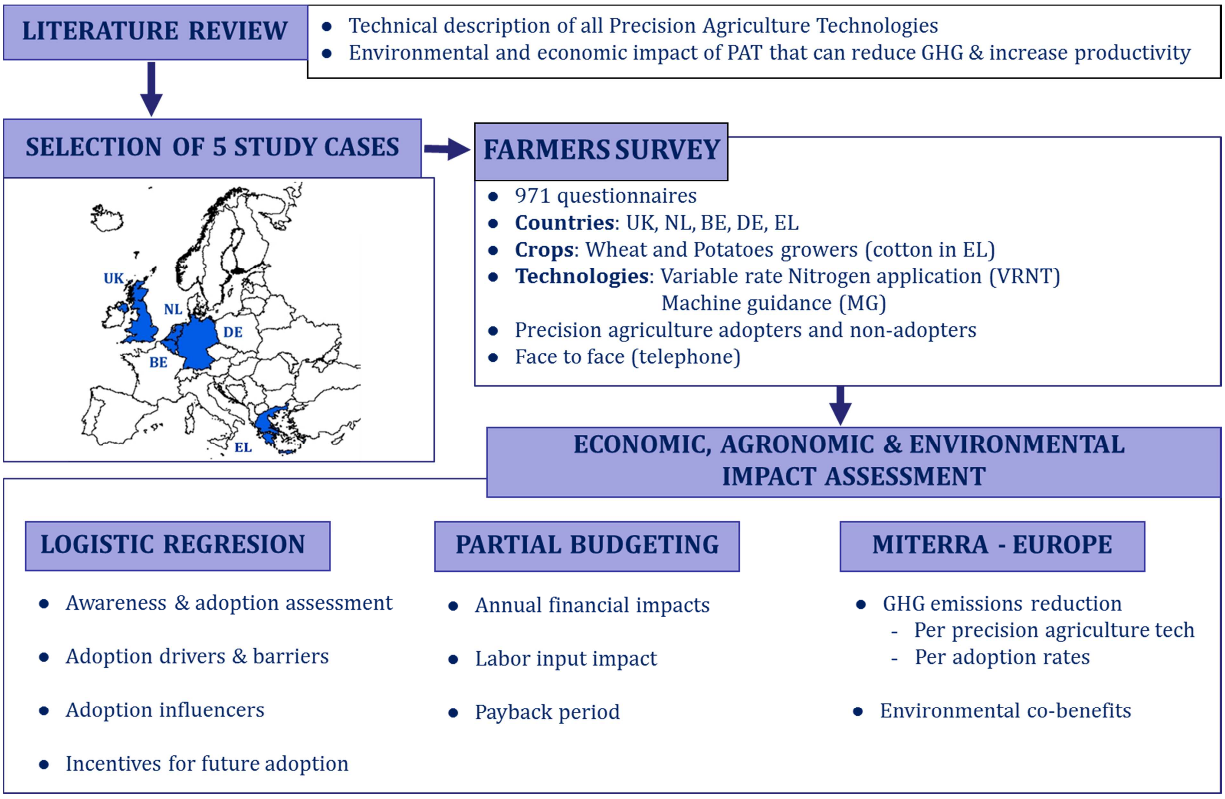


Figure 1: *Methodological framework of the study.*

The literature review was complemented with a survey of EU farmers, implemented in five study cases. Case studies were selected that identified representative combinations of PAT, country and crop. The relevant selection criteria used were:

i) PAT that are available and adopted at present and that have the potential to reduce GHG emissions;

ii) EU countries where the PAT adoption potential is great;

iii) countries with high GHG emissions, particularly of N_2O; and

iv) relevant crops in the EU, focusing on area covered and the crops' economic value (see Annex 3).

A survey of 971 farmers was implemented in the five study sites selected (the United Kingdom, Belgium, the Netherlands, Germany and Greece). The sample was targeted at arable farmers and farm managers who cultivated wheat (the most widely cultivated arable crop in Europe, which covers 24 % of the utilised agricultural area (UAA) of arable land and accounts for 44.8 % of the total cereal production in the EU (Eurostat, 2015)) and/or potatoes (which are a high-value crop, with a high economic output per hectare per year) in the 2015/2016 cropping season. In Greece, cotton farmers were surveyed instead of potato growers, as cotton is extensively grown throughout the country and PAT in Greece are mainly applied in cotton and horticulture production (Gemtos et al., 2006).

The survey targeted farmers who utilised two PAT, namely **machine guidance** (MG) and **variable-rate N-application** (VRNT). The sample of farmers was split into three categories:

i) non-adopters: farmers who currently do not own or rent MG or VRNT or who may have adopted these in the past but have since abandoned the technology;

ii) MG-only adopters (partial adopters): farmers who currently own or rent MG alone;

iii) VRNT adopters: farmers who currently own and/or rent both VRNT and MG (VRNT usually requires machine guidance).

The survey was conducted between August 2016 and February 2017. Farmers were surveyed face to face and/or by telephone (see Table 1), and a structured questionnaire was administered (see Annexes 3 and 4).

Table 1: *Distribution of farmers surveyed by country, interview and contacting method*

Country	**Interview method**	***n***	**Contacting method**	***n***
Greece (*n*=200)	Face to face	200	Machinery dealers	183
	Telephone	0	Personal contacts	17
Belgium (*n*=196)	Face to face	196	Personal contacts	196
	Telephone	0		
Netherlands (*n*=176)	Face to face	175	Trade fair	142
	Telephone	1	Personal contacts	34
Germany (*n*=195)	Face to face	0	Agricultural database	195
	Telephone	195		
UK (*n*=204)	Face to face	134	Trade fair	28
	Telephone	70	Agricultural database	176

The purpose of the survey was to gather information on the perceived impacts of adopted technologies, and the reasons and differences behind the uptake of identified PAT options.

Primary data from the literature review, together with the survey results, were analysed using different statistical, econometric and environmental methods and models (Annexes 5 and 6).

Firstly, logistical (multinomial and binomial) modelling approaches were used to assess the elements that determined the decision to adopt PAT. We also assessed the elements that influenced farmers to adopt the technology and the incentives that would encourage both non-adopters to adopt PAT and current adopters to increase the number of technologies adopted.

Secondly, a cost-benefit analysis (partial budgeting) was used to quantify the impact of the adoption of the selected PAT on the associated farm's economy (i.e. gross and net margins). The partial budgeting projected the perceived economic impacts on the relevant farm budget items as gathered from the survey utilising Farm Accountancy Data Network (FADN) data of the case study countries. The impacts were calculated for the different farm types (i.e. wheat, potato and cotton farms), and different farm sizes (i.e. < 50 ha, 50-100 ha, > 100 ha) in the different study countries.

Finally, the Miterra-Europe model was used to assess the potential environmental impacts of large-scale application of precision farming technologies in EU agriculture. Miterra-Europe is an environmental assessment model that calculates GHG (CO_2, CH_4 and N_2O) emissions, soil organic carbon stock changes and nitrogen emissions from agriculture on a deterministic and annual basis. The model is based on the Common Agricultural Policy Regional Impact Analysis (CAPRI) and Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) models, supplemented with a nitrogen leaching model, a soil carbon module and a module for representing mitigation activities. Miterra-Europe covers the agriculture sector at different spatial scales i.e. Member State and nomenclature of territorial units for statistics (NUTS2). The model assesses all agricultural GHG emissions up to the farm gate and considers the application of PAT (MG and VRNT) over two main arable farm types as derived from the FADN: 'Specialist cereals, oilseed and protein crops' and 'General field cropping'.

The Miterra-Europe model was used to quantify, at EU level, the effects of the adoption of PAT (MG and VRNT) on GHG emissions, specifically on:

i) direct soil N_2O emissions from reduced application of fertiliser;

ii) indirect N_2O emissions from N volatilisation and N leaching; and

iii) CO_2 emissions from fertiliser production and fuel use for field operations.

Miterra-Europe also assessed the impacts of PAT on other environmental co-benefits, i.e. reductions of ammonia (NH_3) emissions and nitrate (NO_3) leaching and runoff, and of their negative effects on air and water quality.

The environmental impacts were calculated for three different scenarios:

i) <u>low adoption potential scenario</u>: when the technologies (i.e. MG and VRNT) are adopted in farms larger than 100 ha;

ii) <u>medium adoption potential scenario</u>: when the technologies (i.e. MG and VRNT) are adopted in farms larger than 50 ha and smaller than 100 ha;

iii) <u>high (full application) adoption potential scenario</u>: when the technologies (i.e. MG and VRNT) are adopted in all farms.

4 Results

4.1 A typology of precision agriculture technologies and the potential contribution to greenhouse gas emissions reduction

Precision agriculture is a farming management concept based on observing, measuring and responding to spatial and temporal field variability and needs in crops with the use of digital technologies. The application of PAT in agricultural field operations could positively contribute to GHG emission reduction by:

i) enhancing the ability of soils to operate as carbon stock reserves, through reduced tillage and reduced nitrogen fertilisation;

ii) reducing fuel consumption through fewer in-field operations (direct GHG decrease); and

iii) reducing inputs for agricultural field operations (indirect GHG decrease).

These practices also positively affect farm productivity by optimising the use of agricultural inputs, leading to the production of higher or equal yields at lower cost than conventional practices.

A comprehensive categorisation of PAT could be the following, which results in three main types of technologies that span almost all agricultural practices (Figure 2):

— **Guidance technologies** are hardware and software that guide tractors and implements over a field. They include all forms of automatic steering and guidance for tractors and self-propelled agricultural machinery, such as driver assistance, MG and controlled traffic farming.

— **Recording technologies** are sensors that can be mounted on ground-based stations or affixed to rolling, airborne or satellite platforms. These gather spatial information, which includes soil-mapping, soil moisture mapping, canopy-mapping and yield-mapping information.

— **Reacting technologies** are hardware and software that together can vary the placement of agricultural inputs in the field. They include technologies such as variable-rate irrigation and variable-rate application technologies for nutrients, crop protection agents, irrigation, seeding and precision weeding.

The right combination of these three categories of PAT should increase or at least maintain yield, with the additional advantages of increasing yield quality and reducing environmental impact. All three categories require the use of global navigation satellite system (GNSS) technologies. GNSS is the generic term for satellite navigation systems that provide autonomous geospatial positioning with global coverage. Any GNSS can be used to pinpoint the geographic location of a user’s receiver anywhere in the world.

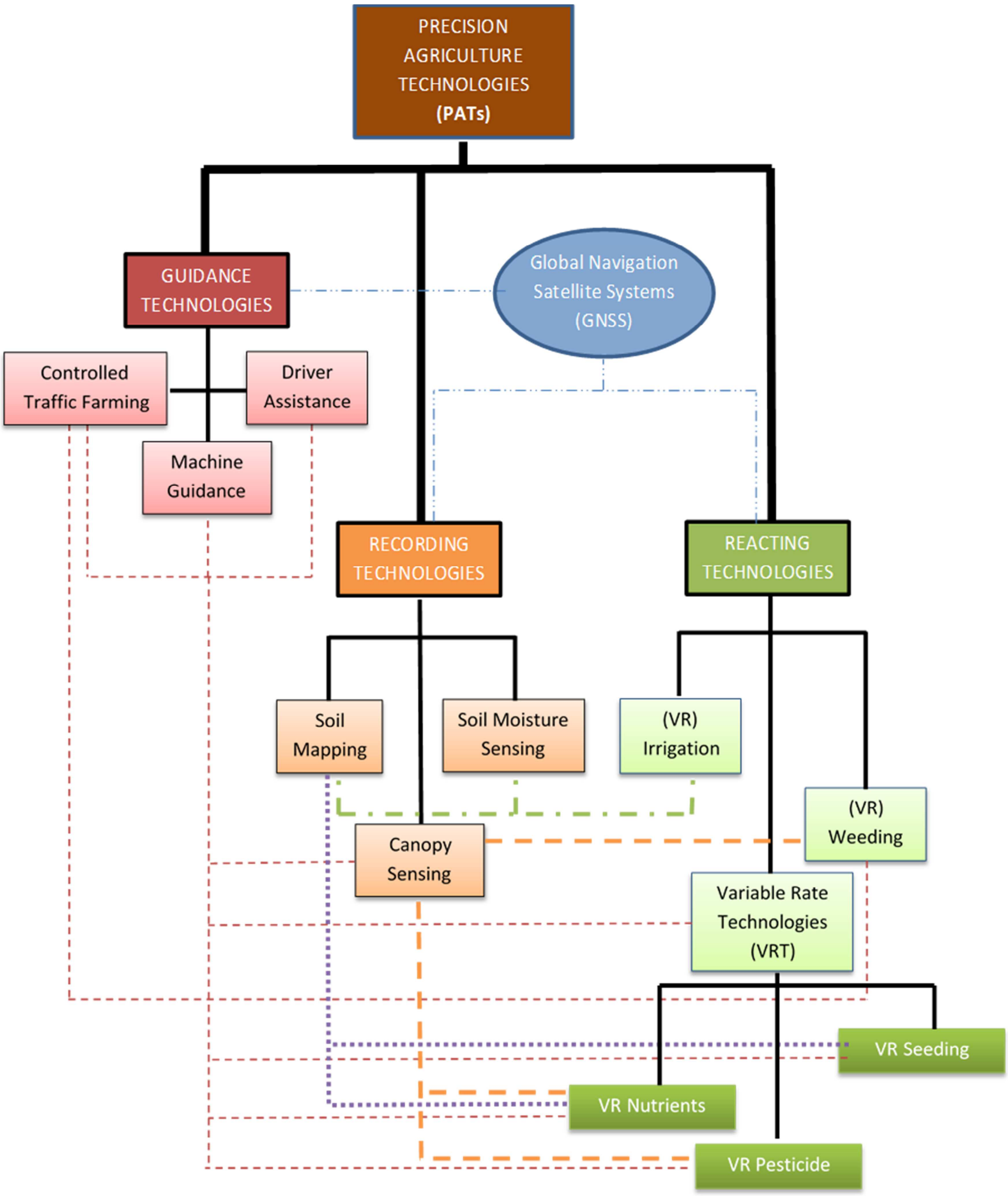


Figure 2: *Precision agriculture technologies overview.*

Guidance technologies include **controlled traffic farming** (CTF), which is a system that confines all machinery loads to the least possible area of permanent traffic lanes. Techniques such as CTF have the capacity to benefit all types of crop farming. Guidance technologies also include **driver assistance**, which works through separate add-ons that help drivers keep their line in the field (e.g. lightbar guidance). Driver assistance aids are not integrated into the tractor's systems and can be simply installed. Besides guidance, many of these systems also provide tracking options. Finally, most tractor manufacturers now implement direct **machine guidance** by applying GNSS for steering and guidance though two main systems: driver assistance and machine auto-guidance. In the latter technology, navigation signals are directly transferred to the hydraulics of the machine to manipulate the wheels automatically.

On-board computers interface the system with the driver. The driver simply selects a speed and driving map/pattern.

Recording technologies include **topographic and soil-mapping** technologies that measure specific aspects of soil quality (e.g. elevation, texture, nutrient and water availability) that will enhance a farmer's ability to understand and utilise soil heterogeneity and improve farming techniques. The soil, as the substrate of agriculture, is essential in the production of food and feed. Recording technologies capture not only the soil's chemical and physical composition, but also data related to the terrain and climate. Improved technologies, including plant-breeding technologies, cultivation technologies and automation, have created changes to the ways that agricultural land can be evaluated. Different types of soil maps that are of use for PATs are discussed in Annex 1.

Canopy maps are produced using crop sensors that detect the characteristics of the crop canopy, provide information on the crop growth level and quality, and possibly assist in predicting the final crop yield. **Yield mapping** refers to the process of collecting georeferenced data on crop yields and yield characteristics (such as moisture content) during the time that the crop is harvested. Various methods, using a range of sensors, have been developed for mapping crop yields (see Annex 1).

Reacting technologies cover **variable-rate irrigation** (VRI). Most irrigation systems apply water uniformly across a field. However, substantial variations in soil properties and water availability exist across most fields. Applying VRI to spatially and temporally variable conditions and biological requirements can increase the efficiency of application, improve yield and product quality, and reduce environmental impacts, most notably N_2O emissions.

Precision physical weeding (PPW) technologies enable changes to the configuration of mechanical weeders (e.g. in the position of or the resistance exerted by the tines of a harrow) during weeding, to match weed presence and/or density in the field.

Variable-rate planters/seeders (VRP/VRS) modify the rate of planting and seeding during application. This is often accomplished by disconnecting the planting/seeding system from the ground drive wheel, which usually keeps the planting/seeding rate constant when the speed of the tractor varies. By driving the planting/seeding system with an independent engine and gear box (to change the speed of the ground wheel input) or a hydraulic drive, the planting/seeding rate can be adjusted to the local soil potential (Grisso, 2011).

Variable-rate nutrient application (VRNT) allows fertilising at designated variable rates and placement to coincide with specific crop needs in a specific location within the field. Inorganic fertiliser is spread either as liquid or as solid granules, while manure is spread either as slurry or as solid manure.

Variable-rate pesticide application (VRPA), in a similar manner to other reacting technologies, modifies the rate of application to match the actual or potential field pest stress. It also prevents the application of pesticide where it is not needed. This technology is generally also usable for variable-rate fertiliser application.

The precision farming technologies mentioned above vary widely in their contributions to effecting reductions in GHG emissions. In this study, we conducted a literature review to assess the mitigation potential associated with each of the technologies (Annex 2). A classification of the PAT that contribute the most to reduce GHG emissions is provided in Table 2.

Table 2: *Selected PAT with direct GHG reduction potential*

Ranking of PATs	PAT type	GHG reduction potential
1	Variable-rate nitrogen application (VRNT)	5
2	Variable-rate irrigation (VRI)	3
3	Controlled traffic farming (CTF)	2
4	Machine guidance (MG)	2
5	Variable-rate pesticide application (VRPA)	2
6	Variable-rate planting/seeding (VRP/VRS)	1
7	Precision physical weeding (PPW)	1

Scale of importance of GHG reduction potential (Likert-type scale identified by the authors): 5, very high potential; 4, high potential; 3, moderate potential; 2, slight potential; 1, low potential.

Variable-rate nutrient application (VRNT) technologies can reduce GHG emissions significantly. This technology optimises the use of one of the most influential agricultural inputs: fertilisers. This is especially the case with nitrogen-based fertilisers, as, although all inorganic fertilisers contribute to GHG emissions by releasing carbon dioxide (CO_2) during their production and transportation, the global warming potential of N-based fertilisers is much greater, as it also contributes to nitrous oxide (N_2O) emissions. In relation to climate change, nitrous oxide (N_2O) is the most influential GHG produced as a result of agricultural activities.

Variable-rate irrigation (VRI) systems rank second in GHG emission reduction potential, as they have a dual impact: the reduction in the amount of water needed for irrigation decreases the energy needed for pumping water and transporting it from the aquifer; secondly, an optimal irrigation schedule could prevent extreme soil water availability (which boosts N_2O emissions). Controlled traffic farming and MG limit tractors to using only the necessary passes through fields, avoiding overlapping, with respective decreases in agricultural inputs and fuel use (which can be translated into GHG emission reductions). Variable-rate pesticide application (VRPA) is also expected to have GHG emission reduction potential because of lower levels of pesticide being applied to the fields and through lower GHG emissions coming from the industrial production of pesticides. In this case, the environmental effect is extremely significant in terms of lower amounts of chemical substances being applied to and contaminating all natural resources (water, air, soil). Variable-rate planting/seeding (VRP/VRS) and precision physical weeding (PPW) show lower, but not irrelevant GHG emission mitigation potential. VRP/VRS is primarily used to optimise plant density in the field, which can increase farm productivity, while the reduction in seed/plant population is associated with GHG emissions during their production. PPW reduces pesticide application and the amount of fuel used for flame-burning weeds (see Annex 2 for more detailed information).

4.2 Selected case studies

To assess the reasons behind uptake of PAT and the economic and environmental impacts of different PAT options, five case studies were selected with the aim of identifying a combination of EU countries, precision agriculture techniques and arable crop types that could realise the maximum potential economic and environmental benefits of adopting PAT.

The EU countries selected included Germany, the United Kingdom, Belgium and the Netherlands, since they are countries with large farms, high farm incomes and high levels of GHG emissions, in particular N_2O. Greece was also included to represent the heterogeneity of EU environmental and climatic conditions.

The **PAT** selected were MG and VRNT, since they ranked among those with the highest potential to reduce GHG emissions. Descriptions of the technologies selected for the case studies can be found in Figure 3 and Figure 4.

Machine guidance systems

Guidance technologies are systems that pilot machinery using the Global Positioning System (GPS). They enable farm machinery to follow straight lines to reduce overlaps and avoid gaps between passes of the tractor and equipment.

In order to use machine guidance systems, one needs a GPS receiver in the tractor or mounted on the machinery, and a lightbar or an on-board display to provide driving direction. A more advanced option is to use machine auto-guidance systems (or auto-steering), which are integrated into the tractor's hydraulics and can directly take over steering operations.

Machine guidance systems come in different accuracies, from entry-level systems at ±40 cm accuracy to systems with much higher accuracies of up to ±2 cm. Most of these systems can also monitor the performance of the machinery (e.g. fuel usage, engine load) and provide tracking options that help to integrate machine movements and operations in farm management information systems. Thus, they are also essential parts of other precision farming technologies, such as controlled traffic farming (permanent traffic lanes), variable-rate seeding and fertiliser application technologies.

Source: Santana-Fernández et al. (2010).

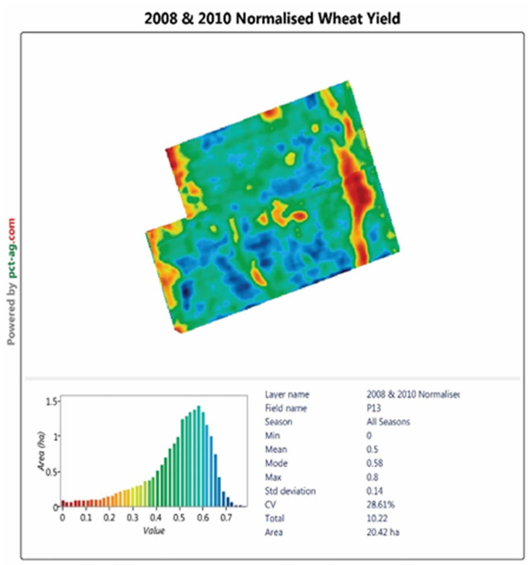
Figure 3: *Description of machine guidance as presented in the survey of farmers.*

Variable-rate application — in particular variable-rate nitrogen application

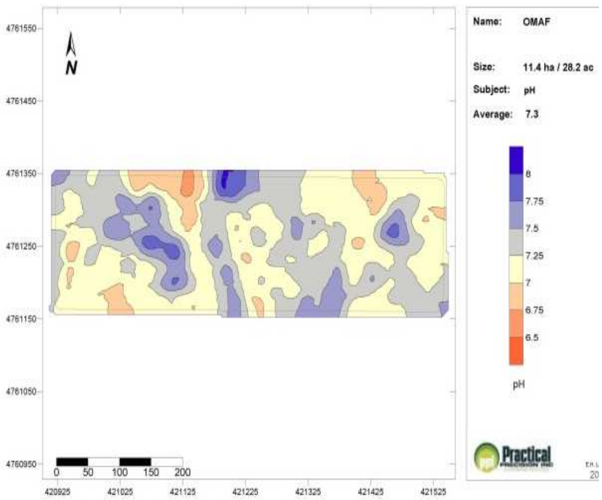
Variable-rate application technologies (VRT) enable changes to be made to the application rate to match the actual need for fertiliser, lime, seeds, etc. in that precise location within the field. The basic idea is that, according to an electronic map or readings from sensors, a control system calculates the input needs of the soil or plants and transfers the information to a controller, which delivers the input to the location.

VRT requires information on the soil properties and/or the crop properties to optimise application rate. The application rate is optimised based on measurements such as soil conductivity, soil pH, current crop nitrogen content, former yield and grain protein performance.

As well as the measurements and sensors, machine guidance technologies are also used on the tractor, and specific applicators with application control systems are required.



Source: www.agrioptics.co.nz



Source: www.ontariograinfarmer.ca

Source: blog.newtoncrouch.com

Source: http://www.purdue.edu

Figure 4: *Description of VRNT as presented in the survey of farmers*.

Two **crops** were selected: **wheat** and **potatoes.** Wheat is grown in all countries in the EU and is the most popular cereal grown in the EU. Potatoes are a high-value crop and economically intensive; potato growers are therefore expected to be among the early adopters, as they have a larger incentive to invest in PAT to achieve an economic benefit from its application. In addition, potatoes, as a root crop, and wheat, as a cereal, are often combined in a crop rotation system within the same farm. In Greece, **cotton** was selected instead of potatoes, as potatoes are not a widespread crop in that country.

The detailed criteria and process followed to select the study cases are described in detail in Annex 3.

4.3 Awareness and adoption of PAT

Awareness of both MG and VRNT was generally high among surveyed farmers. The average awareness of MG was high (94 %) in all countries (see Figure 5). The awareness of VRNT was lower, with an average of 74 % of farmers indicating they were aware of VRNT. The countries with lowest awareness of both VRNT and MG were Belgium and Greece (Figure 5). Responses from both these countries indicate small-scale agriculture and/or limited arable land area, and farmers on a smaller scale would be expected to be less inclined to seek automation than those with more homogeneous and larger fields.

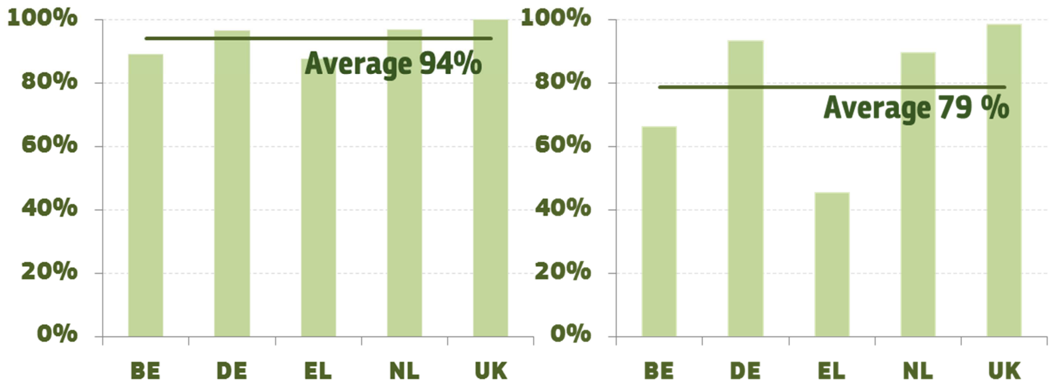


Figure 5: *Awareness of machine guidance and variable-rate N-application.*

The levels of adoption of MG are higher than the levels of adoption of VRNT, and for both technologies there is still an adoption potential. Belgium is the country with lowest adoption levels of both technologies (see Figure 6). The United Kingdom and the Netherlands have the highest adoption levels of MG and MG + VRNT respectively.

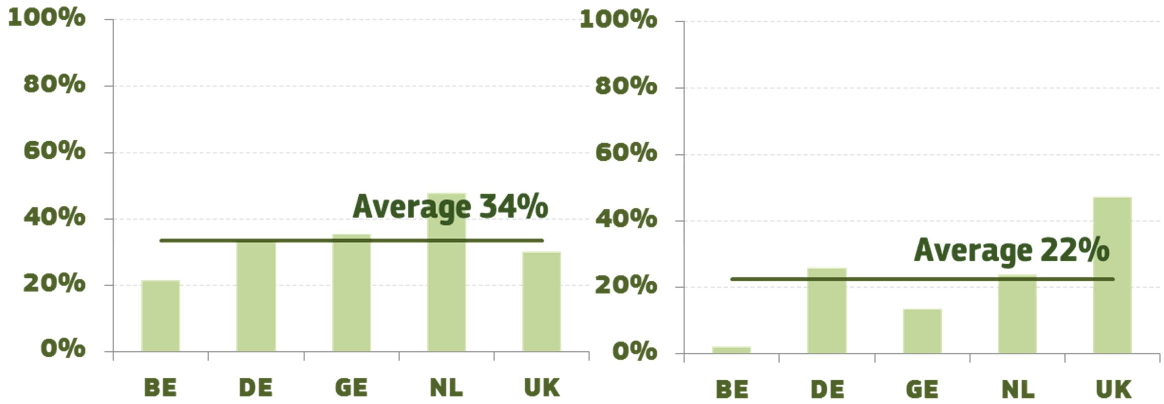


Figure 6*: Adoption shares of machine guidance and variable-rate N-application.*

These results need to be taken with caution, as the sampling method was not random and a stratified sample was taken instead. The awareness and adoption rates are therefore overestimated and are not representative of PAT adoption rates in the EU. The survey figures, as presented in Figure 6, can be interpreted as a current upper adoption limit of PAT in the EU.

4.4 Factors behind the adoption and non-adoption of precision agriculture technologies

In order to understand the elements that determine the decision to adopt PAT in the five EU case studies, a set of questions was asked within the survey to uncover barriers to or enablers of adoption. Questions were based on socioeconomic, agro-ecological, attitudinal, informational, behavioural and technological characteristics of the farmers and the farm (for further details, see the questionnaire in Annex 4).

The main barriers to adopting PAT tend to focus on **high initial investment costs** and longer associated payback periods. Uncertainty around the potential positive economic effects of PAT and therefore **uncertainty around the possibility of recovering this investment** creates a significant barrier to adoption, especially for those farmers with lower incomes, who are less able to afford the technology. By contrast, adopters provide a more positive view on the ability of the technology to ease and **reduce workloads** or to **extend working times during key moments** (e.g. working at night during the harvesting period). There seems to be a different perspective in that non-adopters focus on financial barriers while adopters highlight the ancillary benefits of these technologies.

Farm size is another important barrier to PAT adoption. Our study shows that larger farms have a greater capacity to adopt these technologies, probably because they might be looking for increasing economies of scale. Larger farm size tends to be related to greater production potential and control of resources (e.g. labour, land) and therefore those farmers who own larger farms might be better situated to bear the risk of adopting PAT. In addition, larger farms tend to have a higher variability of field characteristics — the potential economic benefits of adopting PAT are therefore expected to be higher than on fields where heterogeneity is low.

Perception about PAT is also an important determinant of the willingness of farmers to adopt these technologies. Farmers who positively perceived that PAT would pay back their initial investment in a suitable length of time adopted the technology to a greater extent than those with a less optimistic outlook. Given the high level of investment required, those farmers who decided to venture into purchasing PAT were more convinced than non-adopter farmers about the positive outcomes of the technology even though they had not yet experienced them.

The role of **socioeconomic factors** seems to be less apparent in determining the uptake of PAT. Younger farmers are more likely to adopt PAT. This might be related to the fact that older farmers might be less interested in, or less skilled in dealing with, new technologies. Although farmers' education has traditionally been considered an element that determines technology adoption, in this study there was no evidence to support this view. Education has not proved to determine PAT adoption even when the education variable was specifically focused on agricultural education.

Currently, there is no regulatory incentive to adopt PAT in the EU, nor any government subsidy that promotes the technology. There are some instruments that could boost their adoption, such as the support for the modernisation of tractors. It might be the role of public administrations to promote these technologies by offering demonstrations of actual benefits, support for training and, if these benefits are economically justified, potential subsidisation for smaller farmers to engage in precision agricultural technologies on farm.

4.5 Drivers and incentives boosting the adoption of precision agriculture technologies

The results of the survey show that farmers adopting PAT were influenced by different institutions, events and persons that provided information to them and that acted as information points. Those information points made farmers aware of the existence and usefulness of the PAT they adopted.

Peer-to-peer learning emerged as the most important element that influenced farmers to adopt both VRNT and MG technologies. Visits to **trade fairs, researchers and industry dealers** were also important items that influenced the farmers using PAT (see Figure 7). The role of researchers had a greater impact on VRNT users than on MG users, probably because VRNT is less developed than MG technologies and experimental trials are being conducted with VRNT. Similarly, industry dealers had a greater impact on the adoption of MG than VRNT, probably because MG technologies can be installed with minimal effort (e.g. when renovating a tractor).

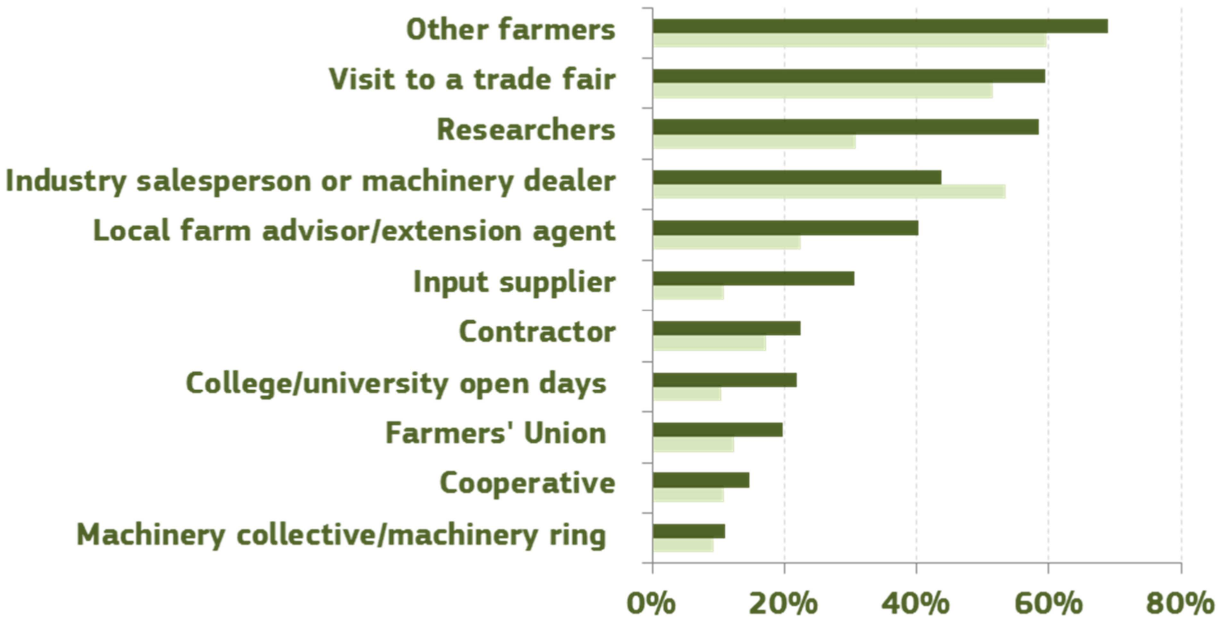


Figure 7: *Elements that influence a farmer's decision to adopt MG (light green bars) and VRNT (dark green bars). The horizontal axis represents the percentages of MG and VRNT adopter farmers influenced by the different elements.*

There are also different incentives that might boost the adoption of PAT by EU farmers (see Figure 8). **Monetary incentives**, both financial and the promise of improved economic performance by adopting these technologies are the elements that are encouraging the uptake of PAT to a greater extent. However, non-monetary incentives also seemed to be of interest to the surveyed farmers.

Providing support to improve the performance of the machinery by direct **technological assistance, training and technical support** might encourage adoption by 58-70 % of surveyed farmers. The only incentive that motivated fewer than 50 % of the respondents is the training provided to staff. Training non-permanent operators might be seen by farmers as less secure, as these operators could move to other farming businesses.

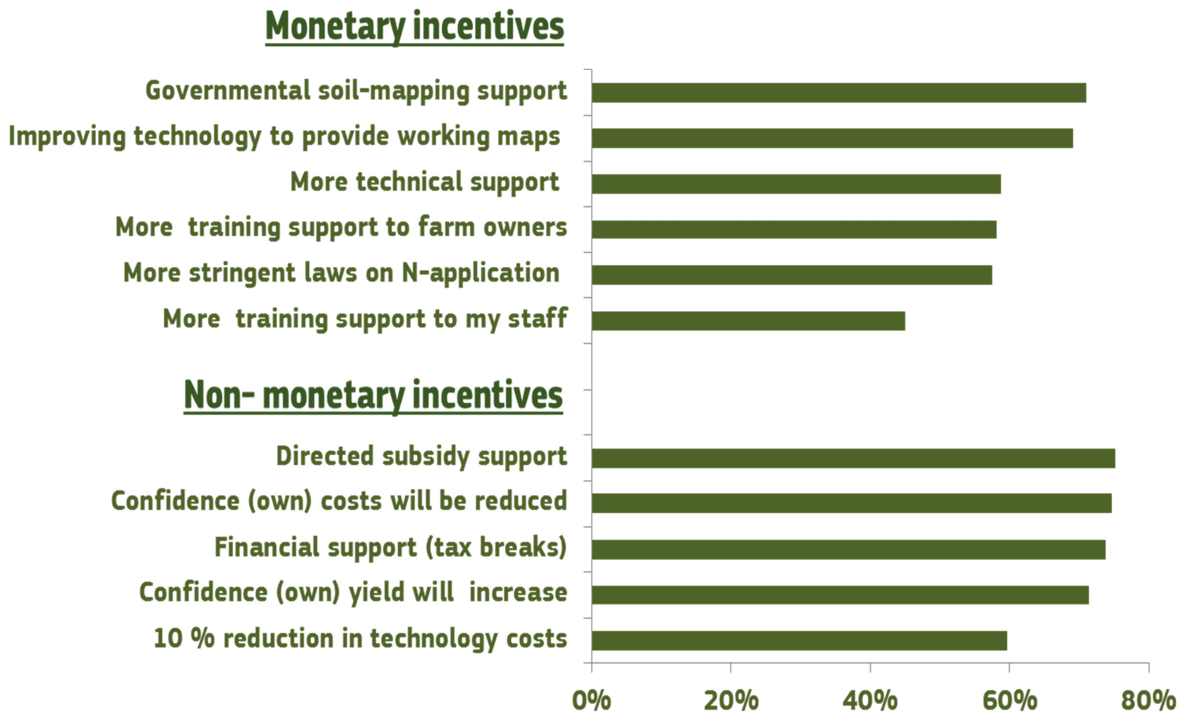


Figure 8: *Incentives influencing the decision of farmers to adopt PAT.*

4.6 Quantification of the agronomic and economic impacts

The survey assessed the farmers' perceptions towards different agronomic impacts. Production, use of fertiliser and use of fuel were three of the main agronomic impacts assessed by farmers (see Figures 9 and 10). Although many farmers indicated no effect on production, fuel or N-fertiliser, average figures indicate that MG and VRNT reduce the use of fuel by 5.4 % and 2.8 % respectively.

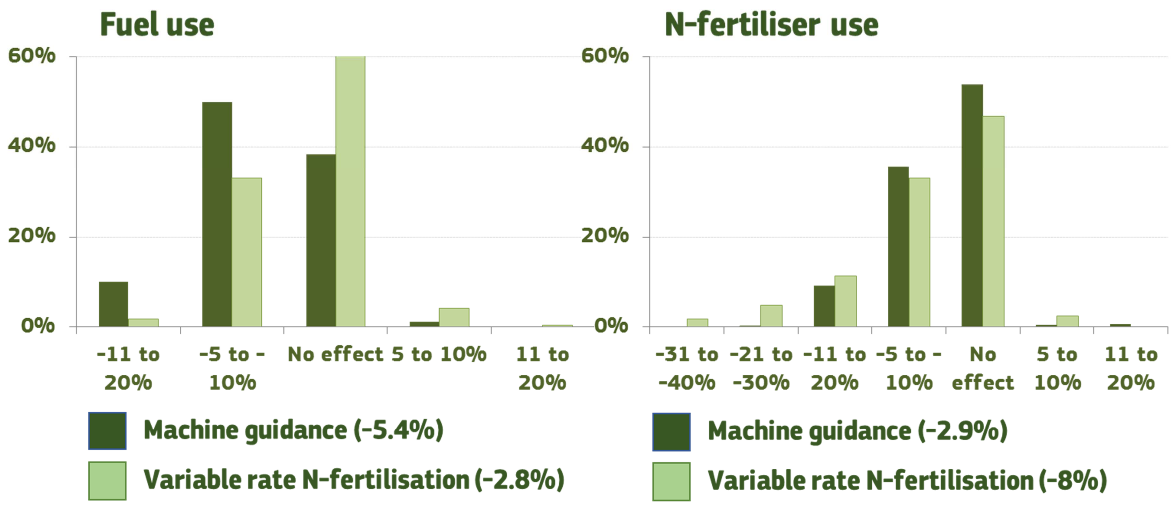


Figure 9: *Farmers' perceived impacts of the use of PAT (MG and VRNT) towards fuel and N-fertiliser use. Average impacts in brackets.*

Fuel reduction linked to the use of MG is associated with the improvement of the tractor's driving system and the consequent reduction in overlapping of the tractor passes over the field for all input applications. The decrease in the use of fuel, linked to the use of VRNT, is associated with the reduction in the number of overlapping passes during fertilisation activities. However, the average reduction in N-fertiliser is greater for VRNT than for MG, (8 % for VRNT and 2.9 % for MG). While fertiliser savings made by using MG are obtained by the prevention of overlapping when applying N-fertilisers, the fertiliser saving through the use of VRNT is caused by both the reduction of overlapping and the adjustment of the fertilisation rates according to specific plant needs. The impact of the use of MG on production (in terms of yield) is null, as its uptake does not affect the application of inputs directly. However, farmers who adopted VRNT reported that, on average, their production increased by 4.1 %.

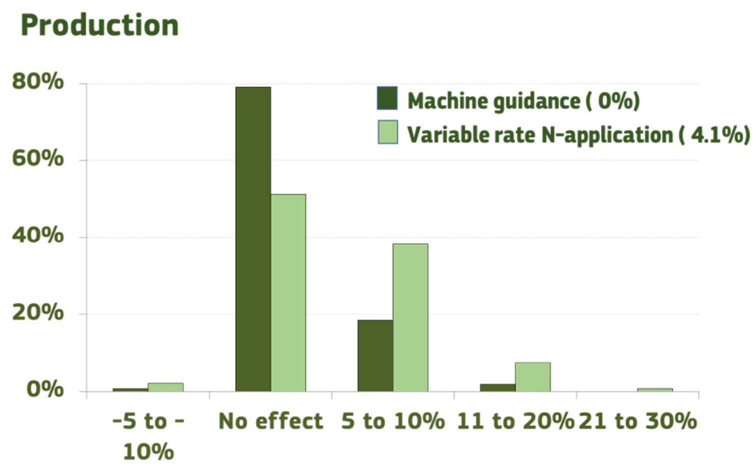


Figure 10: *Farmers' perceived impacts of the use of PAT (MG and VRNT) on yield production. Average impacts in brackets.*

A partial budget analysis was utilised to assess the influence that the uptake of PAT has on farm profitability. This assessment was based on the surveyed farmers' perception of the impacts that using PAT had on different economic features (see questionnaire in Annex 4). Data on perception were projected on to the relevant farm budget items of the FADN data for the different case study countries. Data were also projected taking farm type and farm size into account.

The results of the partial budget analysis, not including the capital costs of the PAT, present great variability: the impacts change by country, by farm size and farm type, and by the specific technology (see Annex 6). In general, the uptake of the two technologies can positively affect annual farm finances and significantly affect labour requirements. It appears that **implementing VRNT tends to increase net income more than installing MG**. However, this **increase is low for both** (ranging from -EUR 18/ha to EUR 34/ha annually for MG and from -EUR 16/ha to EUR 411/ha annually for VRNT). In some cases, the impacts on net income are even negative for some farm size classes. When it comes to labour impacts, **using MG technology seems to reduce labour requirements more than using VRNT**. This might be because training requirements for VRNT, as an information-intensive technology, are higher than those for MG.

The average impact of the use of PAT (both MG and VRNT) on labour is twofold (see Table 3). PAT might reduce the costs of hiring labour and reduce the time committed to field activities; however, the need to spend time on training staff and farm management might be increased. Farmers using PAT also reported an **increase in outsourcing contractor costs** for support and advice on the management of these technologies.

Table 3: *Average perceived impact (in %) of MG and VRNT uptake on labour (costs and time)*

Technology	Contractor costs	Hired labour cost	Training time	Management time	Field time
MG	0.27	-2.14	1.34	0.27	-6.16
VRNT	4.38	-1.25	2.19	2.19	-1.56

This study also assessed the perception about the payback timespan of MG and VRNT by adopters. As with potential income, the responses regarding the payback period also showed high variability (Annex 6). In general, many farmers (i.e. 40-47 %), both MG and VRNT users, perceived the payback period to be shorter than 5 years. Only around 25 % of MG and VRNT users considered the payback period to be longer than 11 years.

4.7 Analysis of EU-wide environmental impact assessment of precision agriculture technologies

The Miterra-Europe model was used to assess the EU-wide environmental impact of PAT, with a focus on GHG emissions, using MG and VRNT under different uptake scenarios (low, medium and high).

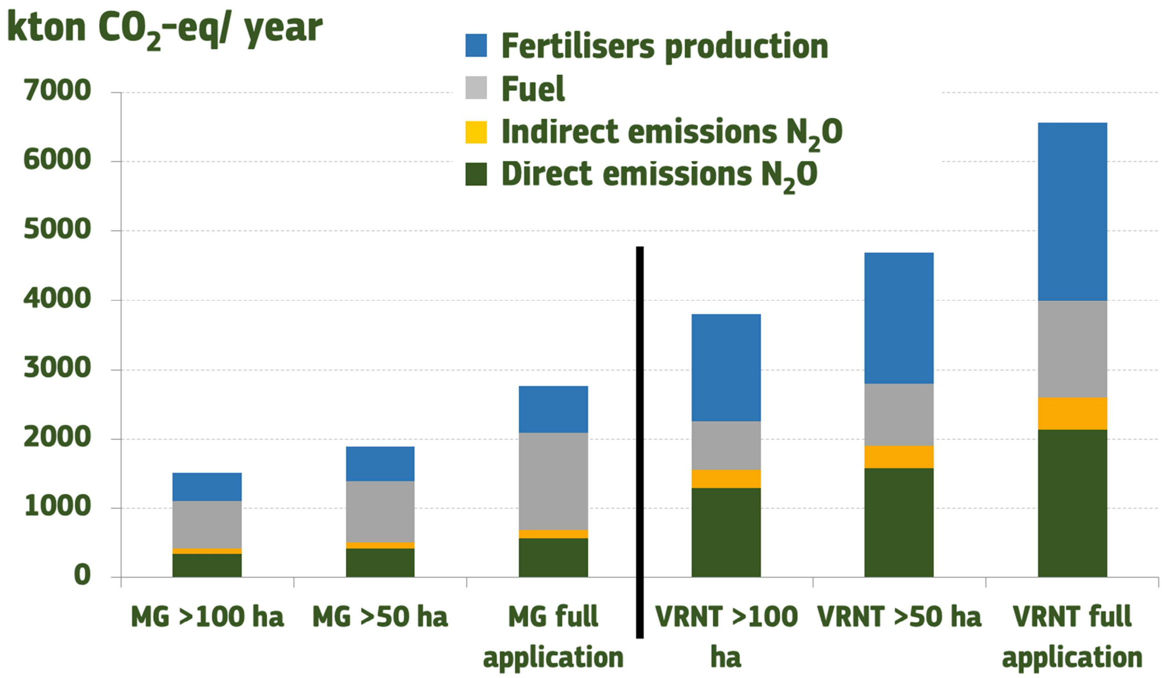


Figure 11: *GHG emission savings under different MG and VRNT uptake scenarios*.

The results of the analysis show that the introduction of PAT, such as MG and VRNT, might have positive effects on the environment, with reductions in GHG emissions from fertiliser application, fertiliser production and fuel use (Figure 11). Greenhouse gas emission savings are higher for VRNT than for MG in all three uptake scenarios. This is because the capacity of VRNT to reduce indirect, but especially direct, N_2O emissions associated with the reduced use of N-fertilisers is higher. VRNT also saves fertilisers, and therefore the CO_2 emissions associated with the production of these fertilisers are also lowered. The fuel reduction capacity of MG is higher than it is for VRNT, as MG is used for field activities additional to the application of fertiliser. The mitigation potential for MG ranges from 1513 to 2760 Ktonnes carbon dioxide equivalent (CO_2-eq) per year. The mitigation potential range for VRNT varies from 3805 to 6567 ktonnes CO_2-eq per year. These potential GHG emission reductions represent 0.3–1.5 % of the total EU 2015 GHG emissions of the Agriculture sector.

Other environmental impacts (such as ammonia emissions and nitrate leaching) can also be reduced. However, the size of this reduction varies locally because of differences in farm size, current fertiliser use and environmental conditions. Farm size is an especially important factor, as the implementation of PAT on large farms has greater potential benefits: there is a lower investment cost per ha and a greater benefit regarding input reduction. France, Germany and some Eastern European countries are therefore the regions where the highest GHG reductions through the use of PAT are found (see Figure 12).

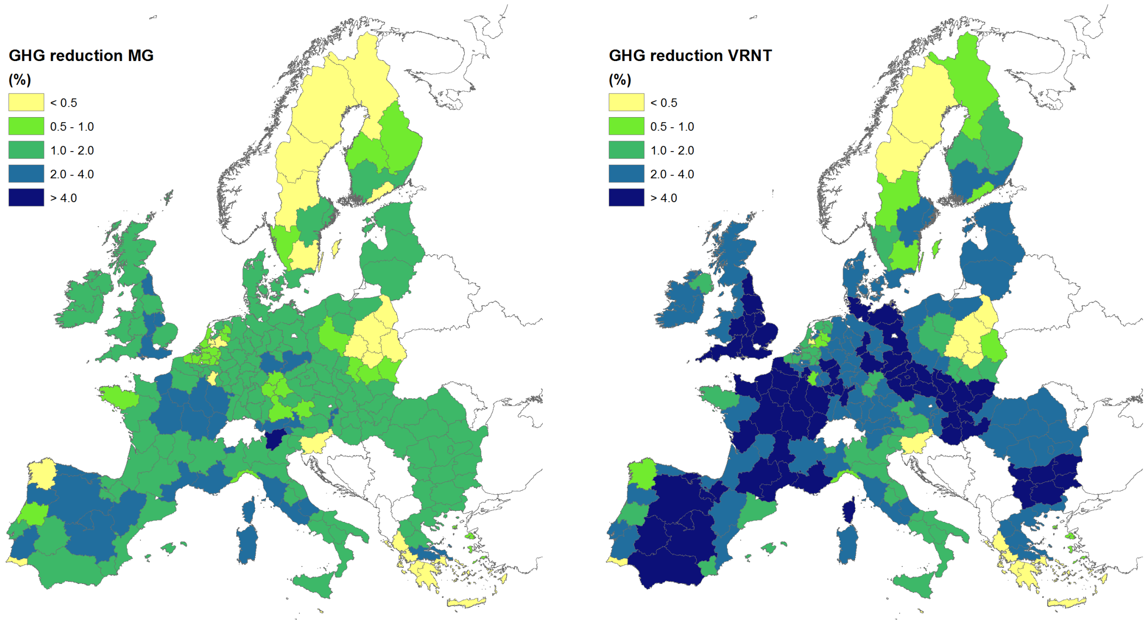


Figure 12: *Maps of GHG reduction for MG (left) and VRNT (right) compared with the baseline scenario. Both maps are based on the scenarios where precision agriculture is applied on farms with more than 50 ha of arable land.*

Although VRNT has a positive effect on the crop yields (on average a 4.1 % increase according to the survey), the increased crop yield has not been taken into account in the environmental impact analysis, as this does not directly reduce the total emissions. However, the environmental footprint (emissions per kg of product) of VRNT will be lower than that of MG, because of this effect on yield.

5 Conclusions

The present report concludes that precision agriculture practices have the potential to reduce GHG emissions. This emission reduction is associated with PAT's ability to optimise agricultural inputs by targeting spatial and temporal on-field variability within fields. PAT can also have a positive impact on farm productivity and economics, as it provides higher or equal yields at lower production costs than conventional practices. Variable-rate nutrient application (VRNT) technologies, machine guidance (MG), variable-rate irrigation (VRI) and controlled traffic farming (CTF) are the technologies that have the greatest potential to reduce GHG emissions while also maintaining or enhancing farm economics.

Current adoption rates of MG and VRNT in the EU seem to be low. These low rates might be associated with different hurdles. High investment costs, small farm size and advanced ages of farmers are three of the main obstacles to adoption identified by farmers. However, peer-to-peer learning, visits to trade fairs, and meeting researchers and industry dealers all have a positive effect on enhancing PAT uptake. Incentives that aim to improve the economic performance of a farm both directly and indirectly, as well as non-monetary incentives, such as technical advice or training, might have a positive impact on boosting PAT adoption among EU farmers.

This study indicates that the use of PAT might have a positive impact on GHG emissions reduction. The mitigation potential of VRNT is higher than that of MG representing 1.5% and 0.3% of the total EU 2015 GHG emissions of the Agriculture sector respectively. PAT could therefore represent a tool for GHG emission reduction in European agriculture. Moreover, those technologies also have positive environmental co-benefits on air and water quality by reducing ammonia volatilisation and nitrogen leaching and runoff.

The economic results of this study are highly variable among the different regions studied. In addition, there were few survey observations for certain of the FADN categories genetared, reducing the robustness of the analysis. In general, farmers perceived the economic and agricultural impact of PAT to be none or low (below 5 % change). However, average impacts of PAT tend to be beneficial for farmers, reducing both input costs and time requirements.

In this study, agronomic and economic impacts have been assessed by considering farmers' perceptions instead of directed experimental trials. The study therefore considers the impacts under prevailing farm conditions and farm management practices.

Precision agriculture technology is likely to be a cost-effective GHG mitigation practice with the potential for significant uptake by EU farmers. It is therefore a relevant technology to be considered in current and future EU agriculture policies.

This study called for more research on the uptake of PAT. Firstly, there is a need to quantitatively assess the current and potential adoption rates of PAT throughout the EU in order to obtain better estimates of the real mitigation potential of these practices. Secondly, as this analysis assessed the use of PAT only for mineral fertiliser application, there is the potential to further assess the impact of the use of PAT for the application of manure, which could increase the mitigation potential in the land-based livestock sector. Finally, as farm size (as a proxy for scale of production and the limits of investment) was identified as an important barrier to PAT uptake, research on assessing the economic impacts, comparing different investments and management systems (individual versus shared), might shed some light on making PAT more affordable to farmers.

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List of abbreviations and definitions

PAT	Precision agriculture technology
MG	Machine guidance
VRNT	Variable rate nitrogen technology
GHG	Greenhouse gas

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ANNEXES

ANNEX 1. Literature review on the impacts of precision agriculture technologies in agriculture

Literature review on the impacts of Precision Agriculture Technologies in agriculture

Deliverable 1

PRECISION AGRICULTURE project

contract no. 199163-2015 A08-NL

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Contractor

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AGRICULTURAL UNIVERSITY OF ATHENS

SRUC

ILVO
Institute for Agricultural and Fisheries Research

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List of abbreviations

CAP: Common Agricultural Policy

CSA: Climate Smart Agriculture

CTF: Controlled Traffic Farming

DOE: Depth Of Exploration

DSS: Decision Support System

EM: Electro Magnetic

FMIS: Farm Management Information System

GHG: Greenhouse Gas

GNSS: Global Navigation Satellite System

GPS: Global Positioning System

LEPA: Low Energy (Elevation) Precision Application

LESA: Low Energy (Elevation) Spray Application

LiDAR: Light Detection And Ranging

MESA: Mid Elevation Spray Application

NDVI: Normalised Differential Vegetation Index

NUE: Nitrogen Use Efficiency

PA: Precision Agriculture

PAT: Precision Agriculture Technology

PPP: Precise Point Positioning

REIP: Red Edge Inflection Point

ROI: Return on Investment

VRA: Variable Rate Application

VRI: Variable Rate Irrigation

1 Introduction

EU agriculture has to cope with global challenges such as food security and the sustainable use of natural resources, including climate change mitigation, as well as domestic issues like making farming more efficient and productive, increasing animal welfare and revitalising the countryside and its rural communities.

The active management of agricultural systems using appropriate technologies and practices could offer possibilities to reduce greenhouse gas (GHG) emissions while increasing agricultural productivity and incomes. One potential example is the adoption and dissemination of Precision Agriculture (PA) in the European Union.

Little evidence is available on **Precision Agriculture Technologies (PATs)** which could mitigate GHG emissions. The present tender study aims to narrow some of the abovementioned knowledge gaps with new empirical evidence by studying current and potential adoption of PATs by EU crop producers which could help increase farm productivity and, at the same time, mitigate GHG emissions.

1.1 Objective

The global objective of the tender study is to empirically investigate the impact of those PATs that are holding the most promise for GHG emissions mitigation while simultaneously being economically attractive for EU farmers (e.g. by increasing or maintaining productivity and being cost-effective). The productivity and economic impacts, as well as the extent of GHG mitigation, will be estimated based on the collection of primary data (survey to farmers) and secondary information when needed.

This document, which is part of this greater study, has two main goals: i) generate a list of existing PATs and ii) conduct a comprehensive literature review on the economic, social and environmental impacts of these PATs on agriculture. Additionally, this document aims at supporting the selection of relevant PATs that contribute to the reduction of greenhouse gas (GHG) emissions.

1.2 Document structure

This report is structured in five chapters, a list of references and four annexes. Chapter 1 provides background information to frame the study and presents its objectives and structure. Chapter 2 reviews the definitions, benefits, drawbacks and adoption of PATs in order to create a common ground into the following parts of the study. Chapter 3 presents a typology of PATs (i.e. a classification system of PATs). Chapter 4 provides a list of PATs that already exist or will become available in the future, along with a review of their economic, environmental and social impacts. Chapter 5 draws conclusions from the discussion of the presented PATs and provides insight in future developments.

Appendix A further explains the classification system from chapter 3 and uses this system to provide additional information about the PATs listed in chapter 4. Precision Agriculture

1.3 Definition of Precision Agriculture

There have been several attempts to define Precision Agriculture (PA) through the years (Arnholt et al., 2001; Pedersen, 2003; Fountas et al., 2005; Zarco-Tejada et al. 2014). Summing up these definitions, PA is a farming management concept based upon observing, measuring and responding to inter- and intra-field variability and needs in crops and to variability and needs of individual animals with the use of digital techniques. Concerning the arable agricultural practices, PA refers to the application of new agricultural practices (mainly based on GPS) aiming to increase or maintain the production rate by using less input of any kind (agrochemicals, water, energy). Thus, improving economic profitability and simultaneously increasing sustainability. Using this definition, PA technologies are a part of climate smart agriculture (CSA), which is defined as an agricultural system that responds to three main challenges:

- sustainably increasing agricultural productivity and incomes – food security and economic growth;
- adapting and building resilience to climate change – climate change adaptation;
- reducing and/or removing greenhouse gases emissions - climate change mitigation.

During the past 10 years, PA has moved from good science to good practice (CEMA, 2016). PA has witnessed unprecedented growth around the globe: 70 to 80% of new farm equipment sold today has some form of Precision Farming component inside (CEMA, 2016).

1.4 Benefits of Precision Agriculture

PA may provide significant benefits to farmers and to the society. Both users and non-users of PA recognise that PA can offer improvements in yield and product quality, reduced chemical usage and increased income. A study by Lencses et al. (2014) points at cost savings due to the reduction of fertiliser and herbicide use.

Economic benefits may be significant and mostly related with cost savings, although yield increases may also be possible: Robertson et al (2007;2009) provided a general example for Australian grain production: economic benefits range between $1 to $22/ha with a break-even period within 2-5 years (Robertson et al., 2007; Robertson et al., 2009). A Dutch survey into precision agriculture in 2013 revealed that 65% of the surveyed arable farms use PA. The main reported benefits are the reduction of gaps and overlaps in fieldwork, more accurate work, reduced fatigue and time saving (van der Wal, 2014).

Other potential benefits include managerial improvements (e.g. better insights in crop growth status) and minimisation of environmental impacts (e.g. less fertiliser, water or pesticide use) (Silva et al., 2011).

The benefits that are specific to certain PATs are mentioned in chapter 3 "PATs list", under each particular technology description.

1.5 Drawbacks and barriers for the adoption of Precision Agriculture

PA Technologies have the drawback that offered services, for many years, were incomplete and benefits, both economic and environmental, were very hard to quantify. As a result, PATs are hard to be adopted by regular farmers, apart from the early adopters. Farmers in the Netherlands that were not using PA were asked in a survey what kept them from it. 28% of the surveyed farmers reported that they found their farm too small while another 24% had no expectation of financial benefit. 16% indicated they were waiting for further developments. (UNIFARM, 2015).

The main drawbacks of PA, which also form the main obstacles for farmers to adopt PA technologies, are (Polling et al., 2010; Lamb et al., 2008; CSA Booster, 2015):

- **Large knowledge gap in the knowledge transfer between developers and users**. Farmers and technologists do not communicate very often. A study among German stakeholders within the PA community explored the barriers in the innovation processes and it was found that there is a gap in the knowledge transfer between science and practice and limited communication and collaboration between farmers and technology providers. They also pointed out that farmers are not only adopters but that they can also propose innovation solutions to technology providers (Busse et al., 2014). The knowledge gap is however not limited to simply knowing how to build and operate precision farming equipment. It is also related to knowing about the return on investment of different technologies. Robertson et al. (2007) corroborate this aspect by also naming perceived risks of economic return next to barriers to using hi-tech elements as an adoption constraint. Fountas et al. (2005) argue that better understanding of the PA technologies and their benefits for the farmers would increase uptake.

- **High investment cost**. The various types of recording, reacting and guidance technology often do not come cheap and have to be added to the cost of the machinery. Lowering the investment costs would increase uptake (Fountas et al., 2005).
- **Time consumption**. It takes time to learn how a new system works. It also takes time to calibrate some systems;
- **The learning process combined with average educational level** (=farmer's expertise). Few farmers are ICT specialists. Robertson et al. (2007) corroborate this statement by claiming that lack of training and technical support are an adoption constraint;
- Low trust on internet-based data storage;
- **GPS operation problems** like signal loss and interoperability problems between brands;
- **Incompatibility of different PA technologies and software**. Some recording, reacting and guidance technology cannot be combined due to software issues (e.g. the data coming out of sensors is not in the right format to be used by the reacting technology) or hardware issues (e.g. connecting cables of the machinery do not fit in the sockets provided in the control unit in the tractor). A survey among Canadian farmers showed that the compatibility of PA technology, and also the role of farmers' expertise (vide supra) were the main issues for PA technology acceptance and diffusion of innovation (Aubert et al., 2012). Robertson et al. (2007) confirm that equipment incompatibility is an uptake barrier.
- **Regulatory issues** (e.g. lacking legislation about Unmanned Aerial Vehicles). The European Climate KIC funded Climate Smart Agriculture (CSA) Booster is a collaboration of research institutes working on accelerated adoption of technologies and solutions for mitigation of climate change in agriculture. Their pathfinder report (2015) tackles this issue (among various other socio-economic barriers): both technology providers and potential users highlighted policy and regulatory issues acting as a barrier. This included a lack of knowledge of available support or subsidies, and inconsistent application of regulations across Europe. Table 1 shows an overview of the key socio-economic barriers identified in their report; many of them overlap with the barriers that are named in this list.

Table 1: Overview of socio-economic barriers. Source: modified from CSA Booster pathfinder report (CSA Booster, 2015).

Economic*	Institutional/ regulatory**	Organisational***
High initial investments	Low institutional support for farmers	Lack required competencies/ skills
Poor access to capital	Use of overly scientific language (jargon)	Poor information
Competing financial priorities	Farmer's knowledge not considered in R&D	Inability to assess technologies
Long pay-back periods (ROI)	Lack of regulatory frameworks	
High implementation costs (actual and perceived)	Overly complex technologies	
Uncertain returns and results	Results/ effects of technology difficult to observe	
Temporal asymmetry between costs and benefits	Farmer's beliefs and opinions	
	Low trust	

* Cullen et al., 2013; Faber and Hoppe, 2013; Guerin and Guerin, 1994; Montalvo, 2008
** Bogdanski, 2012; Eidt et al., 2012; Montalvo, 2008
*** Montalvo, 2008

Besides these major drawbacks, several other obstacles that also hamper the wider applicability and adoption are the insufficient recognition of temporal, multi-annual variation by the technology (in many cases year-to-year variation overcomes spatial variation) is a drawback to use for instance yield maps as a means for next year's heterogeneity. Another drawback is focussing more on fields rather than a farm-level focus (i.e. application of PA techniques in all fields of the farm as a total) disregards the operational problem of managing a whole farm rather than an individual field as an adoption issue. Also, farmers' adoption would benefit from better incorporation of quality standards and traceability of the whole production process in the product price. Another barrier is that the impact of environmental protection data of farming systems in the price is not visible (McBratney et al., 2005).

1.6 Elements affecting Precision Agriculture uptake

1.6.1 Agricultural region

McBratney et al. (2005) have recognized 4 different types of agricultural regions around the world with different potential for PA adoption. This division was based on 3 major factors: 1) general economic development, 2) government support for agriculture and 3) the nature of the production units within the region.

The first type refers to developed countries where the government supports agriculture through subsidies and where the development of PA is the highest (e.g. USA, EU, Japan). In this case, the potential exists, but it is vital that environmental impact and final product quality is incorporated into the product price to boost PA.

The second type includes countries that are developed economically, but farmers receive limited support from the government. In this case the potential is high, as there are big farms with high export tendency, but PA is applied mainly for higher production and the environmental concern is limited (e.g. Australia, New Zealand, Argentina, Brazil).

The third type contains developing countries with big plantations and centrally-planned agriculture. This type refers to regions were plantations of high added value are installed in very big farms and PA is applied mainly for quality increase (e.g. Guatemala).

The fourth type includes developing countries with small-scale agriculture (e.g. Cameroon, (New Agriculturist, 2016)). This category shows the least PA potential as it is based on small family farms that cannot support high-tech PA techniques. However, in these cases PA can be applied by detailed monitoring of the crop from the farmer himself (after training) together with an appropriate Decision Support System (DSS) tool for such farming.

Furthermore, there are also regional differences in the reasons for PA adoption. In North and South America higher profitability is the main driver, whereas in Europe and Japan social, environmental and economic sustainability is most important (Gemtos et al, 2002). Subsidisation of agriculture in Europe and Japan has led to increased inputs to maximise production, leading to severe environmental impacts. These problems are being increasingly recognised (McBratney et al. 2005).

1.6.2 Farm size

Farm size is one of the regional characteristics that influences PA adoption to a high extent. The larger the farm, the higher the PA adoption potential is (Polling et al., 2010). In Germany, Finland and Denmark, surveys have proved that farm size has an impact on farmers' adoption of auto-steering systems (Lawson et. al 2011).

The farm size for precision viticulture has been studied by Matese et al. (2015). They estimated the minimum field size for intra-vineyard variability of vegetation using images from UAV, airborne and satellite. They have estimated that the break-even point for using a UAV exists at five hectares, above such a threshold, airborne and satellite have lower imagery cost.

Farm size, together with farmers' willingness to adopt (which depends on factors like education and labour cost) and country-specific agricultural situation (see section 1.6.1) are important drivers determining differences on PA adoption patterns on a regional scale between Northern and Southern countries (Blackmore et al, 2006).

1.6.3 Education

Education appears to be correlated with adoption of auto-guidance systems (Lawson et. al 2011). The adoption of auto-steering has also been found to positively relate to the perceived future importance of precision agriculture and the input cost savings that it implies.

1.6.4 Crop typology

Crop typology is also an important element determining PA adoption. High added value crops, such as vegetables and fruits together with cereals are more promising for PA applications in comparison to other arable crops, especially in regions of small farm sizes (Blackmore et al, 2006).

1.6.5 Labour cost

Labour cost is a factor that is highly related to regions and countries. Labour cost is an important determinant of PAT adoption because time savings and/or higher labour productivity are important benefits for farmers. Regions with high labour cost have increased PA potential only when land is relatively less costly (Swinton and Lowenberg-Deboer, 2001).

1.6.6 Field heterogeneity

Field heterogeneity also plays an important role, as regions with high within-field heterogeneity are more appropriate for PA applications because the effect of PA will be quickly and easily shown, as opposed to a uniform application.

1.6.7 Examples

In Australia, the adoption rate of variable rate application (VRA) among grain producers has increased in recent years, where in 2010 twenty percent of farmers used VRA, much higher than the less than 5% recorded 6 years earlier. A significant observation was that non-adopters were also convinced of the agronomic and economic benefits of VRA. The application of VRA was mostly on manually operated systems, with the use of soil tests and electromagnetic (EM) maps, rather than yield maps (Robertson et al., 2012). As the adoption of PA is closely related to the adoption of Farm Management Information Systems (FMIS), a survey among European farmers revealed differences in the weekly hours spent in the office among the countries and the use of FMIS for different farming activities (Lawson, et al., 2011). Among cotton producers, younger and better educated producers were correlated to more PA systems being used, while farmers using computers for management decisions also adopted a larger number of PA technologies (Paxton et al., 2010).

A survey among cotton producers in the USA showed that auto-steering adoption was related to the perceived future importance of PA and input cost savings, as well as the characteristics of the cotton picker (D'Antoni et al., 2012).

1.7 Routes towards increasing adoption of Precision Agriculture

Although PA systems are likely to raise the profit on many farms, the adoption of PA technologies remains low due to the many barriers identified in section 1.5. Therefore, a comprehensive approach that facilitates the different stakeholders' understanding of the technology, the initial investments, the running costs and the various benefits can offer the chance to significantly enhance the level of adoption of the most suitable PA technologies both at strategic and operational level.

According to a study among Danish and US farmers regarding the use of PA technologies, the main prerequisites for PA to increase its adoption are (a) lower cost, (b) better understanding of the PA technologies and their benefits for the farmers, (c) financial support from the government, (d) ease to use the huge amount of data (storage) in field level and (e) user friendly software (Fountas et al., 2005).

Furthermore, a survey among cotton producers in the USA indicated that the potential for improved environmental quality was a strong PA technologies adoption motivator (Watcharaanantapong et al., 2014). Greater adoption rates for Variable Rate Irrigation will require higher costs for water and energy and enforcement of environmental regulations for water use. There is a need for training personnel on variable rate irrigation prescriptions, as well as informing government officials and bankers on the potential benefits of PA technology. At the technology end there is a need to define dynamic management zones, automatically sense within-field variability and adaptively control site-specific variable rate water applications (Evans et al., 2013).

Development of protocols and realistic performance criteria by technology providers, should result in a positive influence on the rate and breadth of adoption (Lamb et al., 2008). In addition, it is believed that the increment of PAT adoption is governed by three aspects (ERA-Net ICT-AGRI Strategic Research Agenda, 2012):

- Developing ideas from different areas of academic expertise to arrive at innovative solutions that reflect the perspective of different disciplines (agronomy, engineering, computer science, economics and social sciences) and provide the optimum answer to food and feed production;
- Achieving the greatest profit by combining stakeholders' expertise (public or private or their combination) and finding the technology application that suit their needs;

- Investing in compatible systems to harness the full potential of the technologies by endorsing and disseminating standards to be used by all related industry.

Reducing investment costs might increase the adoption of PATs. Joint investments (e.g. through farmers' cooperatives) are considered as an option for small farms investment cost reduction (Kutter et al. 2011). However, outsourcing of field management tasks to service providers is more probable (Kutter et al. 2011). Agricultural contractors might be major driving forces behind the adoption of PA over the next 10 years, especially in areas with smaller-sized farms. Engaging contractors and consultants with the appropriate tools, allows interested farmers to evaluate the technology before investing heavily in PA tools. Meanwhile farmers can estimate the degree of variation present in their fields and the potential benefits of PA for them (Jochinke et al., 2007). An extra advantage of the adoption through service providers is that data management by service providers is generally seen as acceptable by farmers as opposed to data management by technology providers and/or governments (Kutter et al. 2011).

During the CAPIGI-GEOAGRI conference (24-26 May 2016) a special session was dedicated to mainstreaming precision agriculture. The solution to existing barriers were discussed by several speakers.

To overcome the problems with incompatibility, the PA industry is already converging and standardising their systems in order to allow different makes to be used in an integrative way on the farm. More in particularly, companies are working together in the Agricultural Electronics Foundation (AEF) to overcome incompatibility problems.

To overcome the low trust on internet-based data storage, for instance 365Farmnet decided to use only EU based server farms. And there are facilities in this and other Farm Management Information Systems to give access to trusted parties by the farmer himself. Trust must be earned, but it can also get lower priority when farmers have benefits from sharing data.

Also the problems with GPS operation (e.g. signal loss and interoperability problems between brands), are being solved bit by bit. GNSS guidance systems require a constant connection to the satellites. The emerging Galileo system will provide more satellites in space and hence reduce the chances of broken connections. Also, receiver software is updated to get a lower effect of a broken connection. To get high-accurate locations again, a procedure called re-convergence needs to take place, which is typical to RTK systems; less accurate navigation like EGNOS based augmentation does not have this issue. Brand interoperability is getting solved by the manufacturers, who realise that this former 'lock-in' feature is now working against them.

The longer term vision of PA involves the perspective of farm adoption of PA technologies based on autonomous machines and not on traditional agricultural machinery (Blackmore et al. 2006). This is now starting to take form. The outlook for autonomous machinery is still confirmed by visions presented by machine manufacturers (CEMA, 2016) and research projects (e.g. RHEA, 2016).

2 Typology of Precision Agriculture Technologies

A wide variety of tested PA technologies (PATs) exists, ranging from only a parallel tracking system on a tractor with Differential Global Positioning System (DGPS, a GPS system which is supplemented with a series of ground-based stations, giving enhanced accuracy (i.e. down to 10 cm) compared to the normal GPS accuracy, which is around 15 m) to a full suite of PATs with full mapping capabilities of the fields, variable rate applications (e.g. fertiliser) and automated guidance systems.

The list of PATs here presented, focuses on:

- PATs that can be used in various types of crops: arable crops, orchards, vineyards, field vegetables;
- PATs that can be fitted into various farming procedures;
- PATs that are available at present, in the near future (i.e. within 5 years), or by the year 2030.

Any predictions for future PATs development should be treated with care, because the technology for PA is changing rapidly. For example, the Real Time Kinematic-GPS (see section 3.1.1.1) is now in widespread use for auto-steering systems (see section 3.1.2), but was far from common 10 years ago.

In the literature there are only three attempts to provide a typology of PATs. One of the most prominent studies on PA (McBratney et al. 2005) classifies PATs in three main categories:

- Hardware and sensors (i.e. positioning and guidance, crop sensing for water stress, nutrients and yield sensing, environmental sensing, seed bed preparation, fertiliser placement in the soil profile);
- Data Analysis and Decision Support Systems (i.e. protocols and standards for field data layers production, methods for data analysis for delineation of management zones, easy-to-use software);
- Commodity and whole-farm focus (i.e. development of DSS to apply commercially in farms including environmental impact assessment, apply PA at farm level and not at field level).

Based on the JRC Report on Precision Agriculture and New CAP, Zarco-Tejada et al. (2014) categorised PATs for crop and livestock farming in a linear manner (i.e. following the timeline of use of the technologies) as follows:

- remote sensing;
- guidance systems;
- variable rate applications.

Finally, from the FP7 project FutureFarm, Schwarz et al. (2011) have provided the most comprehensive typology of PATs, divided into three main categories:

- **Guidance systems** (i.e. hard- and software that guide tractors and implements over a field.), which includes all forms of automatic steering/guidance for tractors and self-propelled agricultural machinery.
- **Recording technologies** (i.e. sensors mounted on ground-based stations, rolling, airborne or satellite platforms, gathering spatial information), which includes field surveying, soil mapping, yield mapping, etc.;
- **Reacting technologies** (i.e. implements, hard- and software that together can vary the placement of agricultural inputs in the field) Variable rate applications, accompanied with other important parameters, such as GPS accuracy, level of PA technology, farming systems and cropping systems. This includes technologies like variable rate application of seeds, fertiliser, lime, pesticides, etc.;

The subdivision of Schwarz et al. (2011) is used for the PATs list in chapter 3.

Schwarz et al. (2011) also defined a list of the main variables (farming system(s), cropping system(s), time slice, PA starting level, PA data integration, knowledge support and farmers motives) for defining PATs. These main variables are explained in Appendix A. Further in Appendix A, a comparison of all PATs on the basis of these variables is given.

All three categories of PATs generally need some kind of geographical positioning system (GPS), which forms the backbone of PA. The term Global Navigation Satellite System (GNSS) is the generic term for all geographical positioning based on satellites, like the European Galileo system and the American GPS. GNSS is most closely related to the guidance technologies, as it provides geo-spatial positioning, and it is therefore included into this category.

3 PATs description

In this chapter, all types of technology relevant to PA are technically described. The list divides individual technologies into the three categories described in chapter 2 (guidance, recording and reacting technology) and their economic, environmental and social impacts are specified and extensively discussed.

Research into the economic impact of each PAT is discussed mainly but not exclusively from the farmer's point of view.

The focus of the environmental impact lies on the environmental effects on nitrogen emissions, especially N_2O, but other environmental impacts (e.g. nitrogen enrichment of surface waters) are also discussed.

From the social impact point of view, the effects of each PAT on farmers' lives, on rural areas and on people in rural areas are extensively discussed.

The PATs list is also summed up in Figure 1.

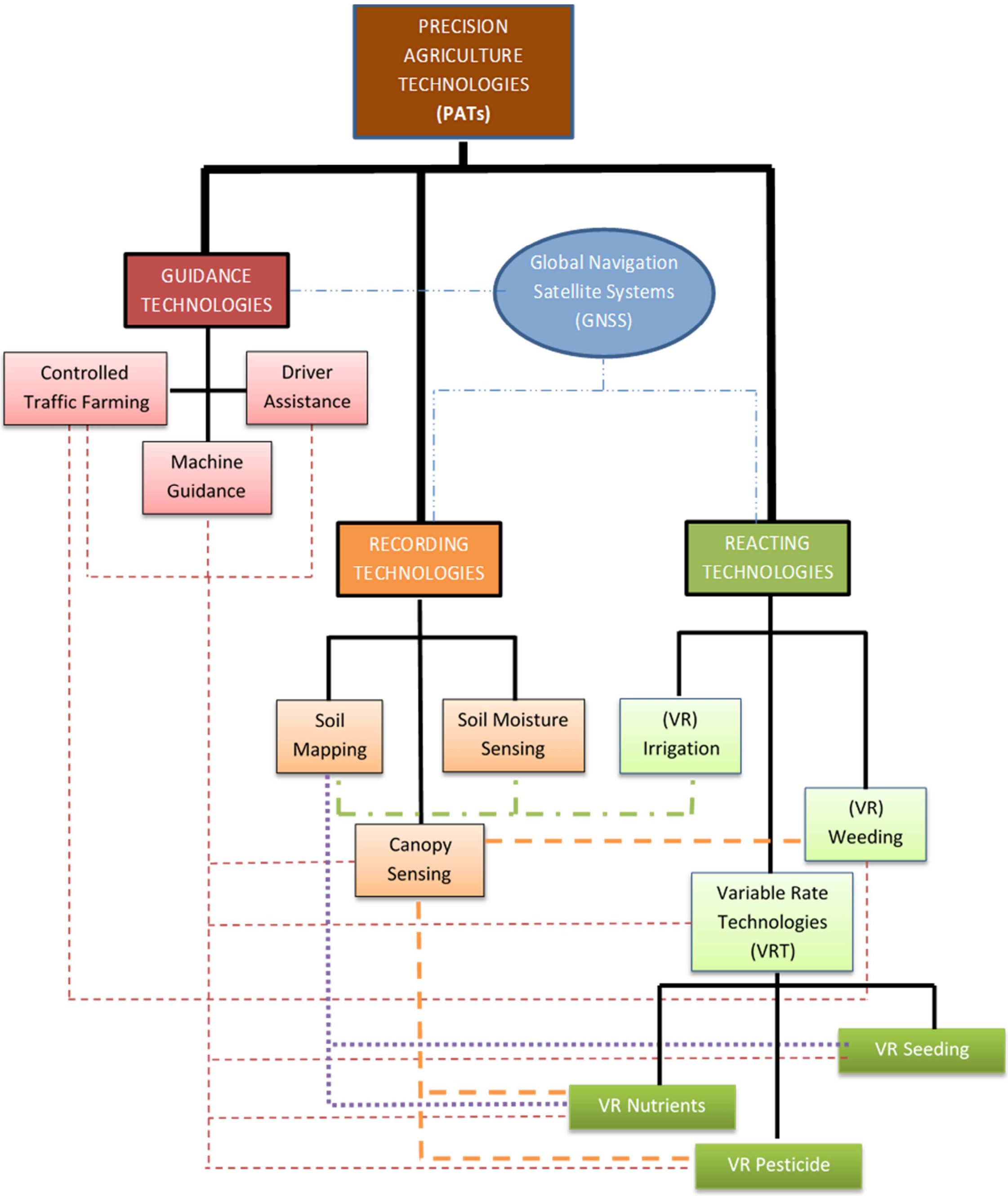

Figure 1: PATs list overview

3.1 Guidance technology

This part of the review is restricted to technologies for directing the movements of propelling equipment (e.g. tractors, harvesters) over fields. The guidance of implements is handled under section 3.3.

Guidance technologies are systems that pilot machinery using GNSS. They help the farmer in measuring, mapping, responding and using the spatial aspects of his fields. The advent of satellite navigation in the '90s of last century enabled automatic and continuous positioning which has since resulted in many different applications. This chapter starts with an introduction into satellite navigation, which is the backbone of guidance technologies, and further discusses essential precision agriculture technologies that are based on it.

3.1.1 Global Navigation Satellite Systems (GNSS)

3.1.1.1 GNSS systems

Satellite navigation provides a precise location on Earth to any device that can receive the radio signals from navigational satellites and compute coordinates out of these signals.

The first and best known system is the *Global Positioning System Navigation Satellite Timing And Ranging* (GPS-NAVSTAR), or just GPS. This is the first space-based radio-navigation system comprised of a dedicated satellite constellation. It has made remarkable contributions to many domains including agriculture for decades already. With the emergence of other similar satellite constellations, the need for a generic name was required. This generic name is Global Navigation Satellite Systems (GNSS). There are currently 4 GNSS systems available (each one using its own satellite constellation):

- **GPS**-NAVSTAR: governed by the U.S. Ministry of Defence.
- **GLONASS**: This is the Russian GNSS system, operated by the Russian army;
- **BeiDou**: The Chinese GNSS. The second version of the system also carries the name Compass and has global coverage. It is also under military governance;
- **Galileo**: Galileo is the European GNSS and the first civil governed GNSS. It is in development and the planning is to have operational capacity in 2018.

In addition, there are the regional systems of India (**IRNSS**) and Japan (**QZSS**).

The most common and simple set-up of the system as it is found nowadays in e.g. mobile telephones, car navigation sets and photo cameras, has a single frequency signal and a simple antenna. This provides locations with an inaccuracy[11] of 5-10 meters, depending on the number of satellites in view (4 satellites is the minimum, more satellites in view provide higher accuracy). Professional, survey-grade equipment with two frequencies, amplified antennas and correction signals from a ground network provide 2 cm inaccuracies in horizontal positioning and solutions are developing for even higher accuracy. The vertical inaccuracies are much higher and are in the range of 15-20 meter for simple receivers and 20-30 cm for survey-grade equipment.

All GNSSs together comprise of over 70 satellites. When all four systems (GPS, GLONASS, Galileo and BeiDou) are fully deployed, this number will reach 120 satellites (Li et al., 2015). The more satellite constellations are used the better the navigation performance is.

In order to use GNSS, one needs a GNSS receiver: a device that computes the position based on the radio signals transmitted by the satellites. The GSA provides market outlooks for the GNSS receiver market in agriculture. In their market report of 2015 GSA expects machine guidance to have the largest share in revenues for receiver manufacturers. This will peak in 2018 and then taken over by more advanced applications. Also, GNSS controlled (and tracked) operations can automatically be included in Farm Management Systems and through location be linked to other data

[11] Although accuracy and inaccuracy are interchangeable terms, inaccuracy is preferred in GNSS as it perceives the unknown error.

and data sources. This will allow farmers to improve on their smart farming practices even more.

3.1.1.2 GNSS augmentation

The quality of the antenna, the computation algorithms as well as transmission interference (e.g. obstacles like buildings or trees or atmospheric disturbances) have an influence on the accuracy of the system. Improving the accuracy of GNSS systems is called GNSS Augmentation.

Augmentation systems are ground infrastructures that complement GNSS systems to increase the positional accuracy. There are different types of augmentation systems but all are based on measuring errors at known locations and calculate a correction to the position signal that is shared with other receivers through for instance radio communication.

Lower inaccuracies come at a higher cost. First of all, receiver's chipset, the antenna and other electronic components are more expensive and secondly the best possible quality positioning requires a ground infrastructure.

Improving the GNSS positioning quality can be done in different ways. The most common methods/approaches/tools are Local Differential GPS (DGPS) and Real Time Kinematics (RTK).

Local Differential GPS (DGPS) uses a second receiver at a known point to compute (local) errors in the atmospheric transmission. In North America and in Europe, this method is further elaborated in Space Based Augmentation Systems (SBAS) called WAAS (Wide-Area Augmentation System, America) and EGNOS (European GNSS Navigation Overlay System). Both systems transmit correction codes for their respective territories via telecommunication satellites to receivers. In this way, the inaccuracies for systems are improved to below 1 m. Further improvements can be attained with more dedicated augmentation systems that deploy two frequencies, like the commercial Starfire and Omnistar systems, which reduce positioning errors to decimetre inaccuracies.

Real Time Kinematics (RTK) (Figure 2) is a differential GNSS technique originated in the mid-1990s that provides high performance positioning in the vicinity of a base station (ESA, 2015a). An RTK set-up consists of a **base station** (a receiver at a fixed, known location), one or several **rover users** (receivers that move and of which position data is required), and a **communication channel** with which the base broadcasts information to the users in real time. In a clean-sky location, the main errors (**satellite clock bias**, the **satellite orbital error**, the **ionospheric delay** and the **tropospheric delay**) in the GNSS signal processing are constant, and hence they cancel out when differential processing is used.

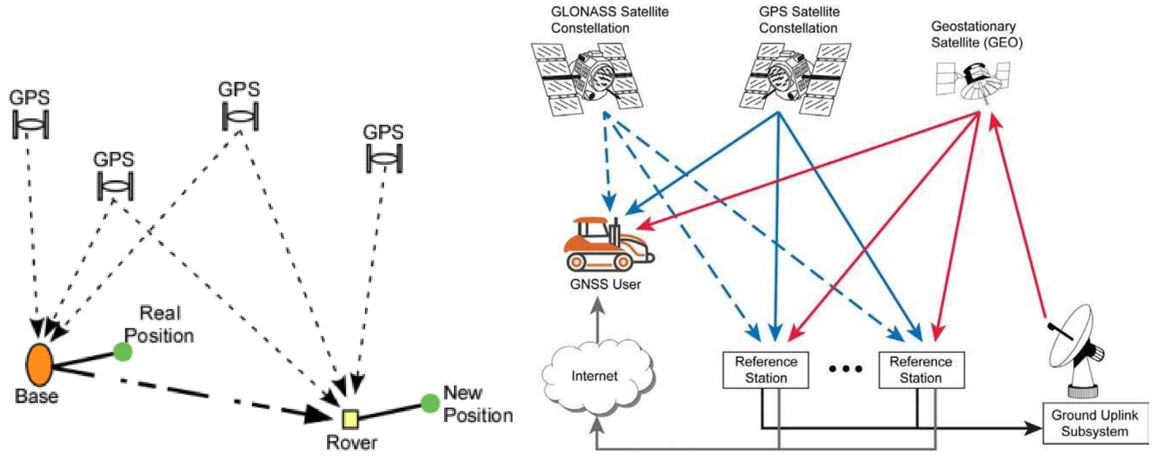

Figure 2: RTK technology (left, source: Rugged Bits, 2016) and Precise Point Positioning (right, source: Forsberg Services, 2016).

An upcoming technology is the Precise Point Positioning (PPP) (Figure 2) that combines precise satellite positions and clocks with a dual-frequency GNSS receiver (to remove the first order effect of the ionosphere) providing position solutions with **centimetre to decimetre inaccuracies**. PPP just requires precise orbit and clock data of the satellite, computed by a processing centre with measurements from reference stations from a relatively sparse station network (thousands of km apart would suffice). This makes PPP a very attractive alternative to RTK and works without a base station. On the contrary, the PPP technique is still not as consolidated as RTK and requires a longer convergence time (in the order of tens of minutes) to achieve the least inaccuracy. Currently, several consolidated post-processing PPP services exists. However, real-time PPP systems are in an incipient development phase.

There are many manufacturers of GNSS receivers used in agriculture. The most commonly known brands are Trimble, Navcom (a John Deere subsidiary) and Topcon. There are also many providers of correction signal and services. Omnistar (a Trimble brand), Starfire (Navcom brand), Novatel and many others provide these services. Locally in the Netherlands a cooperation of farmers and contractors made a collective effort to procure dedicated correction services for their members, called MoveRTK (www.movertk.nl). This service provides 2 cm inaccuracy everywhere in the country with the use of virtual base stations, so no installation on the ground is required.

The European GNSS Agency (GSA) is governing the European satellite navigation system Galileo.

The type of agricultural application determines the required quality (inaccuracy) of the GNSS system. Figure 3 graphically displays the inaccuracies of different GNSS systems against required ranges for different agricultural applications.

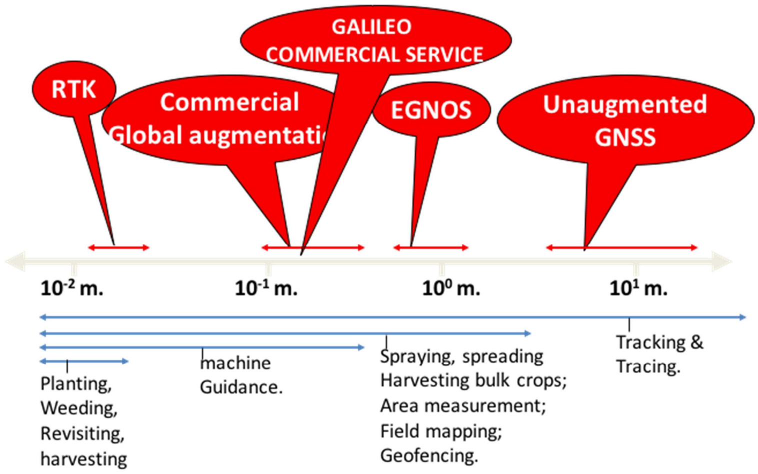

Figure 3: Relation between GNSS inaccuracies and applications (van der Wal, 2010).

In Figure 3 the different inaccuracies are put on a logarithmic scale (the grey bar in the middle) with text bubbles indicating what inaccuracies different GNSS systems provide. Below the range of required inaccuracies for different agricultural applications is shown (not all in scope as PATs).

Systems with better accuracies can be used for more applications. But as mentioned before, better systems have a higher cost. In particular, when GNSS is used for automatic guidance, receivers must be coupled to the tractor-steering hydraulics. This is an expensive fit at a cost of about €25.000 or more. New tractors are GNSS prepared off-factory and in the bigger segment (>100 hp[12]) more than 50% are delivered off-factory with machine guidance, which is at a price range of 80,000 – 130,000 Euro (depending on options and discounts) (all info: personal communication John Deere). In this way, the costs of adoption are much lower than with post-sales fits.

3.1.1.3 Economic impact of GNSS

The FP6 funded project FieldFact (GJU/06/2412/CTR/FIELDFACT) and the FP7 funded project UNIFARM (Contract nr. 287206) were both focussed on characterising and promoting the use of GNSS in agriculture. These projects followed the uptake of GNSS in agriculture. First, GNSS use started in agricultural surveying: Payment Agencies of the EU Member States use GNSS systems to measure and locate fields for the purpose of agricultural income support. As the size of the field has an economic impact on the farmer (e.g. subsidy amount) the quality of the measurement is very relevant. The effect of error on field boundary measurement is estimated by Bogaert et al. (2006) and protocols for quality testing were developed in FieldFact. These tests were formalised by NavCert in a certification protocol (NavCert, 2016).

In parallel to the administrative and control application, the use of GNSS in fieldwork has taken off. The economic impact here is that GNSS technologies applications have a direct effect on farm income. Research stations like PPO in the Netherlands and Harper Adams in UK, to give just two examples (van der Schans et al., 2008), estimated that GNSS application reduces overlaps in fieldwork, leading to an efficiency improvement of 10-15% that directly translates to farm income. The exact savings are dependent on many factors including field layout, crops cultivated and of course the current accuracy of the driver where the savings are set-off against. Although GNSS technologies by themselves do not have economic impact on farms, they are a generic

[12] hp = Horse Power

enabler for almost every PA application. Further economic impacts are discussed within this chapter with dedicated GNSS-based PATs, like driver guidance, machine guidance and controlled traffic.

In the mid-term review of the European satellite navigation programmes as reported to the European Parliament and Council (ref. COM(2011)5), the European Commission anticipates an impact of GNSS on agriculture as an increase of farmers productivity of 10-20% due to GNSS as well as a reduction in CAP enforcement costs.

In general, GNSS technology helps farmers to reduce overlaps and optimise their field traffic. This is a relevant saving in time as well as savings in inputs like fuel, fertiliser, seeds and pesticides.

3.1.1.4 Environmental impact of GNSS

GNSS technologies do not offer direct environmental impact themselves, but rather through their application in different PATs. The environmental impact is discussed in these PATs sections. In general, GNSS technology helps farmers to reduce overlaps and optimise their field traffic. Hence a significant reduction in fuel and inputs is anticipated. Also, controlled traffic reduces soil compaction which is an important impact for improving soil conditions and soil protection. As the environmental impact is related to reduced inputs and higher efficiency, it is a win-win with economic impact. This makes the application of GNSS a very interesting technology.

3.1.1.5 Social impact of GNSS

Similar to the other impact sections above, the social impact of GNSS technology depends on its applications. These applications will be discussed in the respective PATs sections. In some applications, GNSS technology is easily taken up and farmers have accustomed to depend on it. This means that without GNSS – or without the correction services – machines are stalled. Similar to other new technologies, the investments and trainings required cause that contractors are early adopters of GNSS based guidance systems and as such create benefits for themselves to expand their work. This may change the setting in the rural economy.

GNSS receivers do not offer direct social impact, but it is vital together with the GNSS technology itself for any PA application (real-time position tracking).

RTK and PPP technologies do not offer direct social impact, but as it provides very high location precision it can be applied in PA, reducing operation time (less working hours) while also increasing economic output. This of course is linked to specific applications.

3.1.1.6 Discussion - GNSS

GNSS is the de facto enabling technology of precision agriculture. Without GNSS many other PA technologies would not have been possible. Its importance can therefore not be overstated.

3.1.2 Machine guidance

Applications of GNSS for steering and guidance have been developed in two different systems: driver assistance and machine auto-guidance.

Driver assistance works through separated add-ons that help the driver keep his line in the field. These aids are not integrated in the tractor's systems and can be simply installed. Besides guidance, many of these systems also provide tracking options (similar to fleet management options) that help integrating machine movements and operations in farm management information systems.

Machine auto-guidance systems are integrated in the tractor’s hydraulics and can directly take over steering operations. These more advanced systems are coupled to on-board computers that allow for headland steering, section control and that accept drive-maps (routing) and task maps to operate agricultural implements.

Driver assistance

GNSS steering aids have gained increasing interest among farmers as they enable farm machinery to follow straight lines to reduce overlaps and avoid gaps of the tractor and equipment passes. These systems help farmers to reduce fuel costs, input costs, time, labour, soil compaction and increases the overall field efficiency. The driver assistance is offered essentially in two options, lightbar and auto-steer (Figure 4). Both systems use a GNSS receiver to identify the tractor’s location in the field. The basic difference between the two systems is that a lightbar requires the operator to manually adjust steering, while auto-steer technology connects to the steering wheel and adjusts the steering automatically, allowing the operator to monitor the field operation of the implement instead of wheel steering.

Figure 4: Examples of commercially available driver assistance systems. Trimble EZ-Steer (left, source: Trimble, 2016) Raven RGL lightbar system (middle, source: Raven, 2016) and AgLeader OnTrac3 auto-steer system (right, source: AgLeader 2016)

Machine auto-guidance

All manufacturers of tractors now implement direct machine guidance with GNSS off factory. Here, the navigation signals are directly transferred to the hydraulics of the machine to manipulate the wheels. On-board computers interface the system with the driver. The driver simply selects a speed and driving map/pattern. The difference with auto-steer is that this is fully integrated in the tractor. Figure 5 shows a typical advantage of machine auto-guidance: the high precision allows for routings that are alternative to pass-to-pass thus optimising logistics. Figure 6 shows a typical user interface. Here the driver is no longer operating the tractor, but rather controlling the tractor’s own operations.

Figure 5: Machine guidance with RTK allows efficient field operations. As shown here, the planters can skip rows and filling in later thanks to precise machine guidance (photo: Jeroen Verschoore).

Many studies have compared automatic guidance and manual guided operation. The use of an auto guidance system on sugar cane planting operation gathered an accuracy of 0.033 m pass to pass, which was five times greater than what was obtained by the manual steering system (Baio and Moratelli, 2011). Rojo and Fabio (2012) compared a sugar cane harvester with an auto-guidance system to a manually-guided machine. Their work revealed that the use of an auto-guidance system during the day and night periods increased the pass-to-pass accuracy relative to the planned row track, while it did not significantly decrease the sugar cane loss. Shinners et al. (2012) studied the influence of driving experience, operating speeds with manually and automatically guided mowers in a variety of field conditions on 15 farms. They concluded that automatic guidance improved efficiency by eliminating time spent covering already mowed ground, by reducing operator fatigue, and by ensuring a uniform cutting pattern and swath density. In their study, the automatic guidance system reduced overlap from 5.03% to 2.34%. To test different guidance systems, a vision sensing system was developed by Easterly et al (2010). They estimated that higher travel speeds significantly increased measured auto-guidance error, but no significant difference was observed between pass-to-pass and long-term error estimates. Such systems could be used for evaluation of the performance of auto-guidance systems on the market or in prototype stage.

Figure 6: Board computer User Interface showing AB lines and different passes. Source: Farmers Guide, 2016.

Auto-guidance helps farmers in avoiding gaps and overlaps in his multiple passes with the tractor, which is mainly caused by operator error or fatigue. The ability to increase speed during headland turns and more quickly identify re-entry points were recorded to reduce machinery time requirements by 5% for planting and 10% for fertiliser application (Shockley et al. 2011). The use of an RTK-based guidance system was tested for location mapping of planting events occurring on the tractor-drawn tomato transplanter (Perez-Ruiz, et al., 2012). They managed to automatically create centimetre-accuracy plant maps for subsequent precision plant specific treatment systems. On citrus the use of an auto-guidance system was applied on the furrows opening for transplanting (Oliveira et al., 2011). With the auto-guidance system it was possible to work with higher speed and as a consequent larger field capacity. The user reported operation cost of the opening furrow to be smaller for the auto-guidance system than for the conventional system, especially due to the labour involved on the conventional system (Oliveira et al., 2011).

Adoption of guidance systems

GPS guidance systems are regarded as the most adopted PA technologies worldwide. The most recent adoption trends have been recorded by the PA dealership survey conducted by Purdue University, USA in 2013 (Holland et al., 2013). This survey pointed out the increasing trend of using auto-steer and the declining trend of light-bar systems. In respect to GPS correction systems, 70% of respondents used the WAAS correction (a free service for the USA only), while 22% used a personal RTK base station, and only 17% had purchased a satellite correction such as OmniSTAR XP and StarFire2. In Europe the situation is rather different. A survey in the Netherlands in 2013 showed a 65% uptake of GNSS guidance systems in arable farms, with a high uptake of RTK at 50% average of the GNSS systems implemented, with an increasing tendency linear to farm size (van der Wal, 2014). In Germany, 36% of farmers use auto guidance on their farms while only 9% and 1% of the Danish and Finnish farmers, respectively, used auto-guidance (Figure 7) (Lawson et al., 20111).

Among the most common brands used for auto guidance systems, John Deere is the most common in Germany, but Agrocom, Claas and Center Line are also commonly used. In Denmark, John Deere and Claas are most common. In Finland, the brand Agrocom is the one reported by a single farm.

The main drivers of adoption are time savings, more accurate field work, reduced driver fatigue and more attention for the cultivation activity (van der Wal, 2014). Generally, farmers who had adopted auto-guidance systems have from medium (200-300 ha) to large farms (>300 ha) (Pedersen et al. 2015). In general, this is economic size, sometimes also related to physical farm size (>100 ha). The farmers' age appears to be a factor in adopting auto-guidance (D'Antoni et al., 2012).

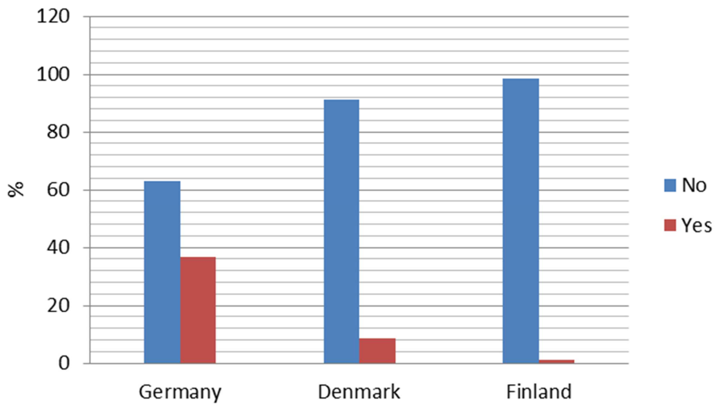

Figure 7: Adoption of auto guidance among farmers in Denmark, Finland and Germany (Lawson et al. 2011).

3.1.2.1 Economic impact of machine guidance

Guidance technologies improve pass-to-pass efficiency by enabling machinery to be accurately guided along a precise track, preventing overlapping applications. Therefore, it is expected that all main agricultural inputs (e.g. seeds, fertiliser and pesticides) will be reduced, which means lower costs and better margins for the farm. As an example, machine guidance during planting and fertiliser application led to cost savings of approximately 2.4%, 2.2% and 10.4% for seed, fertiliser and tractor fuel, respectively (Shockley et al. 2011). In peanut digging operations a study revealed average net returns between 94 and 695 $/ha for the use of auto-steer (Ortiz et al., 2013). Hence the direct economic benefit of guidance is in cost reduction. Machine guidance is furthermore an important enabler of controlled traffic farming (CTF) and variable rate technologies (VRT) utilisation. For many farmers, machine guidance is the entry technology for PA. Guidance can be used for many field operations such as seeding, tillage, planting, weeding, harvesting (Abidine et al., 2002) and for enabling autonomous vehicles.

The impact of widespread adoption of CTF coupled with auto-guidance in Denmark was assessed by Jensen et al. (2012) looking at the four major arable crops in Denmark (wheat, rape seed, maize and sugar beets). They estimated that it may be possible to reduce costs of fuel by 25-27% in cereals due to less overlap, and report 3-5% savings in fertiliser and pesticides in this crop.

An economic analysis of farms adopting auto-guidance systems showed that systems with inaccuracies below 2.5 cm are most profitable for larger farms, while systems with less than 10 cm inaccuracy are a better economic alternative for smaller farms (Bergtold, et al., 2009).

3.1.2.2 Environmental impact of machine guidance

In general, the efficiency gains (by reducing overlaps) of auto-guidance application directly translate into reduction of fuel and inputs and therefore has a direct environmental impact. Other environmental impacts are associated to controlled traffic farming and variable rate technologies (Vašek and Rataj, 2013).

3.1.2.3 Social impact of machine guidance

Guidance technology allows the operator to concentrate more fully on his task. Time that would normally be spent keeping the tractor "straight" is now spent ensuring the task is being performed well and the operator is also less fatigued. This is of particular importance at times of peak workload, i.e. during harvest and planting operations (Halpin et al., 2008).

The uptake of machine guidance with its consequent savings in time and inputs may be a driver for farm enlargement. Saving time on 5 fields all together may allow for cultivating a sixth.

The big (social) drawback of guidance is the increased dependency on technology; When the receiver is broken, or the correction signals cannot be received, it is impossible to maintain the same accuracy of machine movement with manual driving.

3.1.2.4 Discussion – machine guidance

In Europe in particular, machine guidance is for many farmers the entry technology into precision agriculture - compared to yield mapping which had that role in North America. The impact of guidance technologies focuses in first instance on economic benefits, mainly due to time benefits and inputs reduction, as well as facilitating more attention of the driver to the implement and the action. As GNSS and guidance are the basis of variable rate technologies and other PATs its impact can be considered significant also in the environmental and social aspects.

3.1.3 Controlled Traffic Farming (CTF)

Controlled Traffic Farming (Figure 8) is a system which confines all machinery loads to the least possible area of **permanent traffic lanes**. Current farming systems allow machines to run at random over the land, compacting around 75% of the area the first time it is stepped/driven upon and 90% by the fourth time (Colorado State University, 2016). A proper CTF system can reduce tracking surface, and thus compaction, to just 15%, even over several years (Gasso, 2013). The permanent traffic lanes are normally parallel to each other but the definition does not preclude tracking at an angle. CTF allows optimised driving patterns, more efficient operations (i.e. reduced overlaps). As all operations are aligned, input applications can be targeted very precisely relatively to the crop rows.

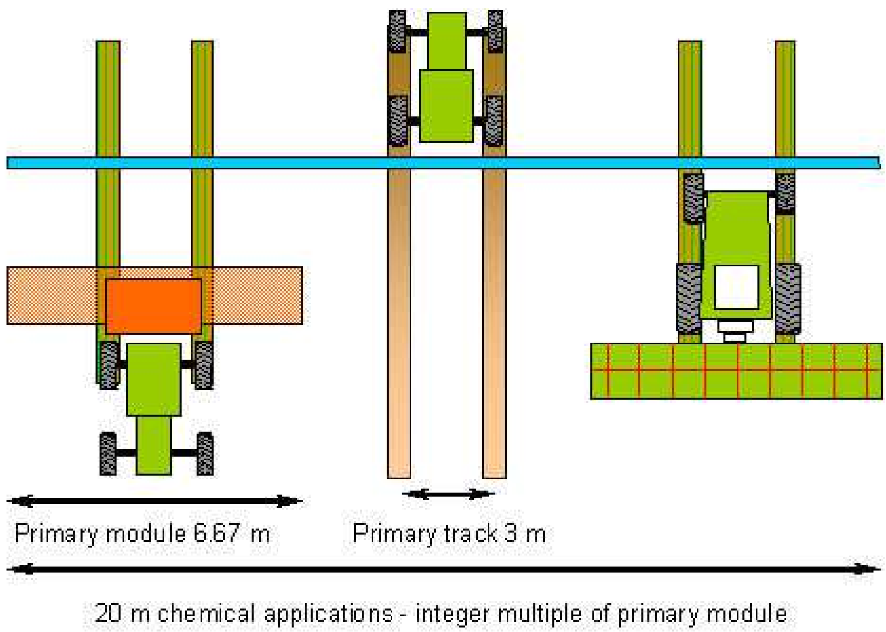

Figure 8: Controlled Traffic Farming. Source: CTF Europe, 2016.

Controlled Traffic Farming (CTF) management can play a key role in sustaining soils and future crop production, which are today threatened by heavy machinery traffic and intensive production systems. To play this role in sustainable intensification, CTF needs to be developed to become a mainstream technology. Therefore, it is required to facilitate and support the development and mainstreaming of CTF at a time where development in allied technologies such as headland management systems are increasing growers openness to the adoption of these systems.

When CTF is combined with headland management type systems it will further alleviate the problems of soil compaction. Soil compaction, because of continually increasing machine weight, is of paramount importance for EU farmers (Nawaz et al. (2016) estimated that approximately 33 Million ha in the EU are compacted) in terms of yield loss, reduced nutrient and water efficiency, soil degradation and alleviation costs. While management practices such as deep soil loosening, the use of certain cover crops and crop rotation, can help alleviate some of the structure damage, these approaches are costly and at best only partly successful. It is better to preventing or avoid soil structure damage then repairing it afterwards as a good soil structure is difficult to restore. CTF offers scope to restrict the extent of soil structure damage. It involves the configuration and application of the field/machinery operations in a way that minimises the soil compaction, by using permanent traffic tracks. CTF also enables other compaction-minimising traffic patterns, such as load determined traffic routing.

Restricting and controlling traffic can facilitate the sustainable adoption of reduced-cultivation, conservation agriculture (CA) techniques, where topsoil compaction is often a constraint. CTF combined with CA techniques like reduced or no-tillage and the use of crop rotations and legume cover crops, will enhance the CTF effects and can lead to higher yields, reduced GHG emissions, reduced use of applied nitrogen fertiliser, lower energy requirements, and reduced water requirements due to improved water holding capacity and improved rooting.

Moreover, many areas in Europe have relatively small arable field size and a preference to maintain hedgerows and other field related features for biodiversity reasons, resulting in relatively large headland areas (as machines need the space to turn). As crop performance and the levels of inputs applied to headlands can vary substantially from the main field area, any resulting crop loss or inaccurate application of inputs can have a very large effect on profitability. Similarly, mechanisation efficiency is impacted by headlands. Crop production costs and losses on headlands have not been accurately assessed in these situations. The availability of accurate positioning systems facilitates more accurate input control (seed, fertiliser, plant protection products) on field headlands. This coupled with CTF on field headlands gives the possibility of restricting damage to defined areas and optimising headland production.

Appropriate agronomy and management is used to maximise the potential of both the cropped and wheeled areas for their specific purposes. CTF means the repeated use of the same wheel tracks for every operation, with all machines having the same wheel track (the distance between the left and right wheel centers) and all implements having a particular span (base module). Percentage area wheeled can be reduced to 30 – 40% even with two different track and implement widths (CTF Europe, 2016).

Adoption of CTF

Currently, the adoption of CTF in Europe is limited. Approximately 50,000 ha are known to be under CTF management (Prof. Sörensen, Aarhus University, personal communication). Although the benefits of CTF have been demonstrated for Australian and Northern European farming systems large scale adoption has not yet occurred even though there is major interest on the subject primarily among large scale farmers. Kingwell and Fuchsbichler (2011) show that CTF is being slowly adopted around the globe. The same authors found that in the USA, automated guidance systems were used on 21% of the crop area in 2009, up steadily from 4% in 2005.

There is now an opportunity to integrate full CTF systems with other position-based machine control systems and capitalise on growers' increasing interest in this area to increase adoption.

In order to create paths for CTF, Alterra (Wageningen UR, NL) has developed an optimisation algorithm to calculate the most optimal routes for paths on irregular shaped fields (see Figure 9). This is now offered as a service to farmers and is known as Geospatial Arable fields Optimisation Service (GAOS). The service is currently extended with the capacity-constraint algorithm as developed by Aarhus University in a more advanced path planning and routing optimisation service called Optimove (WageningenUR, 2016). Farmers that want to apply CTF need a way of managing their tracks. A drive-map and a routing plan is therefore a necessity to make efficient use of the technology.

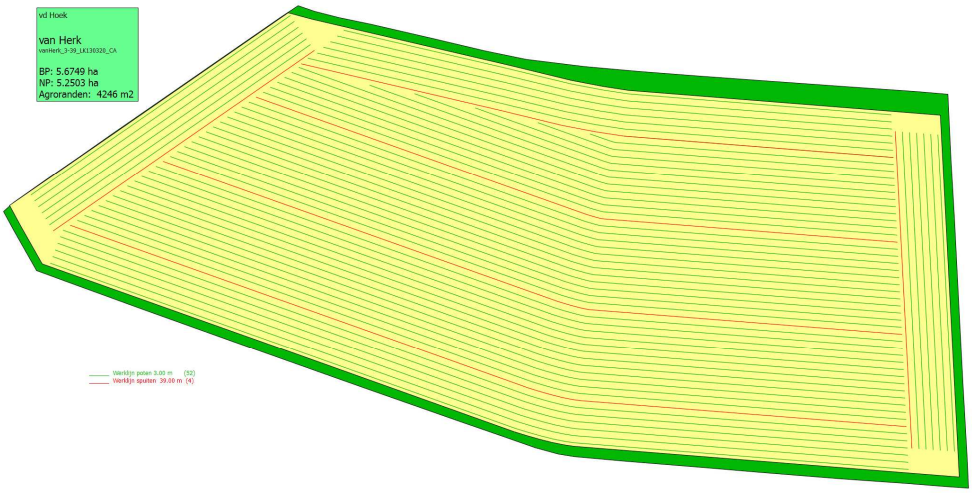

Figure 9: Optimised path planning for an irregular shaped field for CTF. The red lines are for the sprayer and the green lines are the paths for planting. Source: Alterra, 2016.

3.1.3.1 Economic impact of CTF

CTF is a simple way of dramatically reducing production costs (time, fuel & machinery use and maintenance) and at the same time increasing crop yields – both of which are done sustainably increasing farm profit. According to CTF_Europe (2016), some farmers in Australia have cut their machinery costs by as much as 75% while their crop yields have risen. Similarly in the UK, the Colworth project (CTF Europe, 2016) is showing that lowered inputs combined with CTF is resulting in healthier crops and soils.

A report was published in Australia (Bowman, 2008) on the experiences of a group of farmers converting to CTF. Their main objective was in soil conservation. Although not scientific, the report provides insights in the type of data farmers and consultants are using to calculate economic impact.

Furthermore, a study on the potential impact of site-specific application and controlled traffic systems implemented on larger farms in Denmark (300 ha and above) has stressed how a reduction of fuel costs by 25-27% in cereals can be traced back to a lesser overlap, but also how 3-5% savings in fertiliser and pesticide in cereals can be obtained (Jensen et al., 2011).

3.1.3.2 Environmental impact of CTF

CTF can provide the following environmental benefits (CTF Europe, 2016):

- Improved fertiliser use efficiency. Research from around the world has shown that the uptake of fertiliser is improved by around 15%.
- Potential to retain more organic matter and soil living organisms. A soil that is little damaged by wheels or tracks tends to need little in the way of cultivation, and it is these activities which are most likely to oxidise more organic matter and kill soil living animals.
- Improved gaseous exchange. Better soil structure means that conditions will be more favourable for gases that are absorbed into the soil (e.g. methane) and to prevent harmful gases being produced through anaerobic conditions, such as nitrous oxide and methane, both of which are particularly damaging to the environment.
- Improved water storage. The greater number and larger size of pores in a non-trafficked soil means that more water infiltrates and is captured within the profile. This means that not only is there less potential for run-off and erosion but also that there will be more plant available water.

3.1.3.3 Social impact of CTF

The application of CTF has no particular additional social impact. The effects of machine guidance apply here too, maybe in a more exaggerated way. CTF is very popular in organic farming as it has a large effect on soil preservation. Hence, one may argue that CTF enhances the uptake of organic farming practices (Vermeulen et al., 2007). This is also a current debate in the Netherlands where organic farming and precision farming are mutually interested in their concepts and ideas and provide cross-overs.

3.1.3.4 Discussion

Controlled Traffic Farming has a significant economic impact, due to increased yield and reduced inputs (especially fuel). Furthermore, the reduction of soil compaction has significant environmental impact due to better gaseous and water distribution in the soil, which influences nutrient uptake by crops.

3.2 Recording technology

Recording technologies are used to monitor and store data from the farming site as regards to pedoclimatic parameters and crop factors during a full farming period (crop installation to harvesting) The PATs for recording and mapping are divided in the categories below:

1. Topographic and soil mapping;
2. Yield mapping;
3. Canopy mapping.

3.2.1 Topographic and soil mapping

The soil, as substrate of agriculture, is essential to produce food and feed. It included not just the soil chemical and physical composition, but also terrain aspects and climatological aspects. Improved technologies, including plant breeding, cultivation technologies and automation have imposed shifts in the land evaluation and nowadays cultivation of crops is not only a function of soil quality alone, for instance look at the extensive plantations in desert areas around the world. For precision agriculture, measuring specific aspects of soil quality will enhance the ability to understand and utilise soil heterogeneity for improved farming. Particular PATs related to soils are for instance variable rate seeding and fertilisation, based on the distribution of soil physical and soil chemical properties in a field. The different types of soil maps that are of use for PATs are discussed below.

3.2.1.1 Elevation maps

Elevation is a critical variable useful to understand production response of cultivation systems. It influences soil formation, water movement and cropping aspects (Whelan and Taylor, 2013). It can determine waterlogged areas, erosion risk, drainage restrictions, and often is related to soil type (Topography and Drainage, 2016).

Elevation data can be collected with a GNSS receiver. In many cases the data can be obtained by the auto-steering systems (see section 3.1.2) installed in the tractors for producing the elevation map. Using the data from the GNSS receivers, it is possible to produce a Digital Elevation Model (DEM) of a field or a farm, which is a digital model or 3D representation of this terrain's surface. This DEM can be used to identify specific terrain attributes, such as slope, aspect, curvature, solar exposure, landscape water flow directions and topographic wetness indices. A typical elevation map can be seen in Figure 10. Even a simple elevation map can help identifying the agronomic effect of topography or creating cut-and-fill maps for field levelling (Whelan and Taylor, 2013).

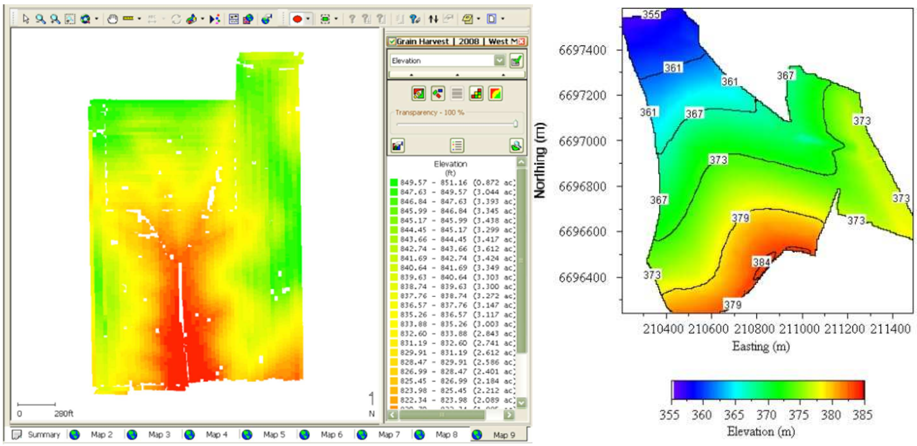

Figure 10: Examples of elevation maps. Source: University of Sydney Precision Agriculture Laboratory, 2016; Agleader, 2016.

Using the specific terrain attributes identified above, it is possible to produce (Topography and Drainage, 2016):

- Contours and topography (elevation) maps, which provide information on the slope of the farm;
- 3D modelling of ponding risk, runoff and velocity maps, which can identify which parts of the farm can flood due to cavity existence, can erode significant due to high runoff and can be dangerous for moving to certain directions due to possible high velocity development;

- Farm layouts designs, which provide the farm manager with a clear perspective of the terrain topography of his property (the slopes and contours of the land parcels are known and then the farmer can apply tilling practices to reduce soil erosion and sustain water and nutrients);
- Contour bank design (when slope is high, contour banks can be constructed to stop erosion and simultaneously increase or maintain good quality agricultural land), drainage plans (in areas with ponding issues it is possible to install drainage systems to avoid crop flooding), and on-ground implementation (change land use according to the terrain attributes of the farm under investigation); and
- Cut and fill land levelling designs, which can reduce slopes within the farm and optimise agricultural practices (less tractor and implement wear) with positive impact on the crop result as well.

3.2.1.2 Soil Mapping

Mainstream soil mapping starts by collecting soil samples from the field under investigation. In this way, information is collected regarding soil texture (sand, silt, clay), availability of nutrients for crops to grow (P, K, Ca, Mg, pH, lime) and other soil chemical compounds (organic matter, salinity, nitrate, sulphate, heavy metals) (Foth and Ellis, 1988). In addition, soil sampling is used to identify soil compaction, moisture content and other mechanical and physical soil properties. In general, samples are collected for a whole field and are representative for that whole field. There are different soil sampling schemes, such as grid or targeted sampling with bulking (with either area or point composite sampling) executed every 6 years, monitoring sampling (frequent sampling at a few representative monitoring plots) every year or spatially dense sampling (Schirrmann et al., 2011). None of the existing soil sampling practices has been recognized as the most effective (Wollenhaupt et al., 1997). Soil maps are produced by georeferencing the soil samples using either traditional topographic methods or GNSS receivers (most efficient).

3.2.1.3 On-the-go soil sensors

An alternative to soil sampling technique is the use of on-the-go sensors. Combined with a GNSS receiver this can create a map of soil properties. These soil sensors can be used in real-time for variable rate application.

There are different kinds of on-the-go soil sensors (Adamchuk et al., 2004; Adamchuk and Viscarra Rossel, 2014) which can indicate different agronomic soil properties (Table 2):

- Electrical and electromagnetic sensors measure electrical resistivity/ conductivity, capacitance or inductance affected by the composition of tested soil.
- Optical and radiometric sensors use electromagnetic waves to detect the level of energy absorbed/reflected by soil particles.
- Mechanical sensors measure forces resulting from a tool engaged with the soil.
- Acoustic sensors quantify the sound produced by a tool interacting with the soil.
- Pneumatic sensors assess the ability to inject air into the soil.
- Electrochemical sensors use ion-selective membranes that produce a voltage output in response to the activity of selected ions ($H+$, $K+$, NO_3-, $Na+$, etc.).

Table 2: Agronomic soil properties that can be provided by on-the-go sensors

Sensors	**Agronomic soil properties**									
	Soil texture (clay, silt and sand content)	**Soil organic matter or total carbon content**	**Soil moisture content**	**Soil salinity or sodium content**	**Soil compaction or bulk density**	**Depth variability (depth of topsoil or hard pan detection)**	**Soil pH**	**Residual nitrate or total nitrogen content**	**Other macronutrients (i.e. potassium content)**	**Cation exchange capacity and other buffer indicators**
Electrical and electromagnetic	X	X	X	X		X		X		X
Optical and radiometric	X	X	X				X	X		X
Mechanical					X	X				
Acoustic and pneumatic	X				X	X				
Electrochemical				X			X	X		

3.2.1.4 Soil Electrical Conductivity (ECa) Mapping

The above mentioned sensor types are in most cases experimental with good quality results, but not yet applicable in commercial products. Electrical conductivity is the technology that has found application in real life with consistent measurements.

Electrical conductivity (ECa) is linear with increased fertility and yield potential, with the exception of very high measurements that indicate high soil salinity (Whelan and Taylor, 2013). Different soil profiles may have similar apparent electrical conductivity (Dabas and Tabbagh, 2003). So, electrical conductivity reveals soil heterogeneity and conductivity values are affected by more than one characteristic: soil texture, salinity, organic matter, moisture content, and the depth of the clay pan (Mueller et al., 2003).

There are either apparatus measuring electrical conductivity by distance or using the invasive method. The first category of instruments does not come in contact to the soil, while the latter requires direct contact with the soil under measurement.

The most commonly used distant electro-magnetic instruments for vehicle-mounted or towed surveys are the Geonics EM38DD and DUALEM-21 (Figure 11). Different models of these instruments can be used for different Depths of Exploration (DOE) (Table 3). The measurements are averaged over this DOE. Some get measurements of more DOE simultaneously.

Figure 11: Geonics EM38 (left) and DUALEM 21 (right). Source: Sandberg GPR, 2016.

Table 3: Electrical conductivity instruments for different depth of exploration (DOE)

Brand	**Instrument**	**DOE (m)**
Geonics Ltd	EM38 horizontal	0.75
	EM38 vertical	1.5
	EM38-DD	0.75 & 1.5
	EM38-MK2 horizontal	0.375 & 0.75
	EM38-MK2 vertical	0.75 & 1.5
	EM31-MK2	6
	EM31-SH	4
DUALEM	DUALEM-1	0.5 & 1.6
	DUALEM-2	1 & 3.2
	DUALEM-4	2 & 6.4
	DUALEM-6	3 & 9.5
	DUALEM-21	0.5 & 1 & 1.6 & 3.2
	DUALEM-42	1 & 2 & 3.2 & 6.4
	DUALEM-421	0.5 & 1 & 1.6 & 2 & 3.2 & 6.4
	DUALEM-642	1 & 2 & 3 & 3.2 & 6.4 & 6.5

Regarding the invasive techniques, there are several attempts to provide mobile instruments that use cultivation discs as metal electrodes. The most common commercial products are provided by **Veris Technologies** (Salina, USA), of which **VERIS 3100** model (Figure 12) is mostly used globally.

Figure 12: VERIS 3100. Source: Veris Technologies, 2016.

The company provides six models that measure electrical conductivity (ECa) (**Q Series, Veris 3100, Veris 3150, OpticMapper, MSP, MSP3**) for different uses. The **OpticMapper** and the **MSP3** measure simultaneously Soil Organic Matter; while **MSP** and **MSP3** measure also soils pH (see section 3.2.1.5 for more information).

3.2.1.5 Soil pH maps

The pH level greatly affects the fertility of soil and quality of plant growth. Under alkaline conditions, the solubility of minerals decreases to the point that nutrient deficiencies occur. Plant growth is limited by deficiencies in iron, manganese, zinc, copper and boron. Phosphorus is also available in alkaline soils and high levels of calcium may inhibit the uptake of potassium and magnesium. Under acidic conditions, many soil minerals dissolve and increase the concentration of metal ions to toxic levels. The primary toxic metal is aluminium, but high levels of manganese and iron can also inhibit plant growth under these conditions. The nutrients phosphorus and molybdenum are less available in acidic soils and calcium and magnesium may also be deficient. Therefore, by gathering pH soil information and producing a pH map (Figure 13), we can consider acid tolerance crop types for acidic soils and salinity tolerance crops for alkaline soils. Soil nutrients are at their optimum availability in the range between 6 and 7. Most plants grow best in this range, although some type of plant growth can take place anywhere between 3.5 and 10. Based on mapped soil pH, measures can be taken to acids or bases and make the field suitable for a wider range of crops (Korte, 2001).

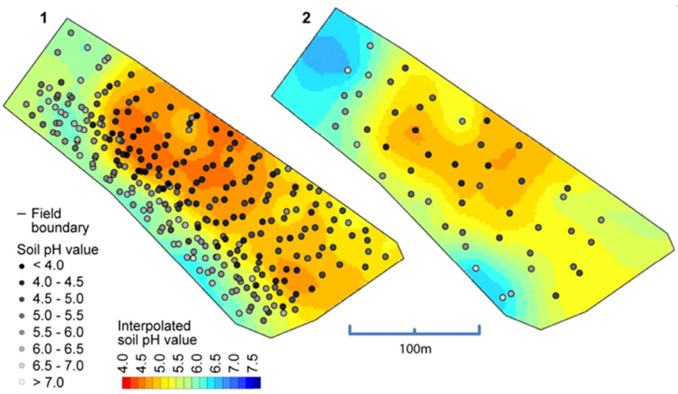

Figure 13: Example of soil pH map. Source: Schirrmann et al., 2011.

The quality of pH maps is predominantly influenced by sampling density, while other factors such as measurement errors are less important (Gebbers et al, 2009). Current standard sampling strategies do not allow for a density beyond 1 sample per ha because it involves manual soil sampling and laboratory analysis, which is costly and time consuming (McBratney et al., 2005). This is however inadequate to create a heterogeneity map of soil pH.

Currently, only one on-the-go soil pH sensor is commercialised and it is provided as extra component of the Veris system (Schirrmann et al., 2011). It is based on a automated system developed by Adamchuk et al. (1999), which is based on the **Direct Soil Measurement (DSM) method**. More particularly, soil sampling is executed while traveling across the field using a soil sampling mechanism located in a toolbar-mounted shank. The sample is scooped from a depth of approximately 10 cm and it is brought into firm contact with the sensitive membranes of two flat-surface ion-selective electrodes (ISEs), called **antimony ISEs** (Figure 14). The measurement is taken after stabilization of the electrode output (typically 5–15 s) and right after a new soil sample is obtained. Every measurement is geo-referenced using a GPS receiver. In the case of Veris system, it was combined with the Veris soil apparent electrical conductivity (ECa) sensor (Christy et al., 2004). The so-called pH Manager is now marketed by **Veris Technologies** (Salina, USA) as a part of the mobile sensor platform **Veris MSP** (Figure 14). Adamchuk et al. (2007) compared the pH maps of the Veris MSP (pH Manager) with standard grid sampling on eight fields and concluded that a field specific calibration was necessary. In another study (Adamchuk et al., 2010), the Veris MSP employing antimony ISEs, was used on two fields and the maps derived were proved to be more accurate in delineating acidic soil areas than corresponding maps derived from grid sampling or field average methods.

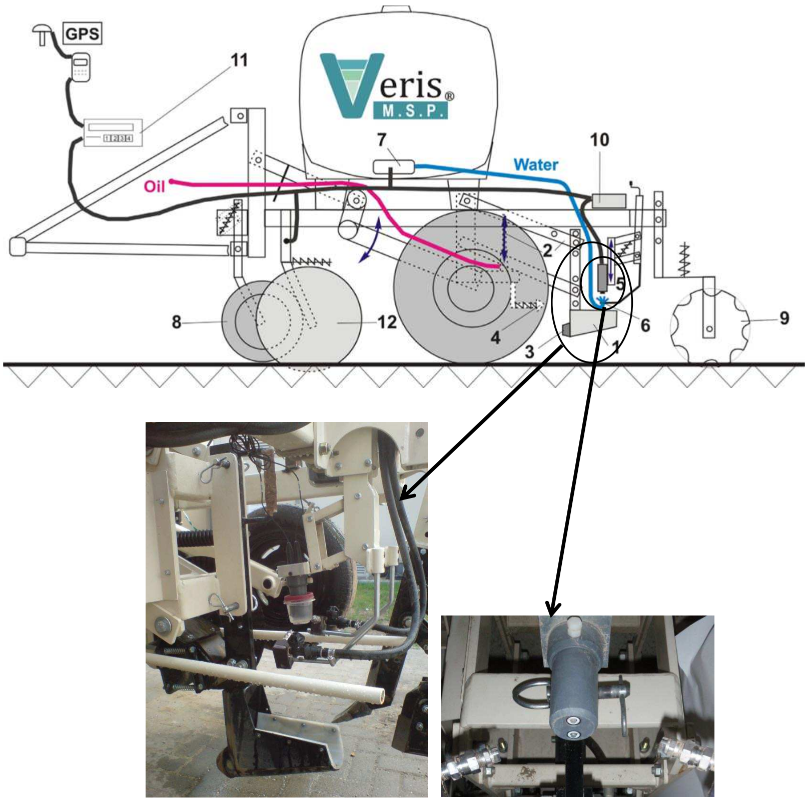

Figure 14: Veris MSP platform with antimony electrode (ion-selective electrodes). Source: Schirrmann et al., 2011;Gebbers, 2014.

An experimental study of VERIS MSP on-the-go soil pH sensor was successfully carried out on three fields in Germany, where a high degree of linear relationship between standard laboratory soil pH values and sensor pH values was demonstrated. However, these tests also showed that additional calibration is necessary to reduce errors when predicting pH ($CaCl_2$). This is of importance because differences in soil pH of 0.1 units can lead to differences in lime recommendations of up to 400 kg/ha CaO (Schirrmann et al., 2011).

3.2.1.6 Soil γ-ray mapping

Γ-ray spectroscopy, also known as radiometrics, is another ground-based proximal soil sensing methods to map soil properties (Mahmood et al., 2013). The γ-ray sensing principle is the analysis of natural γ-ray emission from decay of radio nuclides (Tauchnitz, 2005). Proximal γ-ray spectroscopy has significant advantages when compared to visible-near infrared spectroscopy (measuring the interaction between soil and electromagnetic radiation in the visible and near infrared spectrum) and electromagnetic conductivity (ECa) methods as it is a non-invasive and non-destructive method for topsoil sensing and mapping. Γ-rays can be related with clay mineralogy and soil chemistry and the concentration of radionuclides can be related with soil properties using simple correlation method. Furthermore, unlike ECa sensors, metal objects do not attenuate γ-rays. Γ-ray sensors can be used to map plant available-K, clay content, pH, iron (Fe), P and organic carbon (Wong and Harper, 1999; Rossel et al., 2007). A commercialised on-the-go sensor using a proximal γ-ray spectrometer is the Mole by The Soil Company, Groningen, The Netherlands (Van Egmond et al., 2010). The Mole can be mounted on a tractor, car, and quad bike or can even be used manually (Figure 15).

Figure15: γ-ray for tractor application by The Soil Company, NL. Source: Van Egmond et al., 2010.

3.2.1.7 Soil moisture sensors

Soil moisture sensors determine the volumetric water content of the soil. Measuring soil moisture content informs the farmer if the crop requires irrigation. Soil moisture measurements reveal moisture availability and helps to avoid unnecessary irrigation, which helps on **water preservation**, **reduces costs** (mainly fuel for pumping), **reduces nutrient leaching**, **avoids shallow root pattern** and in some cases **increases yield** (due to optimum water availability). A typical soil moisture map is shown in Figure 16.

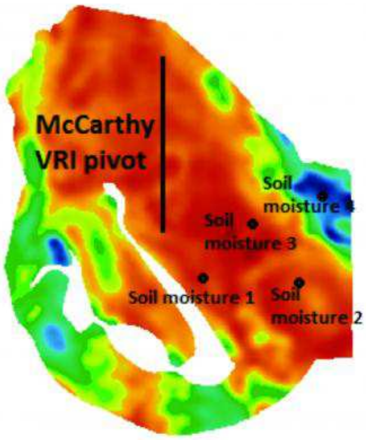

Figure 16: Soil moisture map. Source: Precision Agriculture Association New Zealand, 2016.

Soil moisture is generally measured through installing **static moisture sensors** in a grid specified by soil types (e.g. texture) and topography (e.g. slope). These sensors are interconnected by cables or wireless networks (Coates and Delwiche, 2009).

With such a set-up, farmers can have real-time data that can be fed in crop-water-soil models and he can set alarms for pre-set variable values. Good practice requires that for each soil type within a field, two sensors should be installed. Optimally, sensors should be installed at depths corresponding to the root evolution. One sensor should be placed in depth between 20 and 30 cm and another close to the average final root depth. There are several different types of sensors deploying different techniques to measure soil moisture.

There are two categories of measurement methods: volumetric and tensiometric. The **volumetric sensors** measure the amount of water in the soil and the **tensiometric sensors** measure the difficulty to remove water from the soil. Volumetric methods require a calibration of the sensor to the soil, whereas tensiometric is good to go when installed. The most common volumetric methods rely on **measuring the dielectric constant of the soil** which determines the velocity of an electromagnetic wave or pulse. These sensors have become widely used because they have **a good response time**, **do not require maintenance** and can **provide continuous readings**, allowing for automation.

The most important and widespread volumetric soil moisture static sensors used are neutron moderation, time domain reflectometry, frequency domain reflectometry, amplitude domain reflectometry, phase transmission and time domain transmission. Regarding tensiometric sensors, the most used are tensiometers, gypsum blocks, granular matrix sensors, heat dissipation and soil psychrometer. A comprehensive description of all above mentioned subcategories of soil moisture sensors can be found in Munoz-Carpena et al. (2004).

3.2.1.8 Discussion - Impacts of topographic and soil mapping

Since topographic and soil mapping does not have direct economic, environmental and social impacts, these impacts are not discussed here separately.

Precision agriculture benefits from analytical data of significant parameters for the plant growth. Topography influences climatic impact (e.g. wind impact) and terrain impact on the crop (e.g. soil erosion). Other soil properties have even higher impact on the installed crop because it is the medium on which the plant grows and its store of nutrients and water (e.g. soil texture indicates the ability of soil to retain water and nutrients and plant nutrient uptake capacity, soil pH change the nutrient availability for the crop, soil moisture levels indicate the field capacity and permanent wilting point of the crop). Also, topographic and soil characteristics influence if, when and how farmers can work on the fields (e.g. slopes or too wet soils).

The impact on the farm productivity (yield), income, environment or agricultural society of recording these parameters requires interpretation into diversified agricultural practices to show tangible results to the farmer. In terms of economics, the investment on soil sensors has to be compensated by the increase in farm profitability (e.g. yield increase, nutrient application reduction, irrigation effective use). In a social level, soil sensing technologies will help farmers to avoid manual soil sampling (at least in annual basis) and focus on other activities.

Topographic and soil parameters sensing are already in high standards, with high resolutions and accuracy. The methodology of receiving the appropriate data is documented and the correlation of these parameters with the final outcome of the plantation was verified in several cases (Korte, 2001; Dabas and Tabbagh, 2003; Mueller et al., 2003; Adamchuk et al., 2004; Sethuramasamyraja et al., 2008; Whelan and Taylor, 2013; Adamchuk and Viscarra Rossel, 2014)

However, the pricing (especially of sensors, acquisition and logging) is still in high to medium levels that excludes small farms from using them. It should be though noted that cost is decreasing fast during the last years. Another remark would be that there is capacity of experts in all EU countries that have the capability and knowledge to provide these services to the farmer. It is believed that considering the technology progress in electronics and software together with the increasing need for more and high quality data, the topographic and soil sensing will become more and more accessible for all agricultural uses.

3.2.2 Agricultural output mapping

3.2.2.1 Yield mapping

Yield mapping equipment was introduced in the early 1990s and is increasingly considered a conventional practice in modern agriculture (Cropwatch, 2016). The pioneers of precision agriculture already have generated several years of yield history and have examined different ways of interpreting and processing these data.

Yield mapping refers to the process of collecting georeferenced data on crop yield and yield characteristics, such as moisture content, while the crop is being harvested (Figure 17).

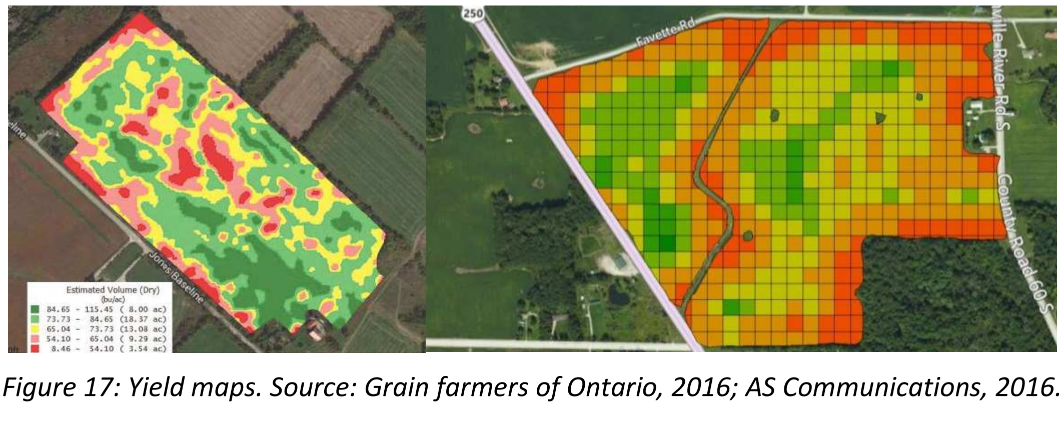

Figure 17: Yield maps. Source: Grain farmers of Ontario, 2016; AS Communications, 2016.

Various methods, using a range of sensors, have been developed for mapping crop yields. The basic components of a grain yield mapping system include:

- **Grain flow sensor** (determines grain volume harvested);
- **Grain moisture sensor** (compensates for grain moisture variability);
- **Clean grain elevator speed sensor** (used by some mapping systems to improve accuracy of grain flow measurements by measuring the speed of grain that provides the flow rate and together with the mass estimate give the final mass);
- **GNSS antenna** (determines the location of the measurement to create maps); **Yield monitor display** (tablet-type screen combined with a processor, data inputs and storage capabilities, placed in the cabin of the operator to give him the opportunity to import filed information, calibration functions, visual sampling display of the yield and moisture);**Header position sensor** (controls the yield measurement according to the position of the header . When the header is lowered with normal operating range, a signal from the sensor initiates recording of data. When is raised to a certain level, data acquisition is stopped);
- **Travel speed sensor** (determines the distance the harvester travels during a certain logging interval. Travel speed is measured with a GPS receiver or a radar or ultrasonic sensor).
  v)

Each sensor **has to be properly calibrated** to convert the sensor's signal to physical parameters. A proprietary binary log file is created during harvest to record the output of all sensors as a function of time. This file can be converted to a text format or displayed as a map using the yield monitor vendor's software.

The yield calculated at each field location can be displayed on a map using a Geographic Information System (GIS) software package. This requires also spatial (time) correction as the grain flow through a combine is **a delayed process** (unless real-time correction is applied, which is only available in new combine harvesters).

Evaluating the temporal (year-to-year) variation of yield distribution within the field is an essential step in defining field areas with potentially high and low yields and **to investigate the existence of spatially variable yield limiting factors**. On the other hand, the yield history can be used **to define spatially variable yield goals** that may allow varying inputs according to expected field productivity. These are important aspects in precision agriculture.

According to Reyns et al. (2002), there are several commercial yield mapping systems that provide full coverage of sensors and data processing up to the final yield map. The most important are the following:

- **RDS Technology Ltd** produces a yield mapping system (Ceres) patented earlier (1982) by Claas company as the **Claas quantimeter II**.
- The **Greenstar** yield mapping system is offered by the John Deere Company.
- Case IH (Advanced Farming Systems AFSTM) utilises a sensor developed by AgLeader.
- The **Deutz-Fahr Teris system** uses the same sensor from **AgLeader**.
- The **GRAIN-TRAK** yield measuring system by **MICRO-TRAK** uses two fingers to measure the impact force.
- The **Fieldstar** precision farming system of **Massey Ferguson (AGCO)** can be deployed with either a radiometric yield meter or impact system with two measuring fingers. Harvest Master registers grain flow by measuring the tension in the elevator chain.

The software used to produce yield maps are **Surfer** (Golden Software Co., Golden, Colorado), **ArcGIS** (ESRI GIS Software Co., Redlands, California), **Farm Works** (Trimble Navigation Limited, Sunnyvale, California, **SMS** (Ag Leader Ames, Iowa), **Farmlogs Free Mapping Software** (Farmlogs, Ann Arbor, Michigan).

3.2.2.2 Grain protein and oil content mapping

According to Whelan and Taylor (2013), grain crop prices, such as wheat, are directly connected to the protein content. On the other hand, the quality of oily crops, such as rapeseed, soybean and also corn is very much affected by the oil content of the product. Therefore, mapping both parameters can increase farm profitability and it is very useful in order to plan agricultural practices for the next growing period to achieve better output results (higher protein and oil content). Both protein and oil content are determined by crop type, crop variety, nitrogen either in the soil content, applied fertiliser and soil moisture availability during the growing season. Grain protein can be very affected by nitrogen availability within field, as different soil types and textures change the nitrogen that the crop really absorb for its needs in different parts of the field. Grain protein has to be measured together with yield in order to assess nitrogen fertilisation application during the growing period and redesign the application for next season, because grain protein production is the main mechanism for the movement of nitrogen off-farm (nitrogen removed through harvested grain is given by multiplying grain yield mass by the percentage of grain protein). Another very important factor is the water availability within field that is affected by the topography, the soil type and the climatic conditions and change significantly nutrient uptake, grain filling and yield, which all control grain protein content.

An example of grain protein map is given in Figure 18.

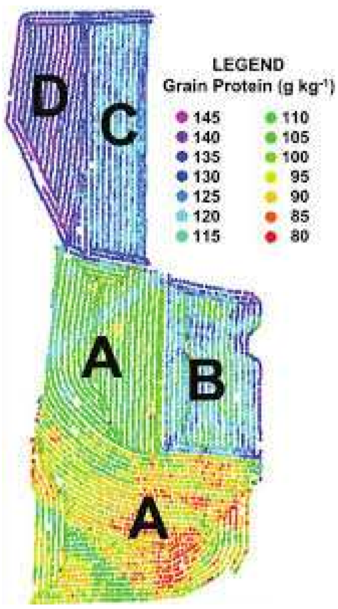

Figure 18: Grain protein map. Source : Long et al, 2008.

The sensors used for both protein and oil content measurements are based on near-infrared (NIR) spectroscopy. NIR spectroscopy method calculates the grain protein or oil content level by measuring the NIR light reflected from either sunlight or an own source (according to the type of sensor; grain quality sensors have their own light source). Whole grain analysers based on the near infrared (NIR) spectroscopic techniques have been developed for combine harvesters and used for continuous in-line measurement of grain protein content across fields (Maertens et al., 2004; Long et al., 2008). These systems are reported to be accurate in the field to within 5.7 g kg^{-1} grain protein content for winter wheat (Maertens et al., 2004), 6.6 g kg^{-1} for hard red spring wheat (Long and Rosenthal, 2005), 3.1 g kg^{-1} for soft white winter wheat (Long et al., 2008), and 4.5 g kg^{-1} for Australian hard spring wheat (Whelan et al., 2009). An example of the accuracy of grain protein sensors is the work of Long et al. (2008) who tested a reflectance sensor named **ProSpectra Grain Analyser** and found out that in both laboratory and field scale the correlation between real grain protein and the values of the sensor were between R^2=0.91 and 0.94.

3.2.2.3 Discussion - Impacts of yield, protein and oil content mapping

Since yield mapping does not have direct economic, environmental and social impacts, these impacts are not discussed here separately.

Any crop production is finally assessed and evaluated based on the final yield quantity and quality. Before precision agriculture technologies, yield was evaluated in the best case scenario in a field basis. Using yield mapping, it is possible to observe the agronomic results over the range of the field and plan different agricultural practices for next growing season. The same applies for protein and oil content mapping. There is documented evidence that both yield and protein, oil content mapping can identify crop growth issues in certain parts of the field and assist on optimisation of production in the coming year through optimised practices (Arslan and Colvin, 2002; Reyns et al., 2002; Whelan and Taylor, 2013).

Yield meters, as stated above, provide high quality yield data representing the yield segmentation within the field. It is a technology that is widely spread worldwide and the majority of new harvesters sold are equipped with such instruments, as their cost is low in comparison to the total price of the harvester (yield monitor kit constitute, according to experts, a 3-10% of the total investment). Regarding existing harvesters, there is a will to install yield mapping systems, which is delayed mainly due to cost.

Yield Mapping as such does not provide economic benefits if it is not interpreted by crop consultants together with the farmer to apply site-specific crop management.

According to the Extension Service of the University of Nebraska-Lincoln (Cropwatch, 2016), the following flowchart illustrates the process one might follow in deciding whether to invest in site-specific crop management, based on analysis of yield maps (Figure 19).

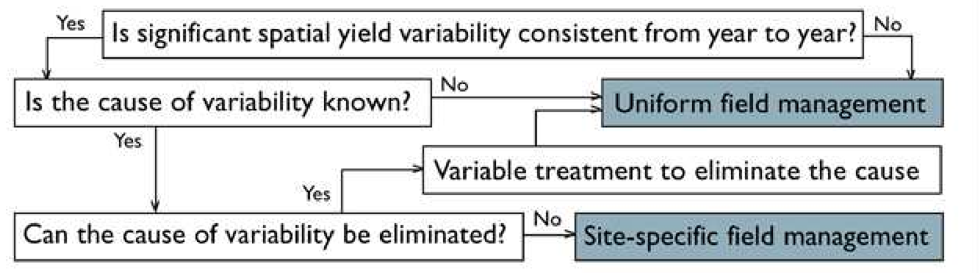

Figure 19: Flowchart of the decision process to invest on site-specific crop management based on yield mapping. Source: Cropwatch, 2016.

If yield variability across the field cannot be explained by any spatially inconsistent field property, uniform management may be appropriate. Site-specific management becomes a promising strategy if yield patterns are consistent from year to year and can be correlated to one or more field properties (e.g. nutrient supply, topography, past management, etc.).

If the causes for yield variation are known and can be eliminated permanently, the entire area could be brought to similar growing conditions and managed uniformly thereafter. This concept was one of the earliest philosophies behind precision agriculture, but is likely only feasible for certain field properties. For example, variable rate liming can be used to correct acidic areas in a field. In this case, the yield map is used only to investigate whether low soil pH is a yield-limiting factor, and the soil map is used to prescribe variable application rates. Another example would be localised deep soil tillage to alleviate compaction in selected field areas.

Most yield limiting factors cannot be modified permanently through single agricultural management measures because of economic or practical constraints. Consequently, site-specific crop management may be used to appropriately account for the existing spatial variability in attainable yield and/or soil properties. There is no direct economic impact of the protein and oil content mapping. Though, these maps can be used from the farmers to take decisions that could increase profit during the next growing period.

According to Whelan and Taylor (2013), grain protein and oil content mapping affect the economic value of the grain directly, as the marketed price of the grain or oil seeds could be different due to these two quality characteristics and therefore increase the farmer’s income. Higher grain protein or oil content of a field part or one of the farm fields can lead to premium contracts for the farmer. Another benefit is that in case of high variability, farmers can select the final product according to quality from different fields to make it to meet the contract requirements.

This perspective opens the possibility of differential harvesting to target product quality or even the substitution of the existing grain storage by two different tanks with a mechanism that diverts the grain depending on the reading of the protein sensor (this methodology is already used in stationary facilities in Australia to separate high protein malting barley from low protein).

The combination of yield maps with moisture and protein maps gives the opportunity to the farm manager to calculate revenue figures and understand production and quality variation within field or farm and finally plan profitable rotations and identify repeatedly unprofitable areas for alternate uses.

The environment is not directly affected by the use of yield, protein and oil content mapping, but as this information is used to optimise agricultural inputs (fertilisers, pesticides, fuel, water, energy) it is more than possible that indirectly they reduce environmental impact.

In a social perspective, yield mapping combined with protein and oil content mapping can primarily help farmers to increase their income by optimising their production in terms of quantity and quality as well. The most important social impact though is that production optimisation will increase food security (higher yields and known availability on time) and food safety and quality (less residual nutrients in water reserves, pesticides on the product).

In the future, if yield mapping would be installed in all harvesters, then by interconnecting the recorded data to a platform through Internet of Things (IoT) technology it could be a tool for the governments to control the exact produce in a regional (site-specific) level and avoid double checking in case of subsidies. It can also assist agricultural commodities trading as the quantities and time of availability could be given in a global database in real time. When yield is combined with protein or oil content measurements, then such a database would change the market completely and benefit primarily the farmer.

3.2.3 Canopy mapping

Canopy mapping is the process of producing maps using crop sensors that detect the crop canopy characteristics and provide information on the crop growth level, quality and possibly reflect to the final crop yield. There are many applications of canopy mapping. It can be used to estimate crop variables like yield, percent of ground cover, photosynthetic activity of the plant, surface water, leaf area index, amount of biomass, pasture performance, rangeland carrying capacities. Typically, canopy mapping is done with vegetation spectroscopy. It most commonly deploys differences of reflectance in specific spectral bands (in particular between red and near-infrared). The most commonly variable used to map canopies is the Normalised Differential Vegetation Index (NDVI) which is a numerical index based on the visible and near-infrared bands of the electromagnetic spectrum that indicates if a target being observed contains live green vegetation or not. Healthy vegetation absorbs most of the visible light that falls on it, reflecting a large portion of the near-infrared light. On the other hand, unhealthy or sparse vegetation reflects more visible light and less near-infrared light. As for bare soils, they reflect moderately in both the red and infrared portion of the electromagnetic spectrum (Bannari et al., 1995).

Having in mind the above mentioned plant behaviour; there is a need of taking sensor measurements on the bands that are most sensitive to vegetation information (near-infrared and red). Therefore, as the difference between the near-infrared and the red reflectance grows, the vegetation represented in the image is higher. The NDVI is given by the following function:

NDVI= (NIR-RED) / (NIR+RED)

This formulation allows us to cope with the fact that two identical patches of vegetation could have different values if one were, for example in bright sunshine, and another under a cloudy sky. The bright pixels would all have larger values, and therefore a larger absolute difference between the bands. This is avoided by dividing by the sum of the reflectances.

Theoretically, NDVI can take values from -1 to 1, but in practice extreme negative values represent water, values around zero represent bare soil and values over 0.6 represent dense green vegetation.

The different types of canopy mapping technologies are the following:

3.2.3.1 Near sensing technologies

Near sensing technologies are using spectroscopy to measure canopy parameters and they are used in close proximity to the crop under investigation. There are several commercial products based on spectroscopy on the ground (active sensors). These sensors are either moving (mounted on tractors/quad bikes or manually carried by the scouter) or stationary and they are used to provide information on the quality of the canopy that remote sensing technologies (aerial or satellite) cannot detect or the accuracy of data is not enough for spatial and temporal analysis. They can find applications in all types of cropping systems (arable crops, orchards, vineyards, vegetables). Their working principle is based on emitting light towards the plant canopy in visible light (VIS) and near infrared (NIR) spectrum that it is either reflected, transmitted or absorbed. According to the plant characteristics the percentage of each of the three behaviours of the light is differentiated (Inman et al., 2005). A characteristic example of the positive impact of these sensors is given by Tim Shaver from the University of Nebraska-Lincoln, who related highly active sensors with N concentration of the plants (r^2>0.89) and explained that they are a valuable tool for in-season N management.

Manufacturer/Product/URL	Placement and Photo	Description
Decagon Devices Pullman, WA, USA Spectral Reflectance Sensor (SRS) www.decagon.com	Stationary 	SRS can measure NDVI/PRI vegetation indices at the plot or plant stand scale. It uses non-destructive sampling of canopy greenup, senescence and plant stress. As it is static, it collects vegetation index data unattended for days, months or years. It use low cost, weatherproof research grade sensors to maximize spatial coverage and data can be remotely monitored from office or phone.
Skye Instruments Powys, UK 2-channel custom radiometer www.skyinstruments.com	Stationary/on-the-move 	This device is of high quality and affordable research grade, waterproof and rugged, individually calibrated, suitable for long-term outside installations, lightweight, standard NDVI/PRI wavelengths or user choice, suitable for installations on masts, flux towers, airplanes, UAVs, systems available with GPRS communications for automatic upload to a website.
Trimble Sunnyvale, CA, USA GreenSeeker www.trimble.com	On-the-move 	This device uses optical sensors to measure and quantify the variability of the crop and then create a targeted prescription to treat the crop variability. It operates night or day, and in fog or clouds. It can be mounted on booms on most sprayers/spreaders. It is used for changing mainly N fertilisation. It provides instant side-dress fertiliser application for inputs such as nitrogen.
Holland Scientific Lincoln, NE, USA Crop Circle ACS-470 www.hollandscientifc.com	On-the-move 	This device provides classic vegetation index data (NDVI, SRI and others) as well as basic reflectance information from plant canopies and soil. It is not limited by ambient lighting conditions—measurements can be made day or night. It is compact, low weight. It incorporates three optical measurement channels and allows the user to select optical measurement bands of interest in-field. It is connected to a data logger and a GPS to easily and quickly data record.
Trimble Sunnyvale, CA, USA GreenSeeker www.trimble.com	On-the-move (handheld) 	This device is affordable, easy-to-use (press a trigger), rechargeable, instantly taking a reading of the crop's health. It measures NDVI which is promptly shown on its easy-to-read even in sunlight LCD display screen. It can be connected to Connected Farm scout app on a smartphone or tablet to calculate fertilizer application rates from crop readings.

Holland Scientific Lincoln, NE, USA RapidScan www.hollandscientifc.com	On-the-move (handheld) 	This device integrates a data logger, graphical display, GPS, crop sensor and power source. It is unaffected by ambient illumination allowing it to work accurately day or night. It is capable of collecting data at sensor-to-canopy distances ranging from 0.3 – 3m. It produces NDVI/ NDRE vegetation indexes, georeference and sample statistics as well as basic reflectance information. It incorporates three optical measurement channels and makes height independent spectral reflectance measurements. Scanned data is stored for later transfer to a PC. The built-in GPS has accuracy < 1 m, it is dust and water resistant and light (0.8 kg)

3.2.3.2 On-the-go treatment sensors

On-the-go treatment sensors are sensors that are combined with an applicator that acts according to the measurement of the preceded sensor. More particularly, these sensors are part of PA agrochemical (fertilizers and pesticides) application implements that are not fed with information taken from the field in previous time (using near sensing technologies), but they apply the exact quantity required from the crop simultaneously. These sensors have the benefit of having wide sensing area of the exact location under investigation and apply the agrochemical quantity required by the plants according to their status at this moment.

AgLeader (Ames, IW, USA, www.agleader.com) has produced also another NDVI sensor named **OptRX** that measures and records data about crops in real time using the reflectance of an integrated active light source. Sensors can be installed across the application boom to collect information while driving through the field. The emitted light offers maximum flexibility to be used day or night. It gives the needs of the crop and provides application rate recommendations for agrochemicals in real time to maximise profit.

Topcon (Livermore, CA, USA, www.topconpositioning.com) is the provider of the treat on-the-go system **CropSpec** (Figure 20) that uses pulsing laser diodes for sensing. The sensor measures plant reflectance to determine chlorophyll content, which is closely related to the nitrogen concentration in the leaf. This non-destructive, non-contact method provides accurate, stable readings and repeatable values.

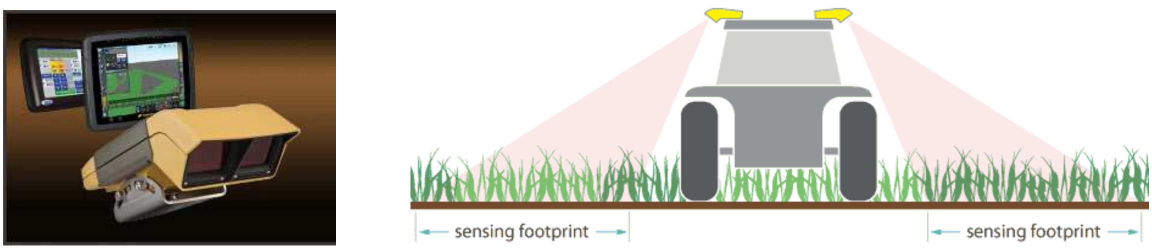

Figure 20: CropSpec Sensor by Topcon. Source: Topcon, 2016.

Yara (Grimsby, UK, www.yara.co.uk) is the provider of **N-Sensor** (Figure 21) which is also a tractor-mounted to treat on-the-go N fertilisation, as it determines a nitrogen demand by measuring the crop's light reflectance covering a total area of approximately 50 m^2. Measurements are taken every second with the system designed to operate at normal working speeds and all bout widths. Sensing technology applied to agriculture is based on the typical light reflectance curve for vegetation. N-Sensor measures light reflectance at specific wave bands related to the crop's chlorophyll content and biomass. It calculates the actual N-uptake of the crop. Optimum application rates are derived from the N-uptake data and sent to the controller of the variable rate spreader or sprayer, which will adjust fertiliser rates accordingly.

Figure 21: N-Sensor by YARA. Source: YARA, 2016.

Fritzmeier (Großhelfendorf, DE, www.fritzmeier-umwelttechnik.com) has produced the **ISARIA** system (Figure 22) that is based on Red Edge Inflection Point (REIP) narrow band vegetation index. LED light of 5 different wavelengths illuminates sequentially the crop canopy in a 60 cm distance from above. The reflected light is detected by a high sensitive detection unit. The measured intensities are used to calculate a vegetation index which shows high correlation to the plants' nutrient supply. This system can be used for on-the-go treatment with Nitrogen fertilisers, growth regulators, fungicides and others.

Figure 22: ISARIA sensor. Source: Demofield, 2016.

Fritzmeier (Großhelfendorf, DE, www.fritzmeier-umwelttechnik.com) has also produced the **MiniVeg** system that measures laser-induced chlorophyll fluorescence in two narrow red and near-infrared spectral bands, respectively. The laser diode emits red light pulses in the frequency range from 1 Hz up to 10 kHz. The laser light stimulates the plant's chlorophyll to emit fluorescent light, which is collected by the detection optics. The size of the laser induced area is about 0.5 mm². Fluorescence sensor detects the fluorescence emission at 609 and 740 nm. The ratio of these wavelengths provides information about the chlorophyll and nitrogen content too.

Rometron (Steenderen, the Netherlands, www.rometron.nl) has produced **WEEDit** (Figure 23) that is based on fluorescence. By emitting red light by the sensor, the chlorophyll of the plants shifts this into infrared light, which is then detected by the

WEEDit detection sensor. With this information the position of the weed is been determined and a solenoid valve will be activated to spray just the weed.

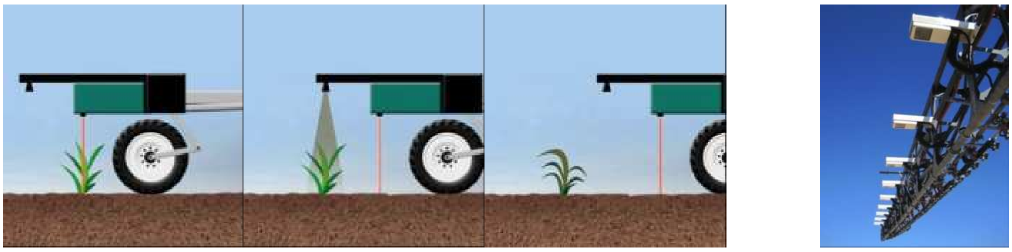

Figure 23: WEEDit working principle (left) and Spraying ramp with the WEEDit Ag (right). Source: Rometron, 2016.

3.2.3.3 RADAR remote sensing

Radar is an active system which transmits a pulse and then measures the time delay and intensity of the reflected echo (Zillmann et al., 2004). Remote sensing techniques have a great potential to provide precise geocoded information of spatial variability of soil and crop characteristics in order to develop efficient and sustainable use of agricultural inputs (Moran et al., 1997). However, adequate measurements and indicators for precision farming are still lacking. There are four application areas for measurements of RADARs for agricultural purposes (**distance**, **soil moisture**, **crop density** and **speed**). The determination of the distance to an object, based on propagation time measurements, is relatively simple and very precise. An example would be a distance measurement between the ground and the crop level in a barley field which equals the crop height. Soil moisture recording is based on measuring the reflection intensity of the soil. However, most systems have low penetration depth and only the topsoil water content is measured. Therefore, lower frequencies must be used to reach the root area. Regarding crop density, if a radar device is moved vertically in a wheat field that has different densities at different places (thin, middle and dense), it can be seen that in the dense areas the distance measured is very low (it is like reflecting in a roof) and in the thin areas is higher as the beam goes to the ground. Finally, speed is measured with RADAR sensors in tractors that transmits a known frequency of radiation towards a surface and receive reflections of the radiation from the surface. The difference in frequency between the transmitted radiation and received radiation, is proportional to speed. (Paul and Speckmann, 2004). Other initiatives are in monitoring the crop season (e.g. changes in above ground biomass; ploughing and harvesting activity) but these seem to have more relevance to other stakeholders than farmers (e.g. water boards, legislation control, logistics).

Radar data is mainly used in agriculture for crop type classification (Bouman and Uenk, 1992). The insufficient understanding of radar backscatter mechanisms according to agricultural soil and plant conditions is the biggest gap of radar data usage in agricultural management practice at present time (Moran et al., 1999). This is still true for the moment of this report’s conception.

3.2.3.4 LiDAR remote sensing

LiDAR (Light Detection and Ranging) is an optical remote sensing technology that can measure the distance from the sensor to other features by illuminating the target with Light. LiDAR technology has been used in airplanes to measure features on Earth's surface, including determining a detailed elevation model. The principle of LiDAR devices is that they send rapid pulses of laser light at a surface and a sensor on the instrument measures the amount of time it takes for each pulse to bounce back. As light velocity is known, the LiDAR devices can calculate the distance between them and the target with high accuracy. A LiDAR device uses a GNSS receiver for its location so data can be mapped. LiDAR can be used in agricultural applications, such as the creation of **topographical map**, **slope** and **sun exposure** of the farm. Another application of LiDAR is **crop mapping in orchards and vineyards** (Figure 24).

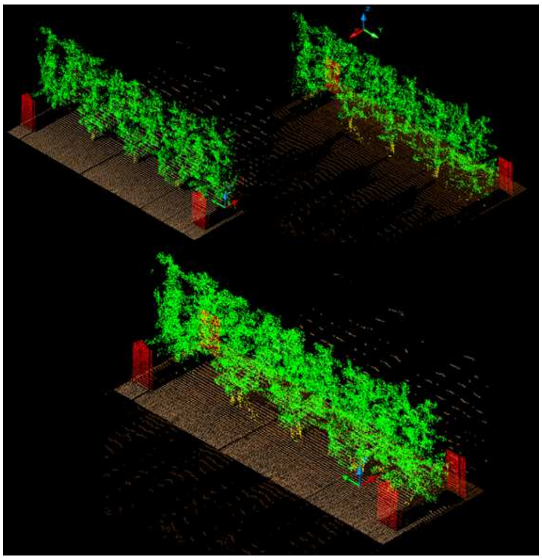

Figure 24: Canopy LiDAR map. Source: Digitális Tankönyvtár, 2016.

Foliage growth can be measured to determine if pruning or other agricultural practice is required, detect variations in fruit production, or perform automated tree counts. Also **Tree Area Index (TAI)** which includes all the surface of the tree (trunk, branches, etc) per unit ground surface area and **Leaf Area Index (LAI)** that reflects one-sided green leaf area per unit ground surface area can be estimated using ground LiDAR sensors (Arno et al., 2013; Arno et al., 2015). For vehicle-based determination of **crop biomass**, commercially available laser scanners have been analysed and tested to measure aboveground biomass in oilseed rape, winter rye, winter wheat, oats and grassland (Ehlert et al., 2010). High functional correlations were found between mean reflection height, which was calculated from measured reflection range and sensor height, and fresh crop biomass from measuring ranges up to 2.5 m. The coefficient of determination for linear regression was more than 0.90 ($R^2 > 0.9$) for oilseed rape, winter rye and winter wheat. However, the accuracy was lower in grassland (pasture). Laser scanners are also used for **crop height** detection (Hoffmeister et al., 2015). In addition, LiDAR is useful in orchards where GNSS signals to farm equipment featuring precision agriculture technology or a driverless tractor may be partially or completely blocked by overhanging foliage. LiDAR sensors can detect the edges of rows so that farming equipment can continue moving until GPS signal can be re-established.

There are many sensor manufacturers that develop LiDAR scanning systems for either static or dynamic operation, for instance on moving tractors, airplanes or UAVs. Well-known brands are **Riegl** (Orland, FL, USA, www.rieglusa.com) **SICK** (Waldkirch, Germany, www.sick.com) and **Velodyne** (Morgan Hill, CA, USA, www.velodynelidar.com). **Ibeo** (www.ibeo-as.com) has launched several laser scanner types mainly for automotive uses, but also for agricultural use (e.g. ALASCA XT) (Ehlert et al., 2009; Ehlert et al., 2010) (Figure 25).

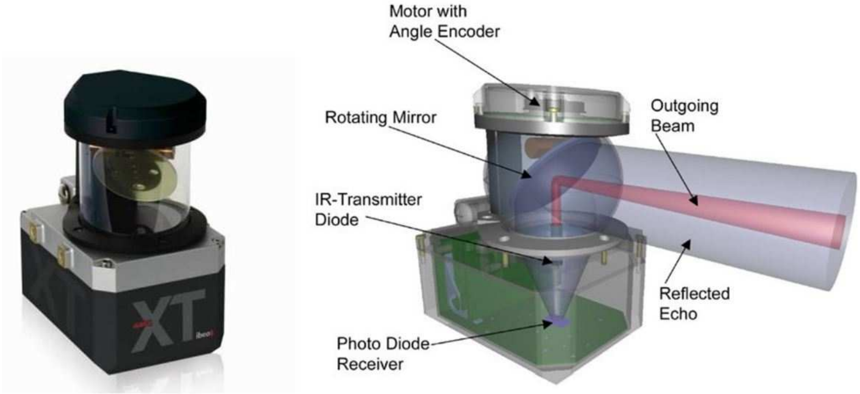

Figure 25: Ibeo ALASCA XT laser scanner. Source: Cajunbot, 2016.

3.2.3.5 Unmanned Aerial Vehicles (UAVs)

An unmanned aerial vehicle (UAV) or Remotely Piloted Aircraft System (RPAS), popularly known as a drone, is an aircraft without a human pilot aboard. The flight of UAVs may be controlled either autonomously by on-board computers or by the remote control of a pilot on the ground or in another vehicle. Developments of UAVs have been mainly triggered by defence applications. In civil use it is popular platform for aerial photography, but for agriculture also 'flying robots' are expected to come to the market for all kinds of cultivation practices. Spraying with drones is already current practice in Japan and Korea and is also emerging in steep sloped vineyards for instance in the Mosel area in Germany.

There are two main platform types for UAVs: **fixed wing** and **multi-rotor** (Figure 26). Fixed wing platform has the advantage of covering large areas efficiently, while a multirotor is able to remain very stable in challenging conditions with large payloads.

Figure 26: Fixed wing UAV (left) and rotor craft (right) UAV.
Source: Farmers weekly, 2016; Nexdrone, 2016.

UAVs are equipped with a **GNSS receiver** that is used primarily for location information for the autopilot and of course for the data collected to be linked to its spatial position. In addition, UAVs have **autopilots** in order to be programmed to fly over a certain area and collect the desired data.

UAV platforms are evolving rapidly both technically and with regard to regulation. Various UAVs offer design and performance advantages over conventional photoreconnaissance aircraft, such as **small size**, **low weight**, **slow flight speed**, **extended range**, **extreme altitude** and **extreme endurance** (Ballesteros et al., 2014). UAVs already offer new alternatives for agriculture and other applications in which high spatial resolution imagery delivered in near-real time is needed (Herwitz et al., 2004). Diagnostic information derived from images collected from on-board sensors, such as **biomass**, **LAI**, **disease** and **water stress** can thus inform decision-making in crop management, **yield forecasting** and **environmental protection** (Zhang and Kovacs, 2012).

The most complex part of collecting good data is having the correct sensor. For **plant biomass data**, the most important spectral range is in the **near infrared spectrum**.

UAVs carry different camera types of which the two most common commercial options include **Tetracam ADC Lite** built specifically for UAVs or a digital camera modified to capture within the near infrared spectrum. The ADC Lite (0.2 kg) is ideal solution for applications in which weight is a critical factor (such as on board small-payload-carrying UAVs). The ADC Lite contains a single 3.2 megapixel sensor optimised for capture of visible light wavelengths longer than 520 nm and near-infrared wavelengths up to 920 nm. The camera and its accompanying software, are suited for capturing and processing multi-spectral images of crops and forests and studying a variety of eco-systems. It has the ability to extract a variety of vegetation indices and a comprehensive suite of image editing tools. The modified digital camera is the most cost effective solution. It is very common for UAVs to have a GoPro camera (or similar) mounted to capture high definition video footage. This video footage is valuable for visually monitoring crops from the sky but is generally not processed to geo-referenced data. There are also solutions of UAVs coupled with a hyperspectral camera.

An important development is the **Piksi** by **Swift Navigation**, which is a **low cost Real Time Kinetic (RTK) GPS** receiver that is expected to be sold for around $1,000 which is unheard of in the world of GPS, as regular RTK GPS devices can reach 20,000 euros. The Piksi offers centimetre level accuracy inside a compact design ideal for small UAVs. The improved accuracy will be invaluable for autonomous landings and improved accuracy of geo-referencing data.

3.2.3.6 Cameras

3.2.3.6.1 RGB Cameras

A digital camera records and stores photographic images in digital form. Most models are also able to capture sound or video, in addition to still images. Capture is usually accomplished by use of a photo-sensor, using a charged coupled device (CCD).These stored images can be uploaded to a computer immediately or stored in the camera. According to Cambridge in colour (2016), a commercial digital camera uses an array of millions of tiny light cavities to record an image. When the exposure begins, each of these cavities is uncovered to collect and store photons. Once the exposure finishes, the camera closes each of these cavities, and then tries to assess how many photons fell into each. However, this way would only create grayscale images, since these cavities are unable to distinguish how much they have of each colour. To capture colour images, a filter has to be placed over each cavity that permits only particular colours of light. Digital cameras can only capture one of three primary colours in each cavity, and so they discard roughly 2/3 of the incoming light, which means that the camera has to approximate the other two primary colours in order to have full colour at every pixel.

There are several uses of RGB cameras in agriculture with the main being **plant (crop or weed) recognition** (Tangwongkit et al., 2010). As the first step of the image processing technique, it tends to **separate plants from soil** and later it attempts to recognise **shape, texture and colour properties of the plants** in order to classify plants into species or crop/weed categories (Samseemoung et al., 2012). The applications of RGB cameras are diverse: Wachs et al. (2010) have used among other optical sensors, an RGB camera for estimating production and direct apple thinning by detecting **apple** fruits on the tree with very good results. An RGB camera was also used for tulip breaking virus detection (Polder et al., 2010). **Leaf diseases** (leaf spot pathogen *Cercospora beticola* or the rust fungus *Uromyces betae*) were captured in **sugar beet** leaves by both RGB and multispectral cameras (Bauer et al., 2011). RGB cameras have been used for the production of day-time images in **maize** cultivation that determine different vegetation indices, like **Visible Atmospherically Resistant Index (VARI)** (index based entirely on the visible part of the spectrum) and **two Green-Red-Blue (2g-r-b)** (it is called excessive green index that represent greenness and transforms a 24 bit RGB source image to a 256 grey level image where plant pixels appear brighter than soil). It was found that using VARI **green LAI** and **green leaf biomass** were accurately estimated (R^2 = 0.99 and R^2 = 0.98 respectively) and that the 2g–r–b was able to accurately estimate total LAI (R^2 = 0.97) (Sakamoto et al., 2012). RGB and colour-infrared digital cameras were used to monitor crop growth and weed infestation in soybean with very good results (Samseemoung et al, 2012).

Lopez-Granados et al. (2015) used a UAV based RGB camera for **weed seedling mapping** in sunflower cultivation used to design site-specific weed management program with very good results (Figure 27).

Figure 27: (a) Ortho-mosaicked imagery showing the sunflower rows and the square frames placed between two sunflower rows ; (b) Detail of vector file created for every square frame (yellow); (c) detail of the vector file created for the sunflower crop (green) and weed (violet) classes. Source: Lopez-Granados (2015).

3.2.3.6.2 Multispectral Cameras

A multispectral image is one that captures image data at specific frequencies across the electromagnetic spectrum. Spectral imaging can allow extraction of additional information the human eye fails to capture with its receptors for red, green and blue. It was originally developed for space-based imaging. Multispectral images are the main type of images acquired by remote sensing (RS) radiometers (device for measuring the radiant flux i.epower of electromagnetic radiation). Dividing the spectrum into many bands, multispectral is the opposite of panchromatic, which records only the total intensity of radiation falling on each pixel. Usually, Earth observation satellites have three or more radiometers (Landsat has seven). Each acquires one digital image in a small spectral band. The shortest is the visible band, ranging from 0.7 μm to 0.4 μm, called **RGB** region. The others are infrared with wavelengths from 0.7 μm to 10 or more μm, classified as **near infrared (NIR)**, **middle infrared (MIR)** and **far infrared (FIR or thermal)**.

In the case of agriculture, with multispectral cameras, it is possible to identify many bands and specify many indices, with NDVI being the most usable.

Multispectral imagery was used for **crop coverage** measurement of different crop types (**cotton**, **grain sorghum**, **corn**, **alfalfa**, **sunflower**, and **pearl millet**) with an overall accuracy within 3% of their true values (Rajan and Maas, 2009). **Leaf diseases** (leaf spot pathogen *Cercospora beticola* or the rust fungus *Uromyces betae*) were captured in sugar beet leaves by both RGB and multispectral cameras (Bauer et al., 2011). A multispectral camera together with an RGB camera were used to measure **NDVI**, Green NDVI (**GNDVI)** that is an index of plant "greenness" or photosynthetic activity, and simple Ratio pigment index (**SRPI)** that is the ratio between the blue and red reflectance in a sugarcane experiment of different nitrogen fertilisation rates and found that there is good correlation of these indices with traditional nitrogen indices (r^2=0.7) and that SRPI showed better characteristics (Lebourgeois et al., 2012).

3.2.3.6.3 Hyperspectral Cameras

Hyperspectral sensors collect image data simultaneously in dozens or hundreds of narrow, adjacent spectral bands which make it possible to derive a continuous spectrum for each image cell, as shown in the illustration below (Figure 28).

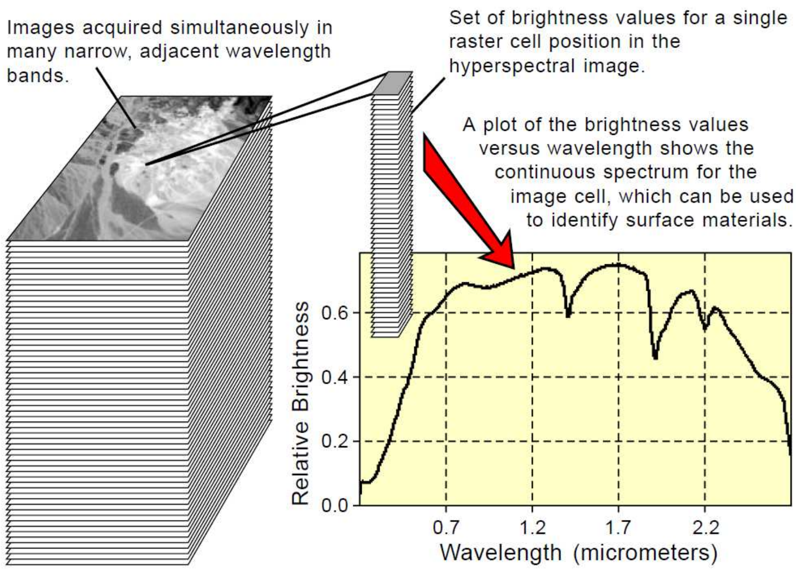

Figure 28: Continuous spectrum derived by hyperspectral sensors. Source: MicroImages, 2016.

Hyperspectral images contain a wealth of data, but interpreting them requires an understanding of exactly what properties of ground materials we are trying to measure, and how they relate to the measurements actually made by the hyperspectral sensor.

Hyperspectral images are produced by instruments called imaging spectrometers (or spectroradiometers) (Figure 29). These instruments are used to measure the light that is emitted by or reflected from materials and its variation in energy with wavelength. In real-life measurement, spectrometers measure the spectrum of sunlight that is diffusely reflected (scattered) by materials at the Earth’s surface. An optical dispersing element such as a grating or prism in the spectrometer splits this light into many narrow, adjacent wavelength bands and the energy in each band is measured by a separate detector. By using hundreds or even thousands of detectors, spectrometers can make spectral measurements of bands as narrow as 0.01 micrometers over a wide wavelength range, typically at least 0.4 to 2.4 micrometers (visible through middle infrared wavelength ranges). Therefore, it is possible to correlate one or more of these bands to crop characteristics that would not be identified with RGB and multispectral cameras.

Figure 29: Hyperspectral camera. Source : BaySpec, 2016.

In Figure 30, representative spectral reflectance curves for several common Earth surface materials over the visible light to reflected infrared spectral range are shown. The spectral bands used in several multispectral satellite remote sensors are shown at the top for comparison. Reflectance is a unitless quantity that ranges in value from 0 to 1.0, or it can be expressed as a percentage, as in this graph. When spectral measurements of a test material are made in the field or laboratory, values of incident energy are also required to calculate the material's reflectance. These values are either measured directly or derived from measurements of light reflected (under the same illumination conditions as the test material) from a standard reference material with known spectral reflectance. It can be observed that vegetation shows higher reflectance in the near infrared range than wet soil (following similar reflectance in middle infrared band) and lower reflectance in the middle infrared band in comparison to dry soil. The combination of these differences can help in identifying vegetation with high accuracy.

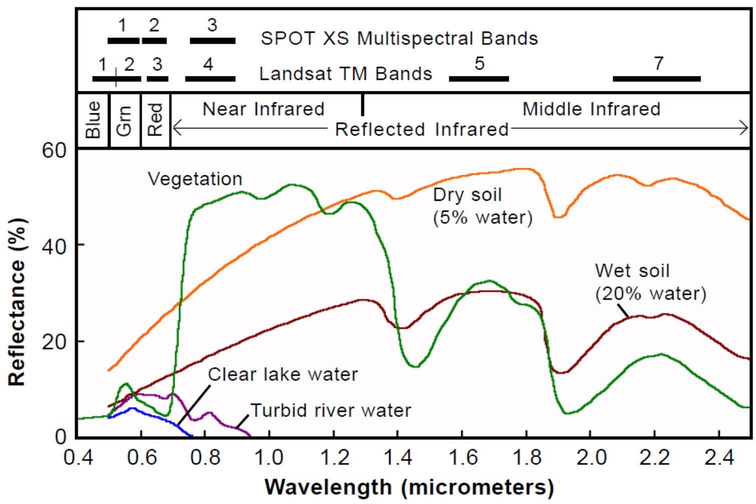

Figure 30: Representative spectral reflectance curves for several common Earth surface materials over the visible light to reflected infrared spectral range. Source: MicroImages, 2016.

Another important advantage of hyperspectral imaging for agriculture applications is the distinction of different types of vegetation (Figure 31) and the difference of the reflectance curves of green vegetation compared to the spectral curve of senescent (dry, yellowed) leaves.

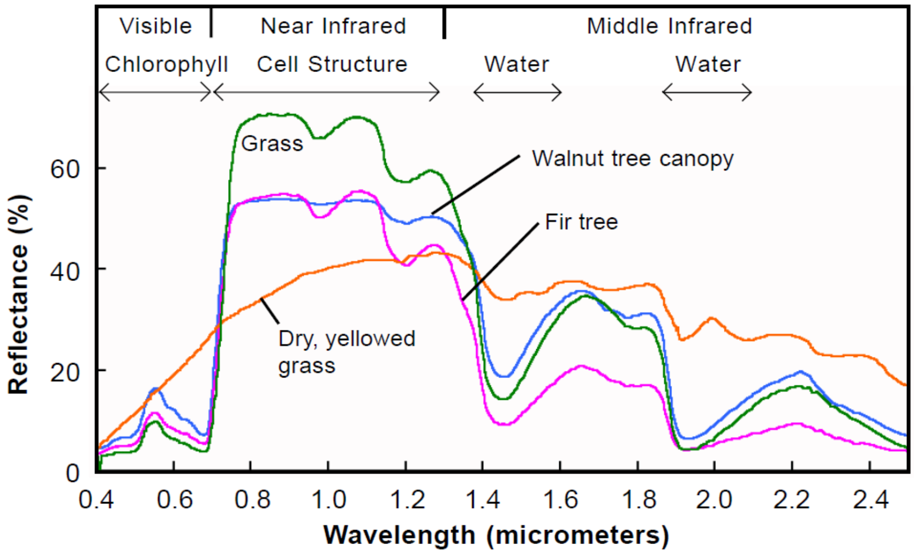

Figure 31: Reflectance spectra of different types of green vegetation. Source: MicroImages, 2016.

There are several commercial hyperspectral cameras, of which the **Resonon Pika** products (L, XC2, NIR and NUV) can cover different spectrum bands from ultraviolet, visible and infrared (350 – 1700 nm). Their weight vary from 0.6 kg to 4.4 kg that limits Pika NIR for use with UAVs. **Bayspec OCI-OEM** hyperspectral camera is compact weighing less than 180 g. **Headwall Micro-Hyperspec** airborne sensors also have a wide range od products covering VNIR (380-1000nm), extended VNIR (550-1700nm), NIR (900-1700 nm) and SWIR (900-2500nm) spectral ranges. These optical engines acquire full, VIS-NIR hyperspectral/multispectral data with high spectral resolution and fast speed. Continuous hyperspectral data capturing can happen at video rates.

3.2.3.6.4 Thermal Camera

A thermal imaging camera is a device that forms an image using infrared radiation (up to 14 μm), similar to RGB camera that forms an image using visible light (400–700 nm). Their use is called thermography. According to Ishimwe et al. (2014), thermal remote sensing uses data acquired in the thermal infrared (TIR) region of the electromagnetic (EM) spectrum. Every object whose surface temperature is above absolute zero (-273 °C) radiates energy at a wavelength corresponding to its surface temperature. Utilizing thermal cameras, this radiated energy is captured in a thermal image of the object being surveyed. Thermal remote sensing differs from optical remote sensing because **it measures emitted radiations from the surface of the target object** (Figure 32), whereas optical remote sensing measures reflected radiations of the target object under consideration.

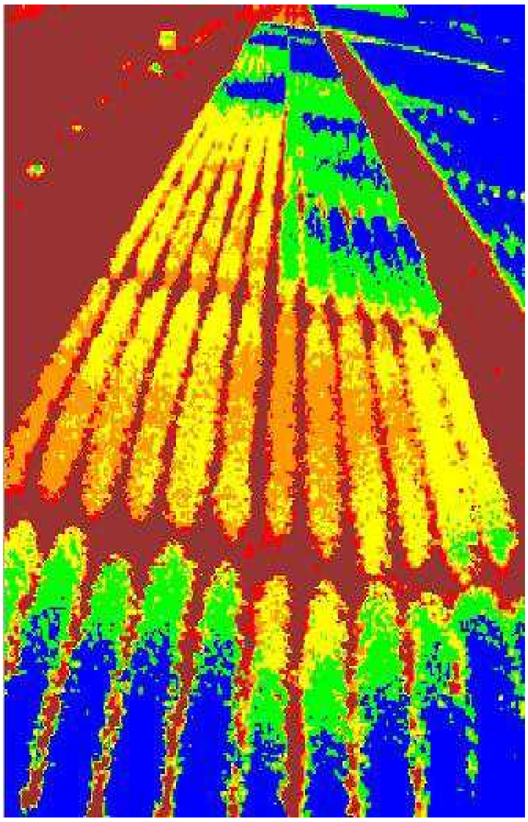

Figure 32: Thermal image of a field. Source: IsraelAgri, 2016.

Therefore, thermal imaging data may be used directly or indirectly for many applications such as civil engineering, industrial maintenance, aerospace, medicine, pharmacy and veterinary. The application of thermal imaging is gaining popularity in agriculture in recent years (Ishimwe et al., 2014) due to the reductions in cost of the equipment and ease of use. This has created opportunities for its application in several fields of agricultural and food industries (Manickavasagan et al., 2005) and therefore work is being done on redesigning and restructuring thermal cameras to be used in precision farming (smaller, lighter, cheaper, durable in bad conditions). Thermal properties of plant leaves are affected by a complex heterogeneous internal structure that contains a certain amount of water per unit area. For that reason, it is possible to identify the leaf characteristics of different crops on individual basis using thermal remote sensing because of the versatility, accuracy and high resolution of the infrared thermography.

Nevertheless, accurate thermal measurements depend on environmental conditions, which influence the thermal properties of the visualised crop. Therefore, calibration of images according to weather conditions is necessary for comparison between image data obtained during different measuring periods and growth seasons (Nilsson, 1995). Potential use of thermography in agriculture includes nursery monitoring, irrigation scheduling, soil salinity detection, disease and pathogen detection, yield estimation, maturity evaluation and bruise detection.

The most common application of thermal cameras in agriculture is to identify **crop temperature** in order to estimate water stress. Luquet et al. (2003) has developed a 3D model to improve this correlation. Canopy temperatures indicate crop water stress and therefore thermal cameras were used for **cotton** and **vineyard** leaf temperature measurement with successful evaluation of **crop water stress** (Meron et al., 2013).

Crop water stress of **potatoes** was indexed using ground and aerial thermal images (Rud et al., 2014). Another study assessed the ability of thermal imaging to provide the spatial distribution and variability of tree water status in a commercial irrigated **olive orchard**, and described strategies and a procedure for choosing which individual trees best represent the orchard (Agam et al., 2014). Several crops were examined for their water stress through thermal imaging, such as **apples** (Wachs et al., 2010; Oerke et al., 2011), **palm trees** (Cohen et al., 2012), **almond**, **apricot**, **peach**, **lemon**, and **orange** (Gonzalez-Dugo et al., 2013), etc.

Water stress identification with thermal imaging can be combined with **nitrogen stress** in wheat with good results (Fitzerald et al., 2006).

Another application of the thermal camera is to **identify diseases**. An example is the detection of downy mildew in opium poppy with the simultaneous use of multispectral and thermal camera on a UAV (Calderon et al., 2014).

An infrared thermal imaging system comprises of a thermal camera equipped with infrared detectors, a signal processing unit and an image acquisition system. Thermal imaging systems are evaluated on their thermal sensitivity, scan speed, image resolution, and intensity resolution (Vadivambal and Jayas, 2011).

3.2.3.7 Copernicus

In regards to environment, climate change and civil security, European Commission (EC) in partnership with the European Space Agency (ESA) has launched the most ambitious Earth observation program up to date named Copernicus (previously names Global Monitoring for Environment and Security program – GMES). In the domain of agriculture, Copernicus helps to assess agricultural land use and trends and their impacts on biodiversity and landscapes. Copernicus can also help assess crop conditions and yield forecasts. It can also help public authorities and farmers to improve irrigation management by monitoring agricultural pressure on water. The Copernicus Land Monitoring Service provides geographical information on land cover, land use and change, thereby supporting rural development, agricultural and food security applications.

The program includes 6 new satellites named the Sentinels. These satellites carry a range of technologies, such as **radar** and **multi-spectral imaging** instruments for land, ocean and atmospheric monitoring. Sentinel-1 (1a was launched on 3 April 2014 and its twin 1b was launched on 25 April 2016) is a polar-orbiting, all-weather, day-and-night **radar imaging mission** for land and ocean services. Sentinel-2 (launched on 23 June 2015) is a polar-orbiting, **multispectral high-resolution imaging mission** for land monitoring to provide, for example, imagery of **vegetation**, **soil** and **water cover**, **inland waterways** and **coastal areas**. It can also deliver information for emergency services. Sentinel-3 (launched on 16 February 2016) has is a multi-instrument mission to measure sea-surface topography, sea- and land-surface temperature, ocean colour and land colour with high-end accuracy and reliability.

Sentinel-1, -2 and -3 will deliver data for agricultural monitoring by providing frequent coverage from C-band radar (Sentinel-1), multispectral optical imaging for land applications (Sentinel-2), continued acquisition and short revisit time over land surfaces with a very large swath of 290 km (Sentinel-2), multispectral optical imaging with 21 bands at 300 m resolution over all surfaces (Sentinel-3) and long-term continuity and rapid data dissemination (Sentinel-1, 2 and 3).

Sentinel-4 will be a payload devoted to atmospheric monitoring that will be embarked upon a Meteosat Third Generation-Sounder (MTG-S) satellite in geostationary orbit. Sentinel-5 will monitor the atmosphere from polar orbit aboard a MetOp Second Generation satellite. Sentinel-5 Precursor satellite mission is being developed to reduce data gaps between Envisat, in particular the Sciamachy instrument, and the launch of Sentinel-5. This mission will be dedicated to atmospheric monitoring.

Sentinel-6 carries a radar altimeter to measure global sea-surface height, primarily for operational oceanography and for climate studies (Copernicus Overview, 2016). Several Sentinel missions will have more spacecrafts to increase the revisit times.

3.2.3.8 Discussion - Impacts of canopy mapping

Since canopy mapping does not have direct economic, environmental and social impacts, these impacts are not discussed here separately.

Between topographic and soil sensing and yield and quality sensing, there is the crop growth period. Within this period there are several technologies that are used to identify how the crop is evolving in order to select the best management practice and optimise the final agricultural product. Such technologies are mainly observing the plant canopy and the recorded data are processed to be correlated with the final outcome of the crop (Ulaby and Bush, 1976; Bouman, 1991; Baronti et al., 1995; Moran et al., 1997; Brisco and Brown, 1998; Macelloni et al., 2001; Paul and Speckmann, 2004; Zillmann et al., 2004). These technologies are using non-destructive methods from distance that range from space through satellites (Copernicus) to airborne (manned or unmanned aircrafts) and proximal sensing. Most of the sensing technologies are available for different carrier (NDVI, RADAR, LiDAR, cameras).

This category of crop sensing is evolving in a very high pace and adds possibilities for more detailed data that can be used for production optimisation. However, the cost of purchasing the equipment or the services is at the moment high, especially for small farm holdings. The economic result of such applications can be positive only in case the recorded data are used for yield increase and/or agricultural input reduction, thus compensating for the cost of investment.

The environmental impact of these sensors cannot be assessed, except if the recorded data is used for the optimised production.

3.3 Reacting technology

3.3.1 Variable rate pesticide application

Variable rate pesticide application technologies enable changes in the application rate to match actual or potential pest stress in the field and avoid application to undesired areas of the field or plant canopies (Karkee et al., 2013). They can also significantly reduce spray overlap (Batte and Ehsani, 2006).

Weeds have received the greatest attention from researchers and from site-specific technologies developers, because of their immobility which makes them an easier target than other pests (e.g. insects) (Swinton, 2003). Therefore, current commercial applications focus on herbicide spraying, while VR insecticide and fungicide applications have not yet reached the stage of commercial breakthrough.

Conventional pesticide sprayers most often are self-propelled machines or machines pulled or carried by a tractor. In some particular high value and/or difficult to reach crops, a spray tank and spray boom can also be mounted on an Unmanned Aerial Vehicle. All sprayers apply a chemical that is tank-mixed with a carrier (generally water) using spray nozzles and a pressure-regulating valve to provide a desired volumetric application of spray mix at a certain ground speed. Any change in the boom pressure or ground speed from that of the calibration results in an application rate different from the planned rate (Humburg, 2003).

Two types of VR pesticide application technology can be discerned when considering the input side of the technology. On the one hand, there is **map-based VR pesticide**

application (Figure 33), which adjusts the application rate based on an electronic map, also called prescription map or application map. Using the field position from a GPS receiver and a prescription map of desired rate, the input concentration is changed as the applicator moves through the field (Grisso et al., 2011).

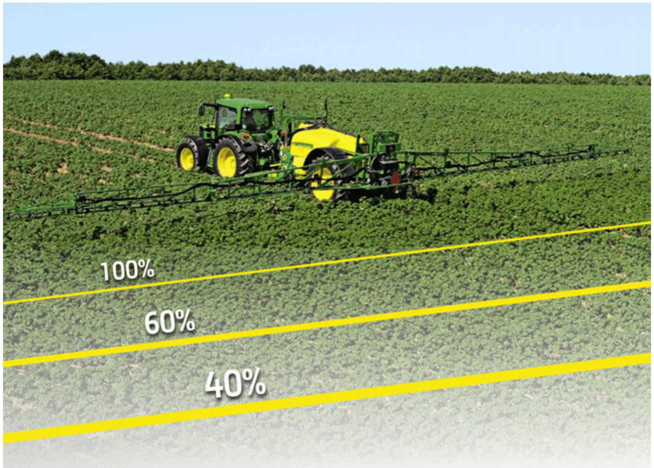

Figure 33: Map-based VR pesticide application. Source: John Deere, 2016.

On the other hand, there is **real-time sensor-based VR pesticide application**, which controls the application rate based on the current situation of pest stress or canopy characteristics (Figure 34), without the generation of a prescription map. These systems involve both contact (e.g. mechanical) and non-contact (e.g. camera) sensing to identify either pests that need to be controlled or the crop and foliage/canopy that needs to be protected. Various types of sensors can be used such as colour cameras, photodetectors, laser scanners, multispectral and hyperspectral cameras, thermal cameras, and ultrasonic sensors (see section 3.2.3.2). These sensors have been used to determine variables such as colour, shape, size, texture, reflectance, and temperatures of pests. This information is then used to categorise pest or canopy patterns, and to identify and locate them. The sensor input can also be used to control the direction and rate of chemical application (Karkee et al., 2013).

On the output side, both rate control systems and nozzle control systems can be used to apply the chemicals in a variable manner (vide infra).

Figure 34: Real-time sensor-based VR pesticide application. Source: Southern Precision, 2016.

One example of a commercial unit is the WeedSeeker®, which is equipped with a reflectance sensor that identifies chlorophyll. Each sensor consists of a light source and an optical sensor. The sensors are mounted on a bar or a spray boom ahead of the spray nozzle and aimed at the ground. When a chlorophyll (green) reflectance signal exceeds a threshold (set during calibration by the operator), a signal is sent from a controller to a solenoid-operated valve to release herbicide (Grisso et al., 2011). The working principle is illustrated in Figure 35.

In addition, sprayers that use information on the environment to reduce drift from the target are currently being developed. These sprayers use for example sensors which measure the wind speed and direction and change the sprayer settings (spray pressure, nozzle type) accordingly depending on where the sprayer is located in the field in relation to vulnerable areas based on GPS (Doruchowski et al., 2009).

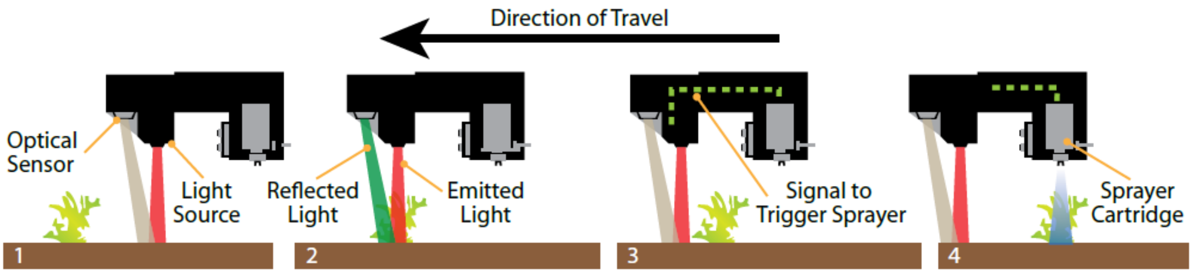

Figure 35: WeedSeeker working principle. Source: Trimble, 2016.

Besides input side, VR pesticide application technology can also be divided considering the output side. The main types of application technology are four:

- flow-based control;
- direct chemical injection;
- chemical injection with carrier control;
- spraying nozzle control.

Originally, the principle of the **flow-based control** system (Figure 36) was to keep the application rate constant by varying the nozzle flow rate in direct proportion to the forward speed (Hloben, 2007). The system combines a flow meter, a ground speed sensor, and a controllable valve (servo valve) with an electronic controller to apply the desired rate of the tank mix. This system can also be used for variable rate applications when a communication link can be established between the controller and a 'map system'.

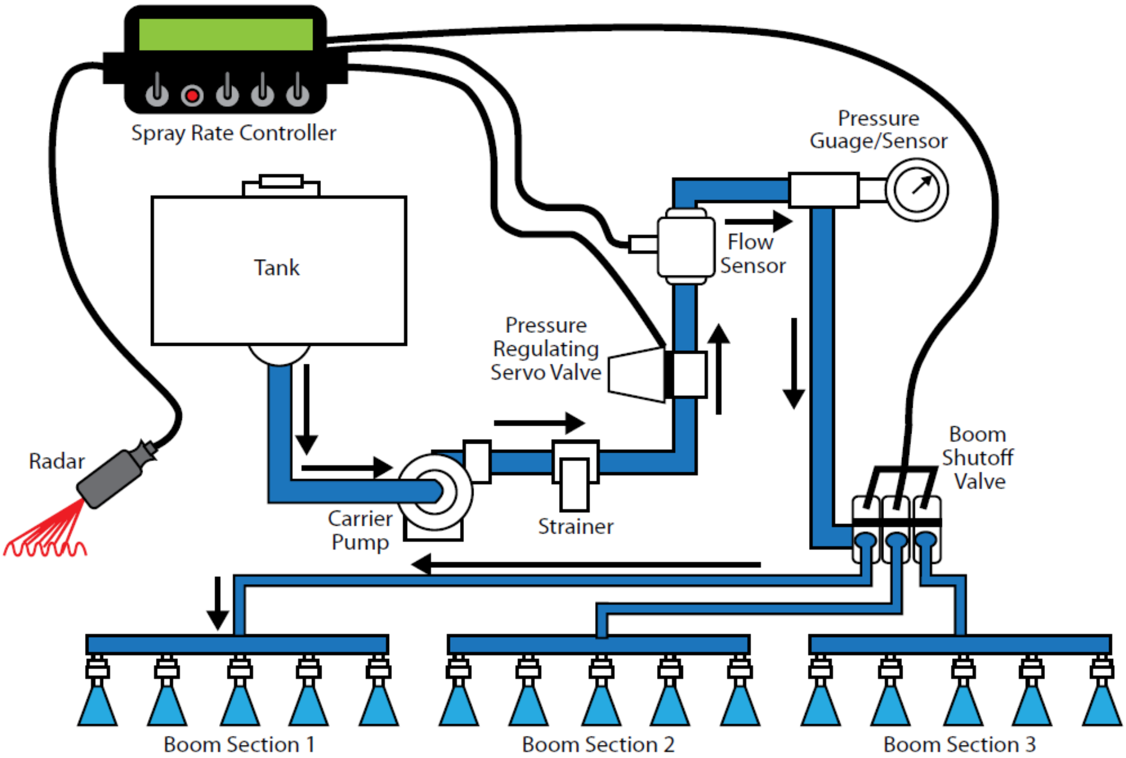

Figure 36: Flow-based control system. Source: Grisso et al., 2011.

Direct chemical injection systems (Figure 37) utilize a controller and a chemical pump to manage the rate of injection of a chemical into a stream of the carrier (water) rather than the flow rate of a tank mix. The flow rate of the carrier is usually constant, and the injection rate is varied to accommodate changes in ground speed or changes in the commanded application rate. If the controller is designed or modified to accept an external command, the system can be used for variable rate application (Humburg, 2003). In direct chemical injection systems the chemical concentrate and the carrier are kept in separate tanks (Hloben, 2007). Behind the carrier pump, the chemical can be injected into all boom sections (centralised), into only one section (decentralised), or directly into individual nozzles.

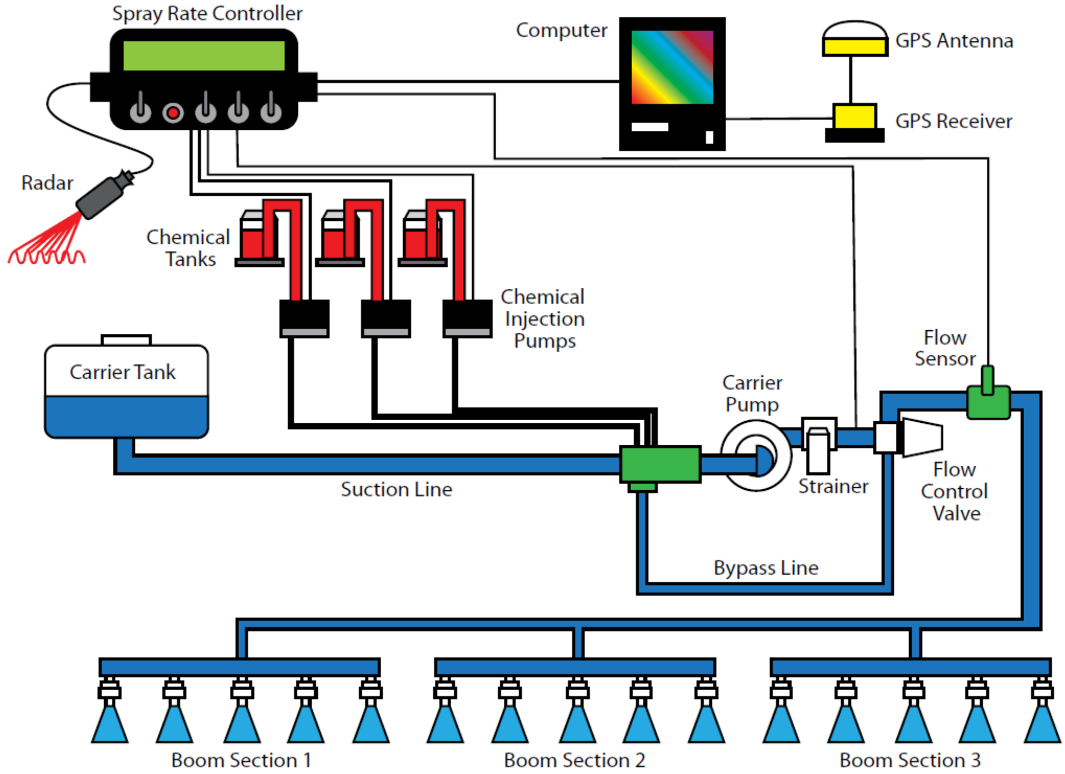

Figure 37: Direct chemical injection system. Source: Grisso et al., 2011.

Chemical injection with carrier control (Figure 38) utilizes a control system that changes both the chemical injection rate and the water carrier rate to respond to ground speed or application rate changes. It essentially is the combination of the two previous types.

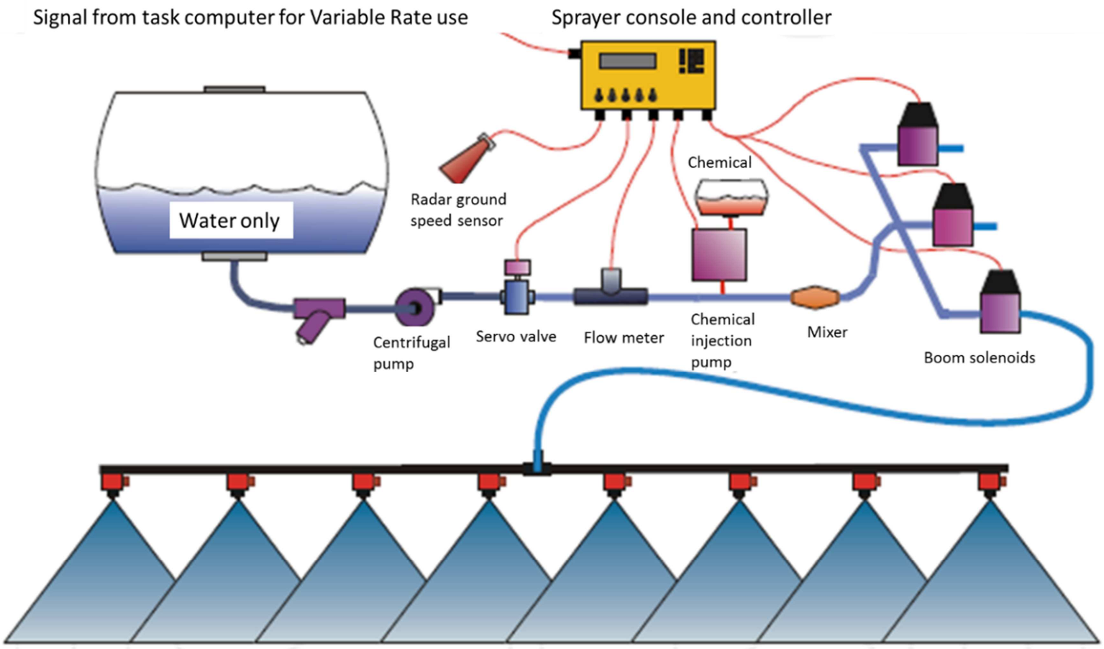

Figure 38: Chemical injection with carrier control system. Source: Humburg, 2003.

Spraying nozzle control systems (Figure 39) use conventional sprayer nozzle assemblies that work in conjunction with direct-acting, in-line solenoid valves to rapidly open and close the outlet of a nozzle. The key is to vary the amount of time the valve stays open to produce variation in the flow rate, and thus the application rate, without changing the droplet size distribution or spray pattern. Typical operating frequencies are around 10 Hz. Other systems used to control the nozzle flow rate are mixing the fluid with air in the nozzles, which can reduce the flow by half, or varying the orifices of the nozzles. The latter can be achieved by a moving, steerable component within each nozzle or by combining several nozzles into one holder and switching between them (Weis et al., 2012). Most VR enabled sprayers with this output technology operate by selective control of small sections (containing several nozzles) of the spray boom (Christensen et al., 2009). Individual nozzle control does however lead to more accuracy.

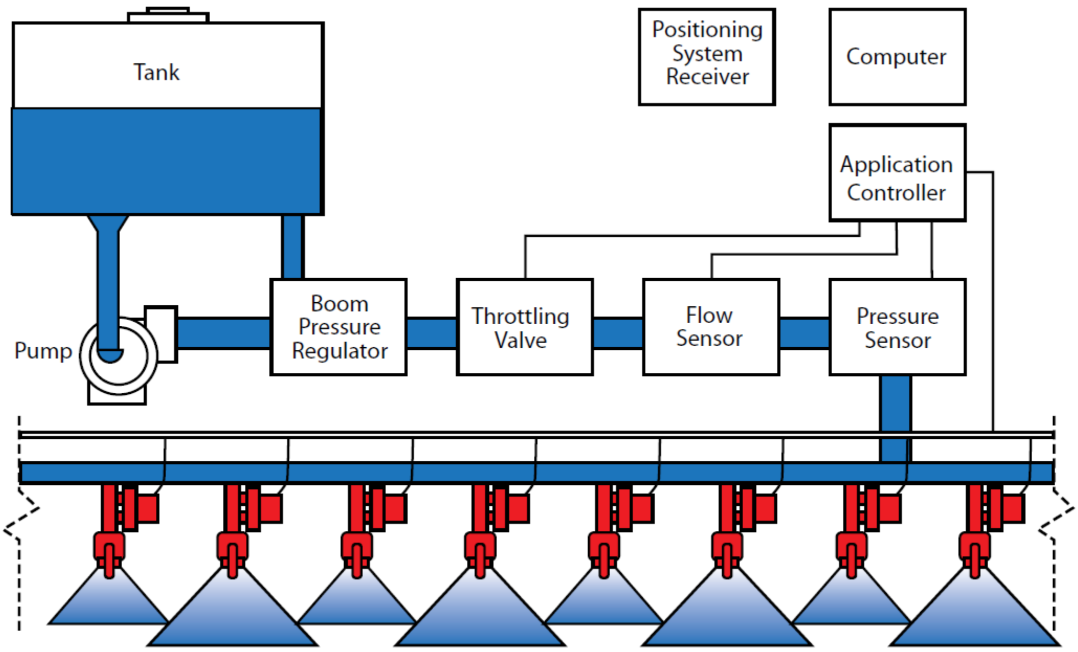

Figure 39: Spraying nozzle control system. Source: Grisso et al., 2011.

When the accuracy of sprayers reaches the size of a single plant, the process is denoted microspraying. The microspraying technique has two significant advantages: (1) high reduction of the amount of pesticide deposited on the soil, which minimizes the issue of leaching and (2) almost no deposition of pesticide on crop plants, which eliminates the potential presence of pesticide residues in the harvested crop plants and potential damages to the crop. A big disadvantage is the working speed of microspraying, which limits the economic feasibility (Midtiby et al., 2011). Micro-sprayers with single drop applications are also being developed (Lund et al., 2006; Urdal et al., 2014).

Boom height control (Figure 40) is an extra technology that, although it is not truly a type of VR pesticide application, it improves the uniformity application of chemical application (Karkee et al., 2013) by preventing yield losses or additional pesticide costs. This technology minimises the application losses by using real-time sensors that prevent oscillations (due to changes on e.g. ground speed or tire pressure) of the sprayer boom above its horizontal axis.

Figure 40: Boom height control. Source: GPS Ontario, 2016.

Ultrasonic sensors measure (40 times per second) the distance to the ground. This information allows the control system to make responsive height adjustments. The system has shown reliable control with average speeds more than 29 km/h in all kinds of uneven terrain. Although boom height control is not a VRA technology as such, it eliminates streaks and improper overlaps, and improves coverage (Grisso et al., 2011). Similar control mechanisms can also be used to position the spray tower at an appropriate distance from the crop canopy in orchards and ornamental nurseries (Karkee et al., 2013).

Variable rate technologies for pesticide application can also be used to apply fertiliser at variable rates (Ess et al., 2001).

3.3.1.1 Economic impact of variable rate pesticide application

Benefits of variable rate pesticide spraying are mainly associated with savings on pesticide use. Since most research has been done in the area of herbicide application (vide supra), the focus of this section lies on the economic impact of VR herbicide application.

Swinton (2003) states that research results on the profitability of site-specific weed management are very variable, because certain studies focus only on potential reduced cost from less herbicide spraying while ignoring the increased capital cost of variable rate application equipment and the increased variable cost of information processing. Other studies do take these last two factors into account, which might results in more realistic numbers on profitability. Timmermann et al. (2003) found that the monetary savings resulting from the reduction in herbicide use varied between crops, depending on the amount of herbicides saved and the price of herbicide. In maize, winter wheat, winter barley and sugar beet, savings of respectively 42 €/ha, 32 €/ha, 27 €/ha, and 20 €/ha were realised. In this regard, savings also depend on the different economic thresholds for pest control (i.e. the pest population density at which it becomes worthwhile to apply a form of pest control) and the different competitive power of the crops. Batte and Ehsani (2006) estimated pesticide savings of about 4 €/ha for a map-based spraying system compared to a self-propelled sprayer without any form of GPS for guidance assistance or sprayer control on hypothetical fields. The magnitude of input savings further increased as waterways were added to the field. Those authors also calculated the costs of the spraying system. Most of the costs are related to the fixed investment which diminishes per hectare as farm size increases. They also conclude that the benefits increase proportionally to the cost of the pesticide being applied and the number of annual *applications, and to the driver error-rate of the non-precision spraying system.*

Gerhards and Sökefeld (2003) evaluated the economic benefits of a real-time, automatic, site-specific weed control system compared to conventional field spraying. They found that although the costs (i.e. investment and maintenance costs) for the VRA technology were larger (9.56 €/ha vs. 5.20 €/ha), the average costs for weed control were lower due to herbicide savings (32 €/ha vs. 68 €/ha in winter wheat and winter barley, 69 €/ha vs. 148 €/ha in sugar beet, and 96 €/ha vs. 103 €/ha in maize). Based on these economic calculations, Dammer and Wartenberg (2007) comment that if sensors were available on the market, it would be profitable for farmers to invest in variable rate technologies. Takács-György (2008) stated that in Hungary, the extra investment in variable rate pesticide application is economically viable for farms with acreage above 150-160 ha. However, this minimum acreage boundary may have moved over the course of the last few years.

Oriade et al. (1996) suggest that weed patchiness is the most important factor justifying the use of site-specific weed control. Using simulation, they show that economic and environmental benefits are almost zero at low weed pressures, particularly if weeds are evenly spread. The benefits were larger as weed populations and level of patchiness increased. At high weed patchiness, return values of 17 €/ha to 33 €/ha were found in corn and soybean. The authors concluded that returns from site-specific management less than 14 €/ha are not sufficient to warrant the practice. The costs of information collection, time effects, and human capital were not considered in this model by Oriade et al. (1996).

Besides pesticide saving, more savings are possible from shorter times per hectare for filling the tank and carrying the spray mixture to the field by reducing the volume that is needed per hectare (Timmermann et al., 2003).

Costs of map-based VRA are attributed to mapping, data processing, decision making and site-specific application technology. Commercial mapping services typically charge 4.5 – 9.0 €/ha to map field boundaries including waterways and other physical features (Batte and Ehsani, 2006). Gerhards and Sökefeld (2003) estimated the costs (fixed + variable) of a direct injection system at 3.9 €/ha (in addition to the costs of the sprayer) for weed control in sugar beet, maize, winter wheat and winter barley in a German study. Batte and Ehsani (2006) state that the extra cost of a precision sprayer equipped with individually controlled nozzles based on GNSS information would be about €8,000. However, Timmermann et al. (2003) comment that several components of variable rate technology, including GNSS, board computer and GIS, can also be used for other precision farming activities such as planting, fertilisation and harvest, and can therefore not be considered as a cost that is solely related to VRA pesticide application.

In contrast to map-based VRA, in sensor-based VRA, an additional step of generating an application map with the help of GIS is not necessary. Therefore, there are no additional costs for computers, GIS software or DGPS. However, the sensor technology can be very expensive, although cheap sensors are available as well. Gerhards and Sökefeld (2003) estimated the cost of a camera system for weed detection at 40,000 euro, whereas Dammer and Wartenberg (2007) used an optoelectronic weed sensor of about 2,000 euro. The latter could however not distinguish between crops and weeds and was therefore limited in its operations.

In a study of Vasileiadis et al. (2011) on maize-based cropping systems, experts within Europe evaluated that precision spraying using GPS spray maps can result in a net profit within a time frame of 3-4 years.

3.3.1.2 Environmental impact of variable rate pesticide application

The ecological benefits of variable rate pesticide application result mainly from a reduction in pesticide use. The potential for herbicide reduction varies between crops depending on the different economic thresholds for weed control and the different competitive power of the crops (Timmermann et al., 2003). As a result of pesticide reduction, the risk of ground and surface water contamination could be decreased by site-specific pest management. In addition, the biodiversity could possibly increase (Timmermann et al., 2003).

Several studies have found reductions in the use of herbicides by site-specific, weed management in Europe. Gerhards et al. (1999) were able to reduce herbicide use by nearly 70% with a system for selective control of each 3 m-section of the spray boom. Heisel et al. (1999) achieved a 54% herbicide reduction. An average herbicide saving of 54% was also reported by Timmermann et al. (2003). For grass weed herbicides, those authors found savings of 90% in winter cereals, 78% in maize, and 36% in sugar beet. For herbicides against broadleaved weeds, 60% were saved in winter cereals, 11% in maize, and 41% in sugar beet. Solanelles et al. (2006) recorded 70%, 28%, and 39% of product savings in comparison to a conventional application in olive, pear and apple orchards respectively, with lower spray deposits on the canopy but a higher ratio between the total spray deposit and the liquid sprayer output (i.e. better application efficiency). These results were obtained using a prototype of an electronic control system mounted on an air-assisted sprayer. The control system was based on ultrasonic sensors and solenoid valves to apply rates proportional to the canopy width of the trees. Comparable, Gil et al. (2007) used ultrasonic sensors and electro-valves to modify the flow rate from the nozzles in real-time in relation to the variability of the crop width in vineyards. In their study, on average 58% less spray volume was applied compared to the constant rate application, while maintaining similar coverage and penetration rates. The same sprayer control system was tested by Llorens et al. (2010) in three vine varieties at different crop stages with a similar average saving of approximately 58%. Chen et al. (2013) compared a variable-rate air-assisted sprayer implementing laser scanning technology to apply appropriate amounts of pesticides based on various tree-canopy characteristics with a conventional air-blast sprayer in an apple orchard. The variable-rate sprayer only consumed 27% to 53% of the spray mixture while still achieving adequate spray coverage inside the canopies. Using a conventional field sprayer with a multiple nozzle body (Lechler VarioSelect) with four different nozzle types to vary the flow rate and a reflectance based weed sensor, average herbicide savings of 22.8% and 27.9% were achieved in cereals and peas respectively, in a study by Dammer and Wartenberg (2007). Takács-György et al. (2013) calculated that herbicide savings due to VR technology can amount up to 30,000 tonnes in the EU.

VR pesticide application can also cause reductions in insecticide use. Dammer and Adamek (2012) found a 13.4% reduction in insecticide use when conventional spraying and VR spraying with the same machine were compared.

Studies have shown that limiting insecticide use and providing floral resources and shelter habitats can increase the abundance, diversity and fitness of natural enemies, decrease pest damage, increase crop yield and the farmer's profit (Vasileiadis et al., 2013).

A reduction of greenhouse gas emissions can be obtained through the use of VR pesticide application technology, because this technology saves on pesticides, and therefore also on the GHG generated during their production. Since the quantities of pesticides used per hectare are rather low, when compared to fertiliser for example, the potential for GHG reduction is lower than in some other VR technologies.

3.3.1.3 Social impact of variable rate pesticide application

Variable rate spraying technologies with separate chemical tanks instead of tank mixes reduce the risk of operator exposure to the chemical (Humburg, 2003). Furthermore, variable rate technologies could reduce the time needed for filling the tank by decreasing the volume needed per hectare (Timmermann et al., 2003), although with map-based technologies extra time and labour may be needed to construct the application maps.

Precision spraying technologies which reduce the pesticide use are also socially important given the public concern about pesticides (Dammer and Wartenberg, 2007). European experts evaluated that precision spraying technologies using GPS spray maps can be accepted by society in terms of their environmental and health impact, and safety of end products (Vasileiadis et al., 2011). Society may also benefit through reduced cost of food and fibre due to reduced agrichemical use (Batte and Ehsani, 2006).

Considering the public concern about pesticides with regard to the environment and public health, precision spraying technologies which reduce pesticide use are also socially important (Dammer and Wartenberg, 2007).

3.3.1.4 Discussion - variable rate pesticide application

Field tests have demonstrated that variable rate pesticide application is appropriate and potentially profitable for managing weeds and diseases. The efficacy is however related to crop type, pest distribution, pesticide price, number of applications, field characteristics (e.g. waterways), farm size, and management. Not all weeds or diseases are good candidates for VRA and traditional uniform spraying remains very effective for many pests (Yang et al., 2015). Nevertheless, these technologies offer several economic, ecological and social opportunities and should be evaluated carefully for future farming systems (Grisso et al., 2011).

The two main input possibilities for variable rate pesticide application, i.e. map-based systems and real-time sensor based systems, have their own advances over the other. Map-based systems use a pre-determined map, whereas sensor based systems determine the actual conditions in real-time. Because farmers sometimes have very narrow time windows for spray applications due to weather conditions, trafficability of the field and growth stages, real-time sensor based systems are more flexible than map-based systems as an additional step of generating an application map is not necessary (Dammer and Wartenberg, 2007). Map-based applications on the other hand, can be used to provide the consumer information regarding pesticide applications, for example for pesticide-free produce (Swinton, 2003). Both systems do however contribute to the reduction in pesticide use, resulting in environmental as well as economic benefits. Values ranging from 10 to 90% pesticide reduction have been reported. In addition, other advantages include a possible decrease in operator exposure and labour.

Commercially available map-based systems are mainly restricted to field crop sprayers and weed control. Similar, some real-time sensor based field crop sprayers for weed control are available on the market, whereas for other types of sprayers, such as orchard sprayers, the technology is promising but not yet established. Currently, the overall challenge is the integration of available individual elements, such as monitoring techniques, decision support systems and precision spray techniques, into one management system. At the moment, the cost of some techniques is rather high but the price will decrease in time (Zijlstra et al., 2011), thus facilitating their implementation. Eventually, future implementation will depend on several factors, such as the context in which the farmer is going to operate, i.e. the development of markets, public concern about pesticide use and policy-making in general (Zijlstra et al., 2011).

VRA pesticide applications have an effect on greenhouse gas emissions, although this effect is only small when compared to VRA fertiliser application.

3.3.2 Precision physical weeding

Precision physical weeding technologies enable changes in the configuration of mechanical weeders (e.g. in the position of or the resistance exerted by the tines of a harrow) during weeding, to match weed presence and/or density in the field. The challenge of physical weeding is to obtain a high degree of selective weed control without producing considerable crop damage as a result of weeding (burning, mechanical weed control with knives, discs, hoes or harrows) Non-chemical weed control methods need to be directed towards a site-specific weeding approach, in order to compete with conventional herbicide applications. Different approaches and prototype systems have been proposed, adjusting the hoeing/harrowing/burning intensity based on the (earlier or real-time) observed soil density or weed density. Precise guidance and detection systems are prerequisites for successful site-specific weed management. An effective detection and identification is a primary obstacle toward commercial development and industry acceptance of robotic weed control machines. Various sensors may be used to detect the weeds, although the most promising approach for weed detection is a continuous ground-based system adopting image analysis (Martelloni, 2015).

Two recently developed examples of physical weeding machine prototypes are given in the next paragraphs.

Peteinatos et al. (2015) developed an experimental harrow (Figure 41) that changed the angle of sets of flexible tines in real-time through an electric actuator, based on ultrasonic sensors detecting the plant density in a specific location. In this way, areas with higher plant densities, and thus higher weed/total plants ratios, received more aggressive harrowing treatments.

Figure 41: The flexible-tine harrow designed by Peteinatos et al. (2015). Left: the full tine with its four actuators. Right: Detail of one actuator.

As part of the RHEA project (FP7), a prototype (Figure 42) of a precision hoeing-flaming implement was designed for use in maize fields (Martelloni, 2013). The correct position of the tools (mechanical and thermal) is guaranteed by an automatic precision guidance system connected to an image based row detection system.

Figure 42: The hoeing-flaming implement designed by the RHEA project.
Source: RHEA project, 2016.

3.3.2.1 Economic impact of precision physical weeding

As this technology is still in its infancy, no specific economic impact figures are readily available. However, a significant reduction of manual labour during physical weeding can be expected, especially in organic agriculture, which may lead to significant cost reductions.

3.3.2.2 Environmental impact of precision physical weeding

As this technology is still in its infancy, no specific environmental impact figures are readily available. Some general observations can however be made.

- Precision physical weeding can replace pesticides, reducing environmental pressure and avoiding the development of pesticide resistance in various weed species;
- By changing the angle of harrow tines, the power (and thus fuel) consumption during harrowing can be reduced (Peteinatos et al., 2015);
- VRA technology applied in weed burning may lead to a reduction of the amount of fuel used for burning compared with conventional weed burning methods.

3.3.2.3 Social impact of precision physical weeding

Autonomous robotic weed control systems hold promise toward the automation of one of agriculture's few remaining unmechanised and drudging tasks, hand weed control (Slaughter et al. 2007). On the other hand, this automation may lead to job loss in agriculture.

3.3.2.4 Discussion - precision physical weeding

This VR technology is in full development, so few studies are available on its economic, environmental and social impact. This technology is expected to save on GHG emissions, through reduced fuel consumption during harrowing and burning.

When this technology becomes commercially available, it can be expected that it will quickly be embraced by organic farmers, especially in regions with high labour costs, to replace the manual labour that is now required for weeding.

3.3.3 Variable rate planting/seeding

Variable rate planters/seeders (Figure 43) modify the rate of planting and seeding **during application**. This is often accomplished by disconnecting the planting/seeding system from the ground drive wheel, which normally keeps the planting/seeding rate constant when the speed of the tractor varies. By driving the planting/seeding system with an independent engine, gear box (to change speed of the ground wheel input) or hydraulic drive, the planting/seeding rate can be adjusted to the local soil potential (Grisso, 2011).

Figure 43: Variable rate seeding. Source: South West Ag Partners Inc., 2016.

For further precision, electronic clutches can be set between the shaft driven by ground wheel or the independent engine's/hydraulic drive and the shafts driving each planting/seeding element. The clutch connects the shaft of to the engine and the shafts of the planting/seeding elements so that they can either be locked together and spin at the same speed, or be decoupled and spin at different speeds, thus varying the application rate. This allows the seeding rate to be varied (i.e. lowered on the go per planting/seeding element (Trimble, 2016).

VR planters/seeders modify the planting/seeding rate by using prescition mpas. VRA planting and seeding is useful in very heterogeneous fields (i.e., fields with large differences in water holding capacity or soil organic matter in the different areas within the field). A simple example of the use of VRA planting/seeding is found in fields with a centre pivot irrigation system. Areas outside the reach of the irrigation system are planted/sown with a reduce rate, to avoid water scarcity caused by a too high plant density (Grisso, 2011).

Besides being used for varying seed density, the technology of VRA seeding is also used to eliminate double planting in headlands and point rows (Figure 44).

Figure 44: VRA seeding avoids double seeding (=intersecting rows) of maize.
Source: No-Till Farmer, 2016.

Another technology, which is not truly a type of variable rate planting/seeding, but which can be combined with variable rate planting/seeding and which has been developed in recent years is **multi-hybrid planting/seeding**. Machine manufacturers have started developing seeding machines that are able to seed two or more different hybrids at the same time: one high demanding and high yielding hybrid which is sown on the high performance zones of a field, while the other hybrid is a more resilient, but less yielding hybrid, which is sown on the low performance zones of the same field. The input-side of the technology is similar to the input used for VRA planters/seeders. The main difference between the two technologies is found on the output side. Multi-hybrid planting/seeding needs two (or more) separate seed hoppers and an adapted seed dispensing system (Figure 45).

Figure 45: Multi-hybrid planting/seeder with two seed hoppers. Source: Real Agriculture, 2016.

3.3.3.1 Economic impact of variable rate planting/seeding

The main factor driving the economic performance of variable-rate seeding is soil variability. In very uniform fields, the return on investment of VRA planting/seeding will be low, while in heterogeneous fields with differentiated crop performance zones, the return on investment will be much higher (Bullock et al., 1998).

In the early years of VRA planting/seeding development, its economic impact was unclear. Bullock et al. (1998) observed differences in economically optimal (i.e. generating the highest profit) plant densities for different field qualities: they estimated that areas of the field with higher yield potential could benefit from a higher plant density. At the time, they concluded that variable rate seeding would be infeasible, because of the high cost associated with characterizing site variability. In the same year Lowenberg-DeBoer (1998) stated that the investments necessary for adopting variable rate corn seeding would only be economically justifiable for farmers with some low yield potential land, where significant seeds savings and yield gains can be made, but not for farmers with a mix of solely medium and high potential land. Taylor and Staggenborg (2000) concluded that variable rate seeding was only economically feasible on their fields of study if less expensive than existing ways to generate the prescription map were available or if corn showed a greater yield response to seeding rate. In 2004, Shanahan et al. stated that "site-specific management of plant densities may be economically feasible", most likely due to technological advances, which may lead to lower investment costs. Dillon et al. (2009) performed sensitivity analysis with respect to alternative soils, seed price, wheat price and cost of variable rate seeding technology to determine the economic feasibility of variable rate seeding and concluded that the practice of VRA seeding of wheat in France is economically feasible.

In more recent years, Hörbe et al. (2013) performed two experiments that tested the economic returns of VRA seeding maize according to a prescription map with three management zones, i.e. a low crop performance zone (LZ), receiving 31% less seeds/ha, a medium crop performance zone (MZ), receiving the normal seeding rate, and a high crop performance zone (HZ) receiving 13% more seeds/ha. This resulted in a yield increase of 1.20 and 1.90 tons/ha in the LZ of the two experiments, and 0.89 and 0.94 tons/ha in the HZ. In a second, identical experiment, carried out one year after the first, this resulted in a partial net income (excluding extra costs for the VRA seeder) that was around 7% higher than in the same field seeded with a flat rate over the entire field. 71.5% of this higher net income was gained in the LZ, although the LZ area was smaller than the HZ area (22% vs 28% of the total field area, respectively).

A study of automatic section control systems in planters among 52 fields showed that the double-planted areas can reach up to 15.5% of the total field area, therefore the savings from the use of PA planters, which eliminates double-planting, ranged from $4 to $26 per ha depending on the farming operation and the field type (Velandia et al., 2013).

No independent scientific research on the economic impact of multi-hybrid planting/seeding is currently available, because this technology is currently under development.

3.3.3.2 Environmental impact of variable rate planting/seeding

No studies on the environmental impact of variable rate planting/seeding were found during the literature review. Nonetheless, an effect of VR planting/seeding on emissions can be expected through the increased yield reported by Hörbe et al. (2013). Less fuel is required for generating the same amount of harvest, since more harvest can be produced on a given soil surface.

3.3.3.3 Social impact of variable rate planting/seeding

No studies were found on the social impact of variable rate planting/seeding and multi-hybrid planting/seeding. It can however be expected that both technologies require more technical know-how from the farmer than uniform planting/seeding.

3.3.3.4 Discussion - variable rate planting/seeding

VR planting/seeding technology has recently been developed, and shows possibilities for increased yield, which in turn leads to increased economic returns and possibly to decreased fuel consumption. The environmental effects of VR planting/seeding should however be further investigated.

For multi-hybrid seeding, the yield increases (if any), and the effect on economic returns and fuel consumption have yet to be established by independent scientific research.

3.3.4 Variable rate nutrient and lime application

Technology for variable rate fertiliser application exists for inorganic fertiliser (N, P, K) application, organic fertiliser (i.e. manure) application and lime application.

The technology for (variable) application of both inorganic and organic fertiliser differs strongly, since inorganic fertiliser is sometimes spread as a liquid (e.g. aqueous solutions of ammonium nitrate or urea), but generally as solid granules (e.g. mixtures of nitrogen, phosphate and potassium), while organic manure can be spread in the form of slurry (e.g. pig faeces) or solid manure (e.g. chicken faeces). Liquid inorganic fertiliser can be variably spread with VR pesticide sprayer technology and is therefore not discussed further in this section.

3.3.4.1 Granular fertiliser variable rate application

Different types of granular fertiliser spreaders exist. Of all types, the spinner spreader and pneumatic spreader are the most used types. These types can also be used for lime spreading. Another type, the fertiliser drill, shows good potential for variable rate application of granular fertiliser.

The **spinner spreader** (Figure 46), also called the centrifugal spreader, is the most commonly used, due to its' price, technical simplicity and longevity. In the spinner spreader system, fertiliser/lime granules from a hopper fall on one or more spinning disks that are equipped with vanes throwing the particles into the field. The dynamics of the fertiliser particles on the machine and in the air are highly dependent on both the machine settings and the fertiliser's physical properties (Behic Tekin and Okyay Sindir, 2013; Hijazi et al., 2014).

Figure 46: A spinner spreader at work. Source: GKN Walterscheid, 2016.

Pneumatic spreaders (Figure 47) use airflow to convey fertiliser particles from the metering units to distributors which divide the granules over the piped spreading boom. In contrast to the spinner spreader, material is distributed uniformly through the distributors along the length of the boom. Therefore, no overlap is necessary between subsequent swaths.

Figure 47: A pneumatic spreader at work. Source: What's new in farming, 2016.

Spinner or pneumatic granular fertiliser spreaders are designed for a large working width. In order to cope with high spatial variability during VR application, **fertiliser drills** (i.e. machinery that delivers the fertilizer into the soil, much like a seeder delivers seeds into the soil) can be used to aim for higher placement accuracy (Maleki et al., 2008). The fertilising unit can be mounted on a row-crop planter (Figure 48) (Maleki et al., 2008). In contrast to the above mentioned broadcast spreaders, the width of the machine equals the working width and particles are not thrown into the air which reduces the sensitivity of the application system (e.g. for wind).

Figure 48: Fertiliser/seed drill at work. Source: Claussen farms, 2016.

Based on the ground speed of the tractor and a prescription map or on online sensor values, variable rate control systems for spinner and pneumatic spreaders generally change the mass flow rate from the hopper to the metering and delivery system. This is generally done in two ways: by changing the size of the orifice at the bottom of the hopper (Chen and Zhang, 2011), or by changing the speed of the conveyor belt or the metering rollers that deliver fertiliser to the delivery system (Fulton et al., 2001; Akdemir et al.,2007; Behic Tekin and Okyay Sindir, 2013). Some systems use load cells (i.e. transducers that create an electrical signal whose magnitude is directly proportional to the force applied to them) to measure the dynamic weight of the spreader with fertiliser, which goes down when more and more fertiliser is spread. Based on this drop in the weight, load cells can provide feedback to the control unit during application, by predicting the application flow rate. Measuring the mass flow is also possible by measuring the torque to rotate the spreading disks. In most cases the system needs to be calibrated before starting.

Variable rate application with spinner spreaders is more complex than with pneumatic spreaders. The trajectories, and therefore also the place where the fertiliser granules end up, are well known and easy to follow in applications with the pneumatic spreader. In applications with centrifugal spreaders, it is much more difficult to find out where each fertilizer granule ends up, because the airborne trajectories of the fertilizer granules depend on many variables (e.g. tractor speed, hopper orifice size, spinning disk speed, wind). By modifying the size of the orifice between the hopper and the spinning disk, the behaviour of particles on the disk changes, which has an effect on the shape of the spread pattern (Olieslagers et al., 1997; Fulton et al., 2001; Fulton et al., 2003). This means that variable rate systems for centrifugal spreaders, especially at large working widths, require online adjustments of machine parameters such as disk speed, vane angle and position of the orifice relative to the disk to compensate for this variation (Behic Tekin and Okyay Sindir, 2014; Van Liedekerke et al., 2006; Fulton et al., 2003). Additional sensors are necessary to provide that feedback (Cointault et al., 2003; Villette et al., 2008; Hijazi et al., 2014; Grift and Hofstee, 2002; Rauch, 2016). These sensors will however increase the costs and the complexity of the machinery.

Fertiliser drills also base their VR application features on the ground speed of the tractor and a prescription map or on online sensor values (Maleki et al., 2008), but in fertiliser drills, the mass flow rate of fertiliser is changed by controlling a metering screw or an electrical actuator changing the rotational speed of the fertiliser metering devices (Maleki et al., 2008; Forouzanmehr and Loghavi, 2012).

3.3.4.2 Liquid/slurry variable rate fertilisation

Slurry applicators work by either pressuring the slurry tank or by pumping the slurry from the tank. In case of a pressurised tank, the application rate can be modified by changing the size of the gate opening that delivers slurry from the tank to the delivery system. In the other case, slurry is pumped from the tank to the applicator by means of a centrifugal or positive displacement pump (Funk & Robert, 2003). In most cases, pumps are driven by the tractor’s power take-off. The application rate can be controlled by changing pump or valve settings.

The required slurry flowrate can be calculated and set by the controller based on an application map or real-time soil sensor measurements, the nitrogen content of the slurry (measured before application), the ground speed of the vehicle (measured with sensor or using GPS information) and the working width (Brambilla et al., 2015).

Variable rate slurry application (Figure 49) can be administered in two different manners: i) by only modifying the flow of slurry from the tank to the application hoses and ii) by also measuring the nitrogen content when determining the appropriate flow rate. This second application manner was developed because slurry is not consistent in nutrient content. The nutrient content of the slurry can be measured online with electrical conductivity or using near infrared spectroscopy (Calcante et al., 2014).

Figure 49: Variable rate slurry applicator at work. Source: Purdue University, 2016.

3.3.4.3 Solid manure variable rate fertilisation

Solid manure spreaders work with an apron that pushes the manure towards a dispensing system. The results of a study on non-uniform application of solid manure indicate that investment in the development of precision spreading equipment is not economically justifiable since there was little impact on crop nutrient response and soil nutrient loading (Agriview, 2013). Current technology, when properly calibrated and employed with attention to overlap from multiple passes (i.e. double fertilisation), is most adequate.

3.3.4.4 Economic impact of variable rate fertiliser/lime application

Sogaard and Kierkegaard (1994) described the relation between nitrogen supply and plant yield with a quadratic equation. The parabolic shape reflects that each further added unit of nitrogen causes a smaller yield increases of the crop. At a certain point, the benefits of an added unit of nitrogen (i.e. extra crop yield) barely outweigh the costs of this unit, and an economic optimum is reached. This economic optimum is found at lower application rates than the yield optimum. By fertilising each management zone near the economic optimum, higher returns can be achieved. The highest returns for VRT application are expected on fields with high and spatially variable nutrient requirements (Raun et al., 2001). Variable Rate granular fertiliser application, (at 1 m² spatial resolution based on optical sensing) increased their simple estimate of revenue (grain revenue minus fertiliser cost) compared to uniform granular fertiliser application. The revenue increases by 11 $/ha when fertiliser was applied before planting (fixed rate) and more than 28$/ha when fertiliser was only applied in-season (Raun et al., 2001). Mamo et al (2003) found a profit increase of 8 to 23 $/ha for corn when using VRT compared to uniform application due to reduction in the use of fertiliser. Koch et al. (2004) found an increase of 25.6 to 38.6 $/ha in net returns for VRT application of N on Colorado corn based on site-specific management zones compared to uniform application rates, both in a farmer and custom applied scenario. Biermacher et al. (2006) showed that a precise system could reduce the overall N application level from conventional levels before planting by 59–82% depending on the site. Furthermore, these authors state that for prices of $0.55 and $0.33 kg N for urea-ammonium nitrate and ammonia, respectively, the maximum net value of a system of precise sensor-based nitrogen application for winter wheat was about $22–$31 per hectare depending upon location and assumptions regarding the existence of a plateau. However, for prices of $1.10 and $0.66 kg−1 N for urea-ammonium nitrate and ammonia, respectively, the value was approximately $33 per hectare. The benefit of precise N application is sensitive to both the absolute and relative prices of urea-ammonium nitrate and ammonia. In a later publication, Biermacher et al. (2009) claim that plant-sensing systems have the potential to be more profitable than traditional non-precise systems, although the traditional and plant-sensing systems they compared in that publication roughly broke even. Bora (2009) claims that in citrus groves in Florida, a cost reduction of $138 per hectare is possible through variable rate application of urea. Next to fertiliser costs other costs can be attributed to VR fertiliser application, such as soil sampling or online soil sensing, delineation of management zones and other fixed or variable costs associated with VRT equipment (GPS receiver, on-board computer, software, and the different mechanical components needed for VR application). Larger farm sizes, due to the economics of scale, allow fixed costs associated with VRT equipment to be spread over a larger area, and therefore decrease the expense of VRT equipment per hectare (Koch et al., 2004). Variable rate application based on grid soil sampling results in a lower net return when compared to delineating site-specific management zones based on bare soil aerial imagery, farmer's perception of field topography and farmer's past crop and soil management experience, primarily due to increased fertiliser uses and soil sampling costs.

Managing **manure** as fertiliser resource for crop production can increase the profit for the producer and the overall production efficiency of an animal-crop farming system (Huber et al., 1993) in much the same way as granular fertiliser management. Precision management of manure has the potential to further improve farming system production efficiency (Morris et al., 1999). As with VR granular fertiliser application, the key to VR manure application in general is the existence of an application map, which is laborious and time consuming to generate when acquired without sensor technology (Schellberg and Lock, 2009). Although no literature is available considering the economic return of VR manure application, many similarities with VR granular (inorganic) fertiliser applications can be seen. The main difference is the fact that here the applied product is much bulkier, heterogeneous and lower in nutrient content (Morris et al., 1999) and financial value. It should be noted that some VR manure systems can be retrofitted to the tankers that farmers already have (Brambilla et al., 2015), which removes the need for large investments to start with VR manure application.

Variable rate (VR) **lime** (which is primarily $CaCO_3$) application can increase crop yields and the economic return of the farm (Weisz et al., 2003). Lime application increases the soil pH to a desired level and an optimal pH level in the soil is important to achieve optimum yields and consistent quality (Kuang et al., 2014). Also, lime improves the uptake and availability of plant nutrients and can also improve water penetration. However, VR liming appears to be only profitable for high value crops (Swinton and Lowenberg-DeBoer, 1998), because even small effects of liming on yield produce favourable economic results in these crops.

VR lime application can lead to improved adjustment of soil acidity at a lower cost and with a (slightly) better yield response than uniform lime application (Kuang et al., 2014). Under-application of lime can cause large yield losses. Over-application of lime can be as detrimental as under-liming (Weisz et al., 2003), as it is costly and can create problems with availability of some nutrients (for example inhibiting P and Zn, or leading to toxic levels of Mn), disease pressure, reduced herbicide performance and herbicide degradation (Kuang et al., 2014; Weisz et al., 2003). Over- and under-liming cannot be avoided if lime is applied uniformly throughout the field.

Limited field studies have shown that variable rate application of lime, as opposed to uniform application, increases soil pH, reduces in-field variability and increases soybean yield but not corn yield (Pierce and Warncke, 2000). In 75% of the studies (4 in total) reviewed by Lambert and Lowenberg-DeBoer (2000) investigating VR lime, a positive economic effect was found, while in 25%, the articles indicated mixed results. The lime application can be more effective in legumes than in corn and wheat, as the response of the latter is limited to pH 5-5.5, where in legumes this can go up to pH 6 (Weisz et al, 2003).

Kuang et al. (2014) found an increase in lime consumption but also an increase in yield and net profit ($4.1/ha) for the VRT approach compared to the traditional approach for Danish spring barley. BonGiovanni and Lowenberg-Deboer (2000) found a net profit increase of $7.4/ha for Indiana corn and soybean production systems.

Weisz et al. (2003) concluded that when performing grid sampling and VR lime for 3 consecutive years in Piedmont no-till soybean fields, the net loss is $12.99/ha compared to uniform lime application. However, when they performed grid sampling only in year 1 and 3, and performed the VR lime in each year (with year 2 based on the PH map of year 1) this turns into a net gain of $4.86/ha over 3 years. Similarly, using the pH map from year 1 to apply lime for 3 years only in the areas were lime was initially required leads to a net gain of $7.31/ha estimated (Weisz et al, 2003).

The main cost in a VR lime application is the cost of grid sampling. The actual amount of lime used depends on the soil variability, field acidity, environmental factors, the sampling method and the sampling resolution (Weisz et al., 2003). The differences in field characteristics and in soil sampling techniques may explain for the differences in the results obtained by the authors cited in the previous paragraphs.

3.3.4.5 Environmental impact of variable rate fertiliser/lime application

Site-specific fertilisation can reduce the total amount of fertiliser used (Koch et al., 2004), indicating an increase in Nitrogen Use Efficiency (NUE). Raun et al. (2001) found an average NUE increase of more than 15% in winter wheat in Oklahoma, USA.

Overdosing of nitrogen fertiliser leads to local peaks in residual nitrogen concentrations in the soil. Excess nitrogen migrates to waterbodies and contributes to eutrophication. Tissot et al. (2002) found that an increasing Coefficient of Variation (CV) of the fertiliser distribution pattern was related to a higher residual soil nitrogen concentration after harvest, which might then migrate into waterbodies. Improving the NUE by adopting VRT can decrease the amount of nitrogen moving to the environment.

Similar to the more efficient use of nitrogen, a more efficient use of manure may lead to reduced loss of nutrients to the environment, avoidance of eutrophication of surface water and a reduction of greenhouse gas emissions. For manure these gaseous emissions include CH_4 and N_2O. Specifically for slurry spreading, there is another advantage of VR spreading compared with uniform spreading: even with changes in tractor speed, the flowrate is continuously adjusted, while in traditional systems, the only way to change the application rate is to modify the tractor's velocity. At lower application rates, which may be wanted from an environmental point of view, non-VRT unregulated applicators can often not be pulled at high enough ground speeds because the draught requirement is too high, because the soil injection toolbar causes an undesirable tillage pattern or because the vehicle dynamic characteristics and conditions of the field make it impossible to maintain control or damage the equipment (Funk & Robert, 2003).

The production of fertiliser and lime contributes to the emissions of greenhouse gases. Thus, a more efficient use of fertilisers and lime, adapted to the crop needs will reduce the amount of fertiliser used thus decreasing total GHG emissions. However, the impact of VR lime technology on lime use is mixed, since both reductions and increases in the use of lime are possible, according to different researchers (Bianchini and Mallarino, 2002; Kuang et al, 2014). This difference in lime use can be explained by the higher sampling resolution employed by Kuang et al. which enabled a better detection of areas with low pH levels.

3.3.4.6 Social impact of variable rate fertiliser/lime application

An increase of automation level of the fertilisation process decreases the amount of work for the farmer or operator during fertiliser spreading compared to traditional approach. The farmer can focus more on maintaining the correct tractor path, while traditionally, he had to control on-and-off switching of the granular fertiliser/manure delivery.

However, in modern machinery systems, extra time before starting may be needed, because some (but not all) online fertiliser flowrate sensors, need calibration before starting. Furthermore, if manure nutrient content cannot be sampled online, it needs to be determined before application (Brambrilla et al., 2015; Calcante et al., 2015).

3.3.4.7 Discussion - variable rate fertiliser/lime application

The economic and environmental benefits of VR fertilisation are quite clear: Due to a higher NUE, a farmer can save on fertiliser costs, while maintaining or increasing yield. Furthermore, due to a more efficient use of the fertiliser, loss of nutrients to the environment, eutrophication of surface water and greenhouse gas emissions are all reduced. The benefits of VR lime application on the other hand are only clear in high value crops.

One important remark about variable rate nutrient application should be made: when applying fertiliser/lime at uniform or variable rate, it is often assumed that the right amount of fertiliser is placed at the right place. However, in practice this is not the case (Lawrence and Yule, 2005). Spread patterns show significant (unwanted) transversal and longitudinal variation (Fulton et al., 2001) which is highly influenced by terrain irregularities. Horrell et al. (1999) reported values from 10 to 80% for uniform applications in New Zealand. Tissot et al. (2002) reported values from 5 to more than 50% for uniform applications in Belgium, in most cases caused by badly adjusted equipment. The importance of good calibration can therefore not be understated, because without it, some of the benefits of VR application may become undone.

3.3.5 Variable rate irrigation

At present, the two most common types of conventional (not VR) **self-propelled (uniform) irrigation** systems are centre pivot and lateral move systems (linear move sprinkler) which apply water to pasture or crop, generally from above the canopy (Berne, 2015). These systems are most used in irrigation today.

Centre pivot and lateral move irrigation systems are designed and generally operated to replace the average water used by the crop and/or drained from the field over the past few days as uniformly as possible across the field. Irrigations are frequent and apply relatively low amounts of water, so that soil water is ideally maintained at relatively constant levels. Water is pumped from a well or nearby water source and distributed along the lateral pipe. Water is generally applied through sprinklers that can be attached directly to the pipe or hang down on hoses. In the USA, 72% of irrigation systems were sprinkler-based in 2000 (Colaizzi et al, 2009).

Both in lateral move and center pivot irrigation systems, there are the same three system subtypes: (1) mid elevation spray application, (2) low energy (elevation) precision application and (3) low energy (elevation) spray application.

Mid elevation spray application (MESA, Figure 50), which delivers water as high as 5 feet (=about 1.5 meter) above the ground, less high than classical irrigation systems, has an irrigation efficiency of 85%.

Low energy (elevation) precision application (LEPA, Figure 51), which delivers water even lower than MESA, through drag hoses in the crop, is the latest and future system. Low energy (elevation) spray application (LESA, Figure 52) sprinkles water through nozzles positioned less than two feet above the soil surface. LEPA and LESA have irrigation efficiency around 97% (Peters, 2016).

Figure 50: Mid elevation spray application. Source: Slideplayer, 2016.

Figure 51: Low energy (elevation) precision application. Source: Washington State University, 2016.

Figure 52: Low energy (elevation) spray application. Source University of California, 2016.

Centre pivot and linear-move irrigation systems are appropriate systems upon which site-specific (=variable rate) irrigation management technologies can be mounted due to their current and increasing usage, large area of coverage, and relatively high degree of automation (King *et al*, 2005).

Variable rate irrigation (VRI) systems are commercially available and can easily be retrofitted onto the uniform sprinkler systems previously explained. There are different methodologies available to deliver varying irrigation amounts along a straight line. One approach is to use multiple parallel sprinkler packages each with different nozzle sizes. In the case of two parallel sprinkler packages, selecting nozzles sizes that provide 1/3 and 2/3 of the original single sprinkler flow rate allows stepwise variable flow rates of 0, 1/3, 2/3 and 3/3 using control valves to control flow through each sprinkler) (McCann et al., 1997; King et al., 1999). Another way to achieve VR irrigation is to regulate the flow of water through each sprinkler drop hose by controlling the "on/off" cycle of a hydraulic valve positioned above the drop hose (Dukes and Perry, 2006; Han et al., 2009; Chavez et al., 2010). A third design changes the orifice size and thereby also the flow rate of a sprinkler nozzle by cycling a retractable pin in and out of the nozzle in a controlled manner (King and Kincaid, 2004).

Currently, most VRI systems use static application maps that often do not change from year to year, and feedback mechanisms to regulate the irrigation process often consist of periodic soil water measurements and soil sampling to monitor the levels of various chemical and biological parameters.

The most common variable rate sprinkler irrigation systems in use today are speed control systems (i.e. systems which control the speed of lateral or pivotal moving booms, and therefore also the amount of water applied per ha) (Evans et al., 2013). However, boom section control systems (i.e. systems that can vary the amount of water applied via specific sections of the entire boom; This system does not have valves for each nozzle, but for example per 5 nozzles; The five nozzles are then called a boom section) can achieve the same effects provided by speed control, but with greater flexibility, and provide more management options.

Micro-irrigation (Figure 53) is especially used in areas with very scarce water supply. Micro-irrigation works with a network of tubes to deliver water to individual plants or small groups of plants in the field.

Three types of micro-irrigation exist:

- Drip or trickle micro-irrigation. The end points of the tubes, which are located near plants or groups of plants, have drip or trickle emitters mounted on them;
- micro-sprinkling & microspray. Here the end points have sprinkler nozzles mounted on them;
- subsurface irrigation. Subsurface irrigation is the irrigation of crops through buried plastic tubes to which emitters are attached at regular intervals. Emitters are located below the soil surface, generally between 15 to 25 cm deep.

Compared to sprinkler systems, these systems give a greater crop yield, a better water use efficiency, maintain warmer soil temperature (in case of subsurface irrigation) and can result in less pesticide use (Camp et al 1998). These systems can be used in small areas, but due to the larger costs, their use is generally restricted to high value crops like orchards and vineyards.

An example of a variable rate/site-specific micro-sprinkling system in an orchard is described in Coates *et al*, 2006. A micro-sprinkler sensor and control system was developed to provide spatially variable delivery of water mainly in orchards. Individually addressable micro-sprinkler nodes, one located at every tree, each contained control circuitry and a valve. A drip line controller stored the irrigation schedule and issued commands to each node. Pressure sensors connected to some of the nodes provided lateral line pressure feedback. The system was programmed to irrigate individual trees for specific durations or to apply a specific volume of water at each tree.

Most orchards planted within the past 15 years use micro-irrigation for both water and nutrient delivery, and many older orchards that currently use flood or sprinkler irrigation are being converted to micro-sprinklers to reduce costs and increase efficiency. This has created substantial interest in site-specific management, although research on spatially variable micro-irrigation systems has been limited. In the case of orchards, long term studies should be conducted to quantify the effect of tree-level orchard management on yield, profitability, and environmental quality.

Both remote sensing techniques measuring the thermal part of the spectrum, and various local sensors can be used to provide guidance for VR irrigation technology.

Figure 53: Micro-irrigation example. Source: Water Changers, 2016.

3.3.5.1 Economic impact of variable rate irrigation

Few hard figures are available about the economics of variable rate irrigation. However, it may be expected that adoption will be crop-value related: adoption will go faster in high-value crops. Threshold prices can be calculated for specific crops and specific contexts. E.g. for precision irrigation in the Texas High Plains, it was calculated the threshold of cotton price to be set above $1.59/kg to make the use of precision irrigation profitable (Seo et al., 2008).

Lambert and Lowenberg-DeBoer (2000) reported economic benefits of the use of VRI due to the yield (corn) increase and an increase in water use efficiency. However, these benefits were not described in numbers.

Many authors (Booker et al, 2015; Colaizzi et al, 2009; Evans et al, 2012; Sadler et al, 2005) mention that opposite to the high costs of VRI systems, benefits are possible due to yield increases, work load reductions, water use reductions and even pesticide use reductions, especially in climatic unfavourable years. For water use reduction, Hedley and Yule (2009) tested different scenarios for New Zealand and showed significant potential water savings of 21.8–26.3%. These potential water savings suggest that VRI will become more affordable as irrigation costs increase (Hedley & Yule, 2009).

Daccache et al. (2015) estimated the benefit to the farmer due to reduced use of water and energy to be typically around 30 euro/ha to areas that are over-irrigated in humid climates. These authors also claim that the development and uptake of VRI would need to be justified more in terms of the wider benefits to crop quality and reduced environmental impacts than solely in terms of reduced water use and costs.

Currently, no economic data about VR micro-irrigation is available because VRI combined with micro-irrigation is still in its infancy.

3.3.5.2 Environmental impact of variable rate irrigation

Computer simulation studies comparing conventional and ''optimised'' advanced site-specific zone control by centre pivot irrigation have reported water savings of 0–26% (Evans and King, 2012). However, water savings depend very much on the soil as sandy soil will generate substantial water savings but heavy soils not (compared to surface irrigation systems).

A review by Trost et al. (2013) compared N_2O emissions from irrigated and non-irrigated fields and showed that availability of reactive nitrogen compounds, which are more abundant in irrigated soils, increased N_2O emissions under irrigation, in most cases. Increases of about 50 % to 140 % in N_2O emissions were reported. This shows that VRA irrigation may significantly reduce N_2O emission from irrigated soils.

3.3.5.3 Social impact of variable rate irrigation

VR (micro-) irrigation may lead to a reduction in work load due to automation. On the other hand, the newest high-tech systems require a very broad knowledge in different technical and biological areas from the farmer.

3.3.5.4 Discussion - variable rate irrigation

At the moment, most irrigation systems apply water quite uniformly. However, substantial variations in soil properties and water availability exist across most fields. Applying variable rate irrigation to match spatially and temporally variable conditions and biological requirements can increase application efficiencies, yield and product quality, while reducing environmental impacts, most notably N_2O emissions.

Assessing the ideal prescribed irrigation quantity (=so-called irrigation depth) is critical for the implementation of site-specific irrigation systems (O'Shaughnessy et al, 2013). Furthermore, the importance of an accurate delivery of the prescribed quantity should not be overlooked, because prescribing the right irrigation quantity is one thing, getting the prescribed quantity of water to the right part of the field another.

4 Conclusions

Recent innovations in low-voltage sensor and wireless radio frequency (RF) data communications combined with advances in internet technologies offer tremendous opportunities for the development and application of real-time management systems for agriculture (Evans et al., 2012).

GNSS, and recording and mapping technologies making use of these new developments in sensor and communication technology, build the basis for a precise data acquisition and information gathering, which is necessary for subsequent site-specific application. It is however still a big challenge to convert the obtained data into useful knowledge for variable rate application.

VRA technologies aim to achieve an optimised use of inputs, which allows for savings in time, cost and fuel as well as for the sparing use of resources for a sustainable agriculture. The possibility of variable rate application is the first main benefit of adopting PATs. The site-specific application of inputs allows for a more sparing use of resources like time, fuel, fertilisers, seeds and pesticides, which leads to a more sustainable agriculture.

Automated machine guidance is another major benefit of PAT adoption. Guidance technologies such as parallel tracking systems and fully automated guidance systems are based on GNSS-positioning technologies and have become the "best sellers" within PATs, as they are preventing gaps and overlaps and reducing time, thus minimizing costs for labour and fuel.

Due to these savings in inputs, PATs are also a driver for the enlargement of farms. Large farms are generally quicker in taking up PA technologies, which may give them a (further) competitive advantage over smaller farms.

Due to the wide range of existing PATs, and the differences in suitability of PATs per European region, farmers, crop consultants and technology providers should be provided with a Decision Support System (DSS) for selecting PATs with suitable characteristics. Such a DSS could also be used to carry out targeted adoption studies among farmers, and for pointing out future directions of PA that may eventually lead to increased PA adoption (Griffin and Lowenberg-Deboer, 2005; Fountas et al., 2005).

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Appendix A: PAT variables + PATs comparison

The following list contains the main variables for defining PATs (Schwarz et al., 2011):

- Farming systems
- Cropping systems
- Time slice for availability of the technique
- PA starting levels
- PA data integration into Farm-Management-Information-Systems (FMIS)
- Knowledge support
- Farmers' motives
- Adoption
- Mitigation potential

This list is further explained in subsections A.1 to A.9. In subsection A.10, the PATs listed in chapter 3 are compared according to these variables in two separate tables.

A.1 Farming systems

A farming system is defined here as a population of individual farms with similar management practices. Three major farming systems with high potential for uptake of PATs, were identified:

- **Organic farming:** The farming system that relies on a wide biological control and mechanical cultivation to maintain soil productivity and pest control.
- **Extensive farming:** Low energy input farming that uses small inputs of labour, fertiliser and capital relative to the land being farmed and where conventional practices are carried out.
- **Integrated farming:** The farming system that use Good Agricultural Practices and/or Integrated Crop Management strategies to produce high quality and certified agricultural products.

A.2 Cropping systems

A cropping system refers to the sequence of crops grown on a piece of land. For precision agriculture this is relevant as cropping systems are related to soil care and farming types. It relates to the farming strategy of the farmer and hence to his incentive to invest in precision agriculture. For the relevance in precision agriculture, the cropping systems are divided into clusters of the cropping environment as are dominantly found in the EU-28:

- Arable crops
- Forage crops
- Orchards
- Vineyards
- Field vegetables

A.3 Time slices for availability of the technique

The time slices for availability of the technique are divided into three categories:

- **Now available:** PATs that are commercially available to be used by farmers today.
- **Next 5 years:** PAT which are currently under development or at prototype stage and are likely to be availability in the next 5 years .
- **In the future (>10 years):** PATs that are in experimental stage in the labs or research institutes, such as robotic harvesters, robotic hoeing, etc.

A.4 PA investment levels

The following investment levels are needed for farmers to adopt PA:

- **Mini:** A low cost investment (e.g. parallel guidance with light bars, yield mapping or soil mapping). Typical investment range is 0 - 10,000 € (expert judgement of the authors).
- **Compact:** A medium cost investment (e.g. online sensors combined with direct controlling, on-board computers or terminals, parallel guidance with terminals, variable rate application of nitrogen). Typical investment range is 10,000-30,000 € (expert judgement of the authors).
- **Combi:** A high cost investment (e.g. fully applicable PA software, variable rate applications in many operations, automated guidance system). Investment level is over 30,000 €, (expert judgement of the authors).

A.5 PA data use

There are four main categories distinguishing how precision agriculture data can be used in Farm Management Information Systems:

- **No integration:** No data are recorded or that the accuracy of GPS data is not sufficient enough, e.g. smartphone GPS data.
- **Low:** DGPS positions of the field boundary or other data without further valuable information content.
- **Medium:** Accurate GPS positions and data for crop and soil parameters. VRA techniques only based on thematic maps bring a medium data integration.
- **High:** On-the-go VRA based on spectrometer sensors or hybrid systems (maps and sensors). The information density is high and the possibility of as-applied maps with underlined dense advanced information is provided.

A.6 Knowledge support

Three categories of knowledge support assessing the level of agronomic and technical support provided to farmers from crop consultants, software vendors, machinery manufacturers, are discerned:

- **No** knowledge support (e.g. farmers have to figure out how an appliance works by themselves).
- **Some** knowledge support (e.g. farmers can get some help from vendors but have to figure out some of the features of an appliance by themselves).
- **Full** knowledge support (e.g. farmers can always contact a vendor if they have a question about an appliance).

Furthermore, the providers of knowledge support are listed:

- Crop consultants
- PA software vendors
- PA machinery manufacturers
- Universities/Research Centres

A.7 Farmers motives

The following motives for adoption are defined:

- Operational Excellence
- License to Operate (e.g. farmers are only allowed to spray pesticides near waterways if they possess the right technology, like boom section control).
- Improving the Whole-farm Information Management.

A.8 Adoption

The following comparative levels of current adoption are defined:

- Low: Less than 5% of farmers worldwide have adopted the technology.
- Medium: Between 5 and 50% of farmers worldwide have adopted the technology.
- High: more than 50% of farmers worldwide have adopted the technology.

These adoption levels are based on the authors' expert opinions.

A.9 GHG emissions mitigation potential

The following comparative levels of mitigation potential are defined:

- Low: the potential of the technology to mitigate N_2O and other greenhouse gases production is likely to be low to non-existent.
- Medium: the potential of the technology to mitigate N_2O and other greenhouse gases production is likely to be significant.
- High: the potential of the technology to mitigate N_2O and other greenhouse gases production is high, when compared to other technologies.

Both the application and the production process (e.g. for fertiliser) are taken into account.

These mitigation potential levels are based on the authors' expert opinions.

A.10 PATs comparison

VR Technology	Farming system(s)	Cropping system(s)	Time slice	PA investment level
GNSS	Organic farming Integrated farming Extensive farming	Arable crops Forage crops Orchards Vineyards Field vegetables	Available now	Mini
Machine guidance	Organic farming Integrated farming Extensive farming	Arable crops Forage crops Orchards Vineyards Field vegetables	Available now	Mini/ Compact/ Combi
Controlled Traffic Farming	Organic farming Integrated farming Extensive farming	Arable crops Forage crops Orchards Vineyards Field vegetables	Available now	Combi
Topographic and soil mapping	Organic farming Integrated farming Extensive farming	Arable crops Forage crops Orchards Vineyards Field vegetables	Available now	Compact
Yield mapping	Organic farming Integrated farming Extensive farming	Arable crops Forage crops Orchards Vineyards Field vegetables	Available now	Mini
Canopy mapping	Organic farming Integrated farming Extensive farming	Arable crops Forage crops Orchards Vineyards Field vegetables	Available now	Mini

VR Technology	Farming system(s)	Cropping system(s)	Time slice	PA investment level
Map-based pesticide application	Integrated farming	Arable crops Forage crops Orchards Vineyards Field vegetables	Available now	Compact
Real-time sensor-based pesticide application	Integrated farming	Arable crops Forage crops Orchards Vineyards Field vegetables	Available in the next 5 years	Combi
Boom height control for pesticide application	Integrated farming	Arable crops Forage crops Orchards Vineyards Field vegetables	Available now	Compact
Physical weeding	Organic farming Integrated farming	Arable crops Forage crops Orchards Vineyards Field vegetables	Available in the next 5 years	Compact
Planting/seeding	Organic farming Integrated farming	Arable crops Forage crops Orchards Vineyards Field vegetables	Available now	Compact
Multi-hybrid planting/seeding	Organic farming Integrated farming	Arable crops Forage crops Orchards Vineyards Field vegetables	Available now	Compact

VR Technology	Farming system(s)	Cropping system(s)	Time slice	PA investment level
Granular fertiliser application	Integrated farming	Arable crops Forage crops Field vegetables	Available in the next 5 years	Compact
Granular fertiliser drill application	Integrated farming	Arable crops Forage crops Field vegetables	Available in the next 5 years	Compact
Granular lime application	Organic farming Integrated farming	Arable crops Forage crops Field vegetables	Available in the next 5 years	Compact
Manure application	Organic farming Integrated farming Extensive farming	Arable crops Forage crops	Available in the next 5 years	Compact
Self-propelled irrigation	Organic farming Integrated farming Extensive farming	Arable crops Forage crops Orchards Vineyards Field vegetables	Available now/ Available in the next 5 years	Compact/ Combi
Micro-irrigation	Organic farming Integrated farming	Orchards Vineyards Field vegetables	Available by 2030	Compact/ Combi

VR Technology	PA data use	Knowledge support	Farmer's motives	Adoption	Mitigation potential
GNSS	N/A	**Level:** Full knowledge support **Source:** Crop consultants Software vendors Machinery manufacturers Universities Research centers	Improving the wholefarm information management	High	Low
Machine guidance	Medium/high	**Level:** Full knowledge support **Source:** Crop consultants Software vendors Machinery manufacturers Universities Research centers	Operational excellence Improving the wholefarm information management	High	Low
Controlled Traffic Farming	Medium/High	**Level:** Full knowledge support **Source:** Crop consultants Software vendors Machinery manufacturers Universities Research centers	Operational excellence Improving the wholefarm information management	Low	Medium/High

VR Technology	PA data use	Knowledge support	Farmer’s motives	Adoption	Mitigation potential
Topographic and soil mapping	Medium	**Level:** Full knowledge support **Source:** Crop consultants Software vendors Machinery manufacturers Universities Research centers	Improving the wholefarm information management	High	Low
Yield mapping	Medium	**Level:** Full knowledge support **Source:** Crop consultants Software vendors Machinery manufacturers Universities Research centers	Improving the wholefarm information management	Low	Low
Canopy mapping	Medium	**Level:** Full knowledge support **Source:** Crop consultants Software vendors Machinery manufacturers Universities Research centers	Improving the wholefarm information management	Low	Low

VR Technology	PA data use	Knowledge support	Farmer's motives	Adoption	Mitigation potential
Map-based pesticide application	High	**Level:** Full knowledge support **Source:** Crop consultants Software vendors Machinery manufacturers Universities Research centers	Operational excellence Improving the wholefarm information management	Low	Low
Real-time sensor-based pesticide application	High	**Level:** Full knowledge support **Source:** Crop consultants Software vendors Machinery manufacturers Universities Research centers	Operational excellence Improving the wholefarm information management	Low	Low
Boom height control for pesticide application	High	**Level:** Full knowledge support **Source:** Crop consultants Software vendors Machinery manufacturers Universities Research centers	Operational excellence Improving the wholefarm information management	Low	Low

VR Technology	PA data use	Knowledge support	Farmer's motives	Adoption	Mitigation potential
Physical weeding	High	**Level:** Some knowledge support **Source:** Universities Research centers	Operational excellence License to operate Improving the wholefarm information management	Low	Low
Planting/ seeding	Medium	**Level:** Some knowledge support **Source:** Crop consultants Software vendors Machinery manufacturers Universities Research centers	Operational excellence Improving the wholefarm information management	Low	Medium
Multi-hybrid planting/ seeding	Medium	**Level:** Some knowledge support **Source:** Crop consultants Software vendors Machinery manufacturers Universities Research centers	Operational excellence Improving the wholefarm information management	Low	Low

VR Technology	PA data use	Knowledge support	Farmer's motives	Adoption	Mitigation potential
Granular fertiliser application	High	**Level:** Some knowledge support **Source:** Crop consultants Software vendors Machinery manufacturers Universities Research centers	Operational excellence License to operate Improving the wholefarm information management	Medium	High
Granular fertiliser drill application	High	**Level:** Some knowledge support **Source:** Crop consultants Software vendors Machinery manufacturers Universities Research centers	Operational excellence License to operate Improving the wholefarm information management	Low	High
Granular lime application	High	**Level:** Some knowledge support **Source:** Crop consultants Software vendors Machinery manufacturers Universities Research centers	Operational excellence License to operate Improving the wholefarm information management	Medium	Low/Medium

VR Technology	PA data use	Knowledge support	Farmer's motives	Adoption	Mitigation potential
Manure application	High	**Level:** Some knowledge support **Source:** Crop consultants Software vendors Machinery manufacturers Universities Research centers	Operational excellence License to operate Improving the wholefarm information management	Low	Medium
Self-propelled irrigation	Medium/High	**Level:** No/Some knowledge support **Source:** Crop consultants Software vendors Machinery manufacturers Universities Research centers	Operational excellence License to operate	Low	High
Micro-irrigation	Medium/High	**Level:** No knowledge support	Operational excellence License to operate	Low	High

ANNEX 2. PATs that positively contribute to farm productivity and mitigation of ghg emissions

PATs that positively contribute to farm productivity and mitigation of GHG emissions

Deliverable 2

PRECISION AGRICULTURE project

contract no. 199163-2015 A08-NL

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Table of Contents

List of abbreviations

AN-N: Ammonium Nitrate

CAP: Common Agricultural Policy

CSA: Climate Smart Agriculture

CTF: Controlled Traffic Farming

CEMA: Conservatoire Européen du Machinisme Agricole (European Agricultural Machinery)

DSS: Decision Support System

FMIS: Farm Management Information System

GIS: Geographical Information System

GHG: Greenhouse Gas

GNSS: Global Navigation Satellite System

GPS: Global Positioning System

LEPA: Low Energy (Elevation) Precision Application

LESA: Low Energy (Elevation) Spray Application

LULUCF: Land Use, Land Use Change and Forest

MESA: Mid Elevation Spray Application

MG: Machine Guidance

NUE: Nitrogen Use Efficiency

PA: Precision Agriculture

PAT: Precision Agriculture Technology

PPW: Precision physical weeding

VRA: Variable Rate Application

VRI: Variable Rate Irrigation

VRNT: Variable Rate Nutrient Application Technology

VRPA: Variable rate pesticide application

VRP/VRS: Variable rate planting/seeding

1 Introduction

European agriculture will have to face adaptation to climate change over the coming years. However, agriculture is also liable for climate change as its activities account for 10.1 % of the total Greenhouse Gas (GHG) emissions in the EU-28 (excluding LULUCF) that corresponds to 464.3 million tCO_2eq (European Parliament, 2014). During the last decade, there is a trend of GHG emissions reduction in the agricultural sector, but more effort on this direction should be put in order to fulfil EU global climate commitments. The main distribution of agricultural GHG emissions is related to cropland soil, enteric fermentation and manure management (European Parliament, 2014).

It should be noted that the application of innovative practices together with high-tech equipment in agricultural land treatment, mainly tillage techniques, (cropland counts for half the surface of EU) could positively affect GHG emission reduction due to the ability of soils to operate as carbon stock reserve (European Parliament, 2014). Except tillage innovations, there is a series of GHG mitigation measures that refer to new technologies and techniques on all agricultural practices (precision/variable rate sowing/planting, fertilizing, spraying and irrigation). These innovations can reduce significantly the amount of inputs that are responsible for GHG contribution and could help on the goal of minimum climate change impact of agriculture, always taking into account that crop production should be maintained or even increased in the challenge of ensuring food security and safety for human alimentation. New techniques applies also in livestock procedures (better quality feed, feed balancing to lower enteric and manure emissions, improved breeding and animal health, manure management practices), which could reduce climate change impact of livestock in a great extent.

Since the end of the nineties, EU agriculture has started slowly applying Precision Agriculture Technologies (PATs) that have the potential to reduce GHG emissions from agricultural activities and maintain or improve farm productivity. However, the current and potential uptake of these technologies in Europe is not systematically surveyed. Therefore, there is a need to produce evidence of the actual and future use of Precision Agriculture (PA) across Europe and identify the current barriers and motivations to achieve higher rates of adoption across Europe. In addition, it is important to acquire information on the required skills on behalf of the farmer/adviser to use such technologies and analyse the impact of these technologies on farm productivity and income.

1.1 Objective

The objective of this report is to identify and describe the Precision Agricultural Technologies (PATs) that have the capacity to increase or at least maintain farm productivity and have positive impact on Greenhouse Gas (GHG) emissions produced from the agricultural sector. This report comes as a descendant of the analytical literature review of the PATs available at the moment and others that will be in the market by 2030 and their economic, social and environmental impacts on agricultural production systems.

1.2 Document Structure

The document is structured in 7 Sections. Section 2 includes a brief introduction on climate change (i.e. definition, causes and impacts) and a short description of all types of GHGs with a particular interest on GHGs that are emitted by the agricultural sector. The greenhouse effect is briefly defined together with the GHG emission intensity (carbon footprint of agricultural systems).

In Section 3, agricultural productivity in EU level is described and in Section 4 the existing situation (i.e. use level of PATs, adoption worldwide and in EU level) of Precision Agriculture in Europe is analysed, in consultation with experts from the machinery industry (i.e. CEMA), including the current limitations. Ideas and suggestions to overcome these limitations are presented and the projection of such solutions in the future agriculture is discussed. In addition, future perspective of Precision Agriculture in EU is presented.

In Section 5 the Precision Agriculture Technologies (PATs) that have direct impact on farming systems including productivity and Greenhouse Gas (GHG) emission production are analysed and a list of the most influencing PATs is given. The chapter firstly presents the criteria to select the most influencing PATs in regards of GHG emissions, then, the technical characteristics of each PAT is shortly described and subsequently, environmental impacts (focusing on GHG emissions) are discussed. It should be noted that literature on PATs impact on GHG emissions is highly limited and therefore the discussion on the mitigation capacity of the different PATs is mainly based on the reduction of agricultural inputs (fertilisers, pesticides, fuel, water, etc.) that can be achieved with those technologies. Then, the cost of adoption (equipment cost, combined mapping cost, personnel training cost) is given (in some cases not all cost categories are analysed) and discussed.

In Section 6, the required skills for PAT use are described.

Finally, in Section 7, the authors make some conclusions regarding the PATs which have the potential to reduce GHG emissions in combination with maintaining or increasing farm productivity and income.

2 Climate Change Mitigation

2.1 Definition of climate change

The Earth's climate continuously changes. According to NASA climate change department, the last 650,000 years there have been seven cycles of glacial advance and retreat, with the abrupt end of the last ice age about 7,000 years ago. These climate changes are attributed to small variations in Earth’s orbit that resulted on fluctuations of solar energy received by Earth. Nevertheless, after the last ice age the modern climate era begun and the human civilisation started its first steps which there are scientific evidence that have influence on the acceleration of the next climate change period.

According to NASA climate change department, global sea level rose by 0.17 m in the last century with the rate in the last decade nearly double than the last century (Church and White, 2006). The global temperature has been rising since 1880, which was increased rapidly after 1970 (Peterson and Baringer, 2009). The oceans temperature was also increased as they absorb a big part of the heat increase on Earth (Levitus et al., 2009). The ocean is acidified by the CO_2 increase in the atmosphere that is absorbed by the oceans in huge quantities (Sabine et al., 2004). The Greenland and Antarctic ices sheets have decreased in mass with significant change in the recent years (2002 – 2005). The Arctic sea ice extent and thickness has declined rapidly over the last several decades (Polyak et al., 2010). Glaciers are retreating almost everywhere around the world and there is decreased snow cover (Derksen and Brown, 2012). There is a rapid increase on extreme events, such as high temperature events or intense rainfall events.

The current warming trend is of particular significance because most of it is very likely human-induced and proceeding at a rate that is unprecedented in the past 1,300 years (Santer et al., 1996; Santer et al., 2003; Ramaswamy et al., 2006).

Pandey and Agrawal (2014) identified that the current climate change has several effects that humanity is already facing, such as shifting weather patterns, receding ice caps, crop losses, altered distribution of precipitation, increased frequencies and intensities of floods and droughts and serious ecological imbalances. They also mentioned that global warming should not exceed an average temperature increase of 2^oC in comparison to the level of 1990, which could be achieved if total atmospheric GHGs will not overpass the threshold of 550 ppm of CO_2 equivalents.

2.2 Greenhouse Gases emissions

A greenhouse gas (GHG) is a gas that absorbs infrared radiation (IR) and radiates heat in all directions. The most influencing GHGs (Figure 1), listed in order of abundance, include: water vapour, carbon dioxide, methane, nitrous oxide, ozone, and any fluorocarbons.

- **Water vapour (H_2O).** It is the most abundant GHG that increases as the Earth's atmosphere warms, but so does the possibility of clouds and precipitation, making these some of the most important feedback mechanisms to the greenhouse effect.
- **Carbon dioxide (CO_2).** It is released through natural processes such as respiration and volcano eruptions and through human activities such as deforestation, land use changes, and burning fossil fuels.

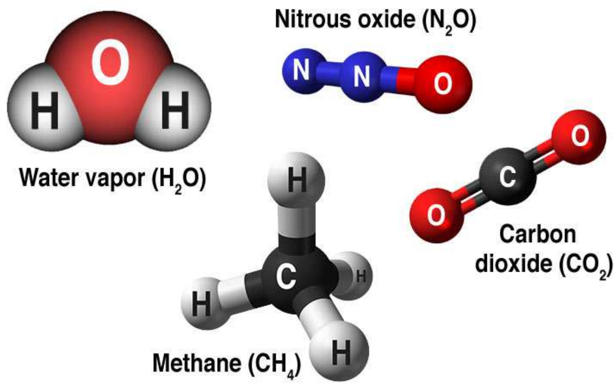


Figure 1: Molecule of the main GHGs (NASA, 2016)

- **Methane (CH_4).** It is produced through natural sources, but more importantly by human activities, like waste decomposition in landfills, crop production (especially rice cultivation), as well as ruminant digestion and manure management. CH_4 has higher global warming potential[13] (GWP) for a 100-year horizon than CO_2, accounting for 25 times higher potential (IPCC, 2007).
- **Nitrous oxide (N_2O).** It is created by soil cultivation practices, especially the use of commercial and organic fertilisers, fossil fuel combustion, nitric acid production, and biomass burning. N_2O shows increase GWP in comparison to CO_2, accounting for 298 times higher potential (IPCC, 2007).
- **Chlorofluorocarbons (CFCs).** They are synthetic industrially produced compounds that are used mainly as refrigerants, propellants (aerosols applications) and solvents but now largely regulated in production and release to the atmosphere by international agreement (Montreal Protocol, 1987) for their ability to contribute to destruction of the ozone layer and also affect global warming as it has 10000 times higher GWP than CO_2 (IPCC, 2007). They are mostly replaced by **Hydrofluorocarbons (HFCs)** that are used in refrigeration (both commercial and domestic), in air-conditioning (homes, cars, offices etc.), and they are also used as foam blowing agents, solvents, firefighting agents and aerosol propellants. They are also very active GHGs with almost 20000 times higher activity than CO_2 (IPCC, 2007).
- **Perfluorocarbons (PFCs).** They can be by-products of aluminium smelting and they are used in semi-conductor manufacture, and as substitutes for ozone depleting chemicals. Emissions of PFCs are small even compared to HFCs, but given their GWP (5,700 to 10,000 times more potential-depending on the exact type- than CO_2), long lifetimes (atmospheric lifetime of up to 50,000 years) and availability of alternatives already on the market, they should be urgently phased out (IPCC, 2007).
- **Sulphur Hexafluoride (SF6).** It is used in shoes production, car tyres, electrical insulation, semiconductor manufacture and in the magnesium industry. It is the most potent GHG (23,900 times higher GWP than CO_2), and has an atmospheric lifetime of 3,200 years. Like PFCs, the effects of SF6 at the moment are fairly small, but there is concern about its continuing build up in the atmosphere.

[13] **Global warming potential** (GWP) is a relative measure of how much heat a greenhouse gas traps in the atmosphere. It compares the amount of heat trapped by a certain mass of the gas in question to the amount of heat trapped by a similar mass of carbon dioxide. A GWP is calculated over a specific time interval, commonly 20, 100 or 500 years. GWP is expressed as a factor of CO_2 (whose GWP is standardized to 1).

2.2.1 Strategies for the Mitigation of Climate Change in Global and EU level

The Kyoto Protocol (an international agreement, which commits its Parties by setting internationally binding emission reduction targets) was adopted in Kyoto, Japan, on 11 December 1997 and entered into force on 16 February 2005. The participating 37 industrialised countries (see Annex II) and the EU were supposed to ensure, individually or jointly that their aggregate anthropogenic GHGs do not exceed their assigned amounts, calculated pursuant to their quantified emission limitation and reduction commitments, with a view to reducing their overall emissions of such gases below 1990 levels to an average of 5% in the commitment period 2008 to 2012. Energy production, industrial processes, solvent and other product use, agriculture and waste treatment sectors are the GHG sources under consideration to emissions cut-off (Kyoto Protocol, 1998). The detailed rules for the implementation of the Protocol were adopted at COP 7 in Marrakesh, Morocco, in 2001, and are referred to as the **"Marrakesh Accords"**. COP 7 also adopted a decision on Land Use, Land Use Change and Forest (LULUCF) with the obligation to undermine the environmental integrity of the Kyoto Protocol.

In Doha, Qatar, on 8 December 2012, the **"Doha Amendment to the Kyoto Protocol"** was adopted, where a second commitment period was assembled from 1 January 2013 to 31 December 2020 in which a revised list of GHGs (included also Nitrogen trifluoride) was given for the participating states to report since then. During this period, Parties committed to reduce GHG emissions by at least 18% below 1990 levels in the eight-year period from 2013 to 2020 (Doha Amendment, 2012).

The last step of actions to reduce the greenhouse effect was the Paris Agreement on December 2015, where 195 countries adopted certain measures (to be into force in 2020). The most essential element of the agreement was to keep the increase in global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. In addition, all countries agreed to aim on reaching the GHGs peak as soon as possible in order to balance GHGs in the second half of our century. Sinks and reservoirs of GHGs should be conserved and enhanced and anthropogenic GHG production should be mitigated by both market and non-market approaches. The agreement recognises that adaptation is a global challenge and that national adaptation efforts can be enhanced by international cooperation. Policies on loss and damage are supported to help vulnerable countries to climate change effect; the obligation of developed countries to support less developed states in climate change confrontation was reaffirmed. All results from the participating countries should be transparently reviewed in an international basis that ensures reliability of each member effort. The so called "Global Stocktale" will be the instrument to be established in 2023 that will assess the progress globally and will reset the actions in 5-year intervals.

Participating countries agree to prepare, communicate and maintain an Intended Nationally Determined Contribution (INDC) and to pursue domestic measures to achieve it. NDCs should be communicated every 5 years. To set a firm foundation for higher ambition, each successive INDC will represent a progression beyond the previous one and reflect the highest possible ambition. Developed countries should lead by setting absolute economy-wide reduction targets, while developing countries should enhance their mitigation efforts, and are encouraged to move toward economy-wide targets over time (Paris Agreement, 2015).

EU have identified the intended NDC for its members states on March 6^{th} 2015 were they committed to a binding target of an at least 40% domestic reduction in GHGs by 2030 compared to 1990. The target represents a significant progression beyond its current undertaking of a 20% emission reduction commitment by 2020 compared to 1990 (which includes the use of offsets). This goal is in line with the EU objective (IPCC commitment of developed countries) to reduce its emissions by 80-95% by 2050 compared to 1990. Furthermore, it is consistent with the need for at least halving global emissions by 2050 compared to 1990. The EU and its Member States have already reduced their emissions by around 19% on 1990 levels while GDP has grown by more than 44% over the same period. As a result, average per capita emissions across the EU and its Member States have fallen from 12 tonnes CO_2-eq. in 1990 to 9 tonnes CO_2-eq. in 2012 and are projected to fall to around 6 tonnes CO_2-eq. in 2030. The emissions in the EU and its Member States peaked in 1979 (INDC of the EU, 2015).

2.3 Greenhouse gas emission intensity

GHG emission intensity is defined as the total GHG emissions released directly and indirectly by human-induced activity, usually expressed in equivalent tons of CO_2 per unit of activity or product.

2.3.1 Main Sources of Agricultural GHG emissions in the EU

The major GHGs produced in the agricultural sector are methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) (Figure 2). **CH_4** is mainly produced from the anaerobic decomposition of organic matter during enteric fermentation and manure management, but also from paddy rice cultivation (as mentioned above together with other sectors); **N_2O** arise from the microbial transformation of N in soils and manures (during the application of manure and synthetic fertiliser to land) and via urine and dung deposited by grazing animals; and **CO_2** arising from (a) energy use pre-farm, on-farm and post-farm and (b) from changes in above and below ground carbon stocks induced by land use and land use change (Macleod et al., 2015).

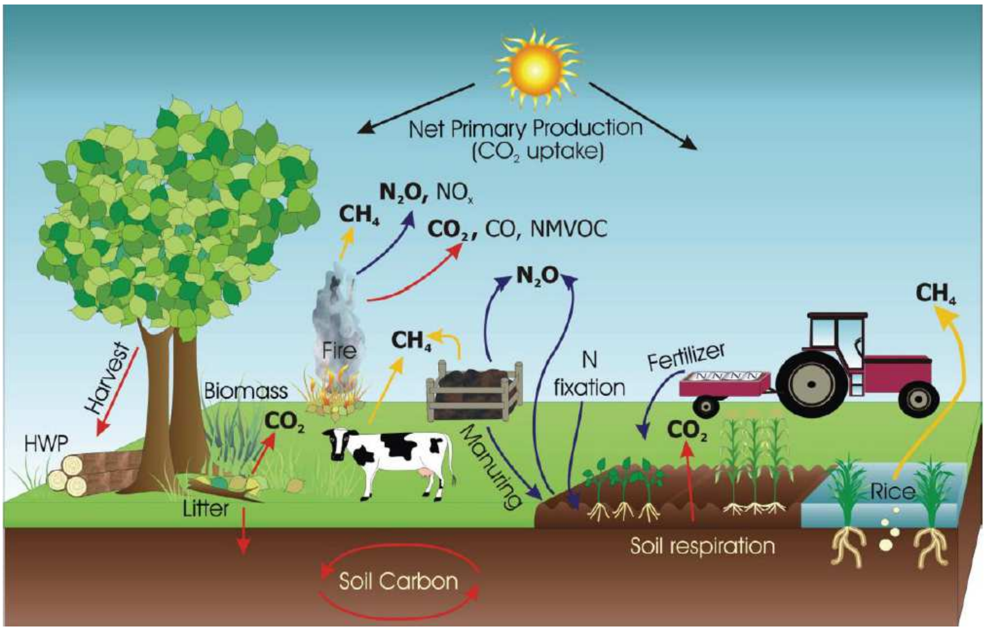
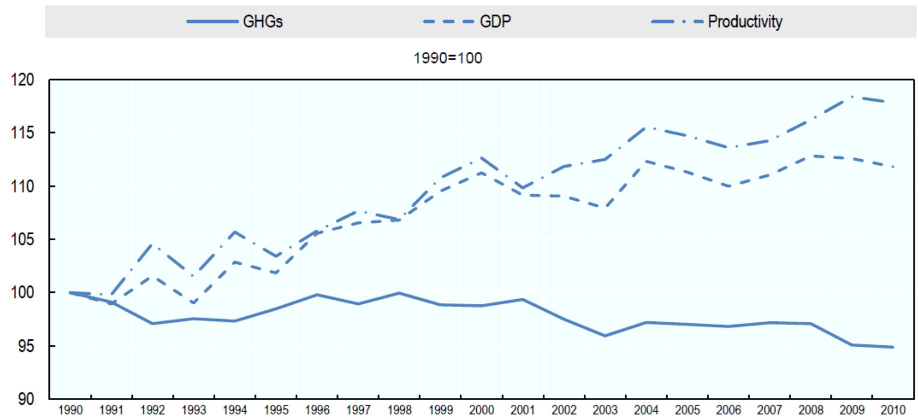


Figure 2: The main on-farm GHG sources, removals and processes in managed ecosystems. Source: IPCC (2006).Note: Note: Carbon sequestration is not explicitly represented but also plays a role in the GHG balance.

The agricultural sector accounts for nearly 13.5% of the total global anthropogenic GHG emissions (25% of CO_2, 50% of CH_4, and 70% of N_2O emissions) (Montzka et al, 2011).

Agriculture produces 8% of the total GHG emissions for the OECD member countries. In the same work it was stated that agricultural GHG emissions in these countries has declined between 2000 and 2010 by an average of 0.4% per annum with simultaneous agricultural production increase of 1.6% per annum, which is interpreted into 1.97% of GHG emission intensity reduction (Figure 3).



Note: Excluding LULUCF (land use, land use-change and forestry).

Figure 3: Trends in agricultural sector GHG emissions, GDP and productivity in OECD countries (1990-2010) (Macleod et al., 2015)

Therefore, the developed country members of OECD are trying to achieve synchronized GHG mitigation and productivity increase, which is the ideal situation and is defined as the "absolute decoupling" (OECD, 2014).

The European Commission Climate Action (2016) stated that within the EU-28 member states, agriculture represented 10.3% of the total GHG emissions in 2012. The share by country depends on the size of agricultural sector. The highest percentage of GHG emissions emitted from agricultural activities in comparison to the total national GHG emission are in Ireland (31%), Lithuania (23%) and Latvia (22%) and the lowest in Malta (2.5%), Luxembourg and the Czech Republic (about 6% each). Agricultural GHG emissions in the EU-28 level show a rather steady downward trend of -24 %, from 618 million tons CO_2eq in 1990 to about 471 million tons CO_2eq in 2012 (reference). While EU-15 emissions decreased by 15 % (-68.4 million CO_2eq), in the newer Member States emissions decreased by 45 % (-78.8 tons CO_2eq) over the period 1990 to 2012.

The larger agricultural economies generally produce higher levels of GHG emissions, but they do not follow the same pattern. An explanation of this statement is that France and Germany together accounted for around one third of the EU-28 agricultural GHG emissions, while the combination of the UK, Spain, Poland and Italy covered an additional third of the total. The EU Roadmap for moving to a low carbon economy recommends a reduction target of agricultural GHG emissions by 36-37 % until 2030, and a more ambitious one (42-49 %) for 2050 in comparison to 1990 levels (EU Roadmap for 2050).

The European Environmental Agency (2015) analysed the breakdown of agricultural GHG emissions in the EU-28 for year 2012 (Figure 4). The highest percentage of GHG emissions are originated from agricultural soils through N_2O (51.3%) followed by enteric fermentation that is attributed only to CH_4 (31.3%) and manure management that is represented by CH_4 and N_2O (16.8%). Rice cultivation and field burning of agricultural residues produce CH_4, but they concern 0.5% and 0.2% of agricultural GHG emissions respectively, making them insignificant in comparison to the three major pillars mentioned above.

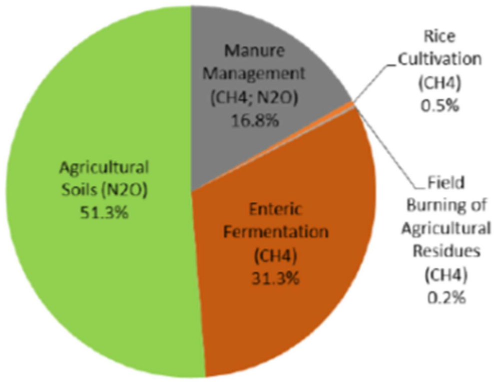


Figure 4: Agricultural GHG emissions breakdown in EU-28 for year 2012
Source: EEA (2015).

Nitrous oxide (N_2O) is the main GHG related to agricultural soil emissions, essentially due to microbial transformation of nitrogen in the soil (the process of nitrification and, denitrification to be analysed in section 4.5.1). This concerns nitrogen mineral fertilisers, manure spreading and nitrogen from crop residues incorporated into the soil or lixiviation of surplus nitrogen. As mentioned above, N_2O has high GWP (298 times higher than CO_2) and it should be minimized to reduce agricultural GHG emissions in total. An example of favourable N_2O increase conditions is when soil temperature is increased and high moisture conditions exist during cooler months. Another example would be the increase of N_2O from upland agricultural soils due to CO_2 concentration (Van Groeningen et al., 2011). In addition, application of mineral nitrogen in the form of chemical fertilisers increases the N_2O emissions.

Enteric fermentation, which is a natural part of the digestive process for ruminants, is the most important methane (CH_4) producer. CH_4 is also produced during manure storage (decomposition). There are several studies targeting on CH_4 measurements (Le Mer and Roger, 2001) and its mitigation from rice fields, mainly through water (Pathak et al., 2003), fertiliser, and manure managements (Linquist et al., 2012). CH_4 emissions increase when mulching and organic manure are applied in soils (Ma et al., 2007). On the other hand, midseason drainage can cut CH_4 emissions significantly (Zou et al., 2005). Aerobic soils may act as CH_4 sinks (Le Mer and Roger, 2001; Smith et al., 2008) or sources (Ma et al., 2013).

As for CO_2, direct combustion of hydrocarbons is the main source together with soil respiration and residual biomass decomposition. However, the majority of the farm operations and inputs (e.g. fertilisers, pesticides, energy, etc.) also have embodied CO_2 content. Direct CO_2 consumed by agriculture as well as indirect CO2 emissions from processing of inputs at farm level showed that this gas can represent between 10 and 20 % of the total GHGE (European Parliament, 2014).

Some agricultural practices, such as tillage, also influence fluxes of soil borne GHGs. For example, when no-tillage practice is applied to rice cultivations, CH_4 and N_2O are reduced significantly, but CO_2 is increased as compared to regular tillage (Pandey et al., 2012).

3 Agricultural productivity in EU

There are two major pillars of practice to increase agricultural productivity. The first is to bring new resources into production by using new land, increase irrigated land and intensify input use with special interest on fertilisers. The second is the attempt to raise the productivity of existing resources. Agricultural productivity in field or farm level can be measured through efficiency indices like land productivity (production yield per field surface) or agricultural value-added per worker, but these does not take into account a broader set of inputs used in production. A global index to identify the growth of agriculture is Total Factor Productivity (TFP), which takes into account all of the land, labour, capital, and material resources employed in farm production and compares them with the total amount of crop and livestock output (USDA, 2016). TFP in agriculture grows when total output is growing faster than total inputs.

Given that food security is in jeopardy due to human population growth and natural resources (soil and water) and agricultural inputs (fertilisers and agrochemicals) are not abundant, it is significant to set TFP increase as a policy priority. EU have realised this priority and in the CAP it is included that agricultural productivity increase is a major objective by promoting technical progress and by ensuring the rational development of agricultural production and the optimum utilisation of the factors of production, in particular labour.

In the early 2000s, Eurostat developed the so-called Multi-Factor Productivity (MFP) index for agriculture that compares the growth in agricultural output to the growth in agricultural inputs, but did not take into account land use changes. This index was published for a couple of years, but then it was discontinued. In 2013 CAP was reformed emphasising in monitoring and evaluating of the CAP results in EU agriculture and EIP-Agri was also formed, giving another reason for TFP to come again to the fore. However, TFP calculation can be problematic due to conceptual and methodological issues and data availability.

TFP growth in EU agriculture published by DG-AGRI can be seen in the figure 5 below. Between 1995 and 2002, TFP growth in the EU-15 was around 1.6% per annum. However, after 2002 the EU-15 member states agriculture grew by only around 0.3% per annum over the period 2002 to 2011. On the other hand, the new member states showed average TFP growth around 1.6% per annum over the same period. The fact that new member states does not account for large share of total agricultural output in the EU, the EU-27 TFP growth in the same period was only 0.6% per annum. It should be noted the calculations are based on the Economic Accounts of Agriculture and that as year-to-year yield variations can affect TFP, DG-AGRI uses a 3-year moving average (e.g. the 2011 data is an average for years 2009, 2010 and 2011).

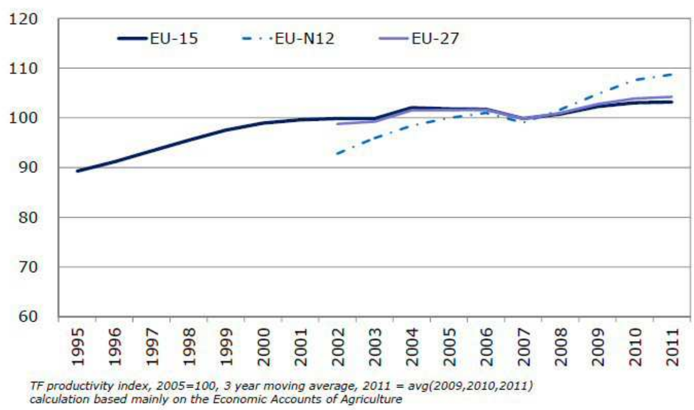


Figure 5: Total Factor Productivity in EU (DG AGRI, 2016)

Impressive TFP growth haS been identified in some of the new member states (Figure 6). The best TFP was achieved by Finland, Austria, Luxembourg and Denmark (from the core of EU-15 member states), while Spain, Ireland and Italy showed negative TFP growth over this period.

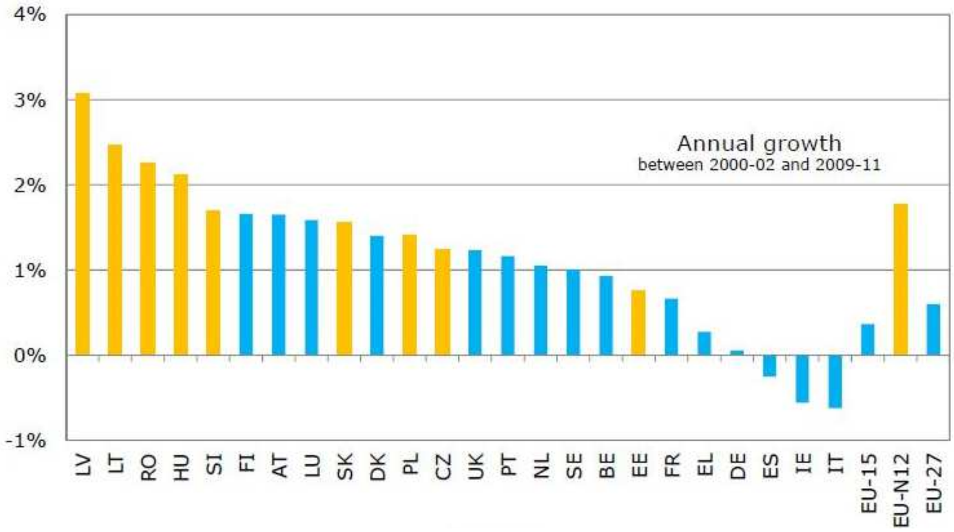


Figure 6: TFP growth in EU member states (DG-AGRI, 2016)

Agricultural productivity in EU seems to reach an upper limit with the resources available especially in the more advanced member states where most available conventional agricultural techniques have been applied over the years. Even if new member states are still keeping growing, it is expected to reach the same limit soon as they are also applying intensive agricultural methods similar to old member states. Therefore, there is a need to find a solution that can move conventional agriculture to more advanced techniques based on optimised use of natural resources (soil and water) and agricultural inputs (fertilisers and agrochemicals) to achieve higher yields in a sustainable manner. Such a method is the so called Precision Agriculture that is based on site specific crop management to control spatial and temporal in-field variability and achieve the most out of a certain piece of land.

4 Precision Agriculture Technologies within the European Union Context

4.1 Current state of Precision Agriculture development in the EU

The existing situation of PA practices in the world and EU basis is in general unclear. There was a strong uptake of PATs during the 1990s mainly in North America, because at that time information technology globally had reached high readiness level to invade new economic sectors (except office and industry sectors) and US and Canadian agriculture had the characteristics to promote new technologies promising better economic results. The main characteristics were the large farm sizes, the organised extension system mainly by the government and the Universities, the farmers/entrepreneurs willingness for progress and technology adoption, the high income, the possibility of financing investment and the limited or absent subsidies in agricultural products (Daberkow and McBride, 2016). PA growth rate flattened during the first years of 2000s, because the results (productivity increase, inputs reduction, fuel use decrease, ease of use of PATs, low maintenance, compatibility between brands) were not as positive as expected by the agricultural community. However, PA technologies are currently taking up again, because technology problems have been gradually solved with more tangible results in farm level and new combinable technologies (software and hardware) that united can increase the positive impact in yield, input and profit. This uptake can be seen by the fact that PA is an important sector in growth with researchers estimating the PA market already amounted to €2.3 billion euros in 2014 on a global level (Euractiv, 2016; Roland Berger, 2016). They expect it to grow at an annual growth rate of 12% through 2020 (Euractiv, 2016; Roland Berger, 2016). The mature US and European markets are considered the most promising (Roland Berger, 2016). However, while most practitioners can see the benefits of PATs in agricultural production, the fast pace of development of the technology, its complexity, the small size and diversity of farm structures (in terms of crops, topography), cultural perception, lack of expertise and economic constraints are obstacles that have hindered adoption by end-users, resulting in a gap between the availability of PATs and their implementation in practice (Zarco-Tajada et al., 2014).

As data on the exact figures of PATs sales are limited, a very good indication of the PATs use worldwide can be given by the GNSS receivers market because most of the PATs applied in the field require georeferencing using GNSS devices. Information on global GNSS receivers market is available in detail from the 2015 GNSS market report of the European Global Navigation Satellite Systems Agency (GSA) in which historic data and future projections are given. In the agricultural section of the report, it is stated that installed GNSS receivers for agricultural use have grown, reaching some 900,000 units in 2013 from 200,000 in 2006 (Figure 7). North America has the biggest percentage of the installed GNSS receivers (57% in 2013). This comes as a result of the more favourable environment for PA use because the 2.5 million farms found across the United States and Canada are typically large-sized, wealthy and farmed using machine-intensive techniques combined with high labour costs that make labour-saving techniques particularly attractive (GSA, 2016).

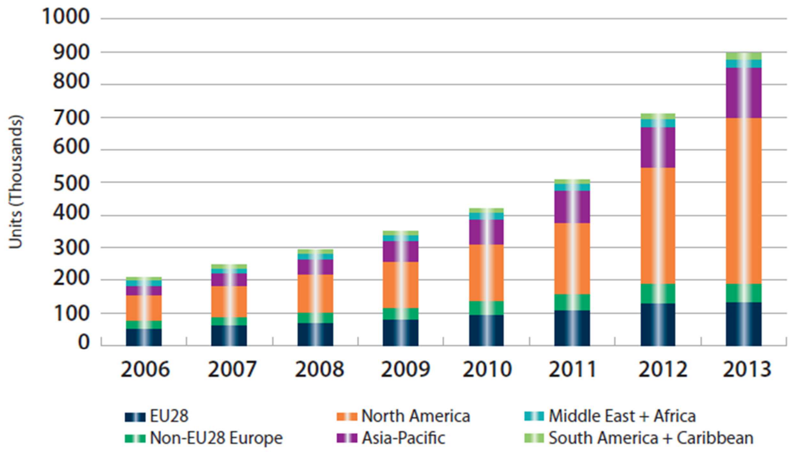


Figure 7: Installed base of GNSS devices by region (GSA, 2016)

The Asia-Pacific region shows the highest rate of GNSS receivers installation increase (from 0.3% of the total installed base in 2006 to 17% in 2013). Europe also experienced an increase in the installed base of GNSS devices, from 51,000 units in 2006 to 129,000 units in 2013. However, this growth has been at a slower pace than the rest of the world (14% per year) resulting in lower global percentage in 2013 (14.3%) than in 2006 (25.5%). Australia is stated as the most mature market, but no figures are given.

Regarding the applications that the installed GNSS receivers are used (Figure 8); tractor guidance was the most widespread application in agriculture in 2006 and remained throughout the years until 2013, when it corresponds to 54% of all devices. Automatic Steering, which requires a higher level of accuracy, grew significantly from 2006 to 2013 thanks to increased adoption in developed countries. This trend confirms that high-accuracy solutions are "addictive" to farmers in that they are not likely to abandon top-end solutions after implementing them. Variable Rate Technologies (VRTs) are also starting to be increasingly adopted by farmers. GNSS shipments in VRTs grew from near zero in 2006 to 38,000 in 2013. Asset Management solutions, which are systems that monitor and maintain the value to an entity, in our case, the farms, are now starting to complement in-field solutions. Their shipments increased from close to zero in 2006 to 43,000 units in 2013.

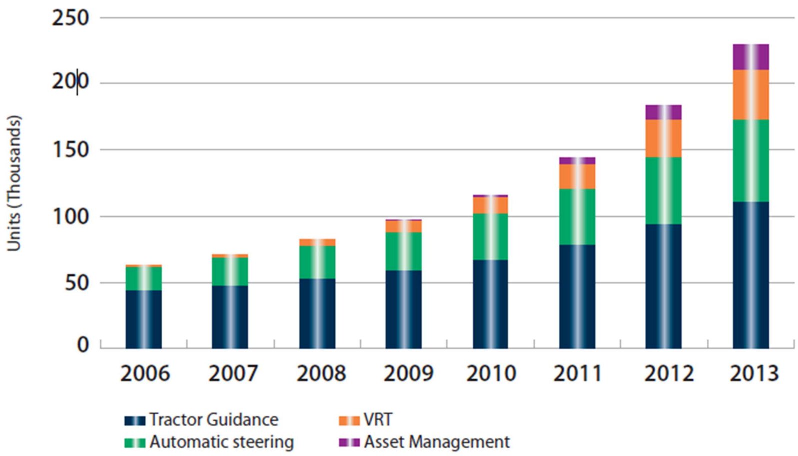


Figure 8: Shipments of GNSS devices by application (GSA, 2016)

In Europe, AgroVision (a Dutch market leader agro-software firm which provides support to a considerable share of arable farmers with their software package CROP) held a customer survey among its customers to investigate the use of computer terminals on field machinery, including questions on GNSS use. Sixty (60) % of the respondents answered they use some sort of GNSS, where forty (40) % of the respondents use RTK. Other (but less used) systems are standalone GPS and DGPS. The survey also showed that more than a third of all respondents use a terminal to control the fertiliser spreader. Twenty (20) % has a terminal on the sowing machine and 9% on the harvester (Reference to the deliverable FP7 UNIFARM Project).

Another survey among 47 representative arable farms in the Netherlands in 2013 showed that 55% of them use some sort of PA tool (Janssens et al, 2013). Machine guidance was the most used PAT (55% of the farmers), followed by spraying section control (34%). Farmers do not show high interest on VRTs (only 5% of the adopters had such equipment) To justify investments in VRT farmers expect that the ease-of-use improves (plug & play) as well as simplified/improved data exchange with farm management software. Interestingly, farms with Business Management Systems (BMS) had a greater PA adoption rate than the ones without such systems. More particularly, only 20% of the machine guidance and section control spraying adopters did not have also BMS. In addition, VRT was adopted only by owners of BMS in their farms. The survey showed that the respondents had a positive attitude towards investing in tools for precision farming. An example was the acquisition of various GNSS tools that are seen as a good investment. However, before investing in such technologies, the respondents expressed their interest in seeing PA and the related tools becoming easier and simpler to use (plug and play). Data exchange between the tools on the field and computer software (BMS) needs to be simpler as well. Another interesting result of this survey was that most of the growers who were surveyed, and particularly growers without BMSs, are not trendsetters when it comes to modern methods of communication (smartphones, tablets, etc.); they consider their current equipment (pc, telephone, etc.) to be sufficient.

In Denmark, the Knowledge Centre for Agriculture (VFL), a major agricultureal knowledge service provider, conducted a survey to more than 6000 farmers after contacting 14000 farmers by email (response rate 43%) in 2013 to identify how widespread was the uptake of GNSS technology use in agriculture giving the example of auto steering, VRT and CTF. The survey showed that 1 in 5 farmers is using some kind of GNSS technology on their machines; in particular they are mainly used in large farms. Respondents having holdings below 100 ha showed less than 10% use of GNSS, while 80% of respondents having farms of 500 ha were already using GNSS (Figure 9). The survey also identified major obstacles to GNSS uptake. Farmers that don't use any GNSS find their farm too small for using GNSS (51%) or don't see the economic benefit of the investment (38%).

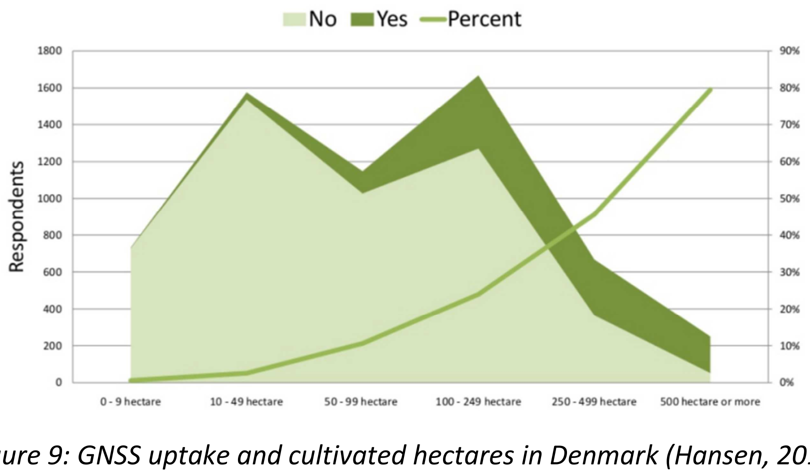


Figure 9: GNSS uptake and cultivated hectares in Denmark (Hansen, 2013)

In USA, which is the leading force of PA application globally, several surveys have been conducted on PA technologies. The latest PA services dealership survey conducted in 2015, which focuses on the agribusiness companies offering PA solutions in the USA, is also a good indication for the likely direction of EU adoption of PATs (Erickson and Widmar, 2015). This survey assessed the current uptake of Precision Agriculture technologies offered by agribusiness companies and used by their customers. The survey accommodated questions about customer adoption of precision agriculture services, how precision technology was used at the dealership, and the profit potential of the technology The majority of respondents in this survey indicated that they were using the U.S. government's free WAAS correction system (69.9%), followed by satellite correction, such as OmniSTAR XP or HP, StarFire2 (27.2%) and RTK correction (25.7%). However, RTK correction in total (personal base stations and purchased corrections) counts for 37.4%. The most popular technology used for dealers was GPS guidance with auto control/autosteer (83%), followed by GPS-enabled sprayer section control (74%) and GPS guidance with manual control (63%). A total of 82% indicated they offered PA services to their customers. The detailed analysis of the PA services offered by the crop retailers in the US is outlined in Figure 10.

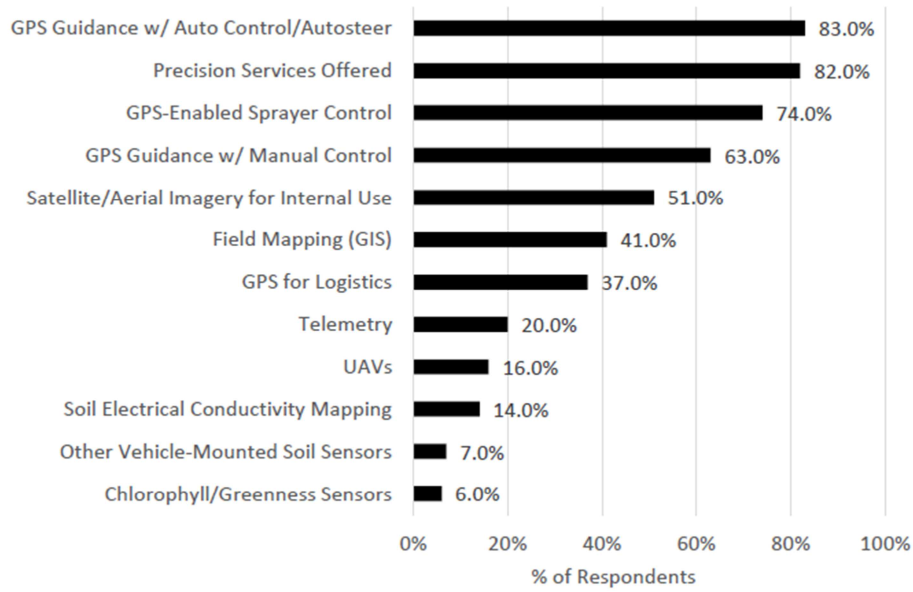


Figure 10: Types of GPS correction used in USA (Erickson and Widmar, 2015)

Interestingly, US farmers prefer to adopt technologies with direct impact on their work (like guidance technology, sprayer section control) or services that can be provided by experts to them with significant results on their farm operation (higher yield, reduced inputs, increased profit). Figure 11 shows the rapid increased use of auto-guidance followed by the sprayer section control.

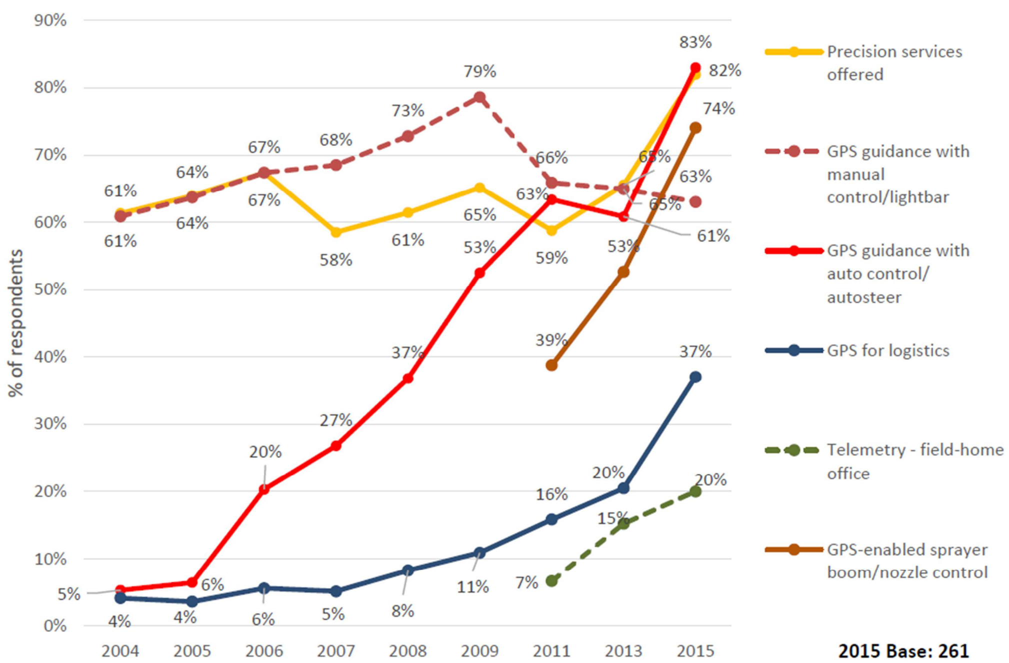


Figure 11: Use of automated technologies over time in the USA (Erickson and Widmar, 2015)

Regarding variable rate technologies (VRTs), USDA assessed the adoption rates of VRTs based on total utilised agricultural area in the USA for year 2011, which were 1% in soybean, 3% in cotton, 5% in corn and sorghum and reached 11% in wheat farms (ICF International, 2013). These rates show that the use of VRT, even in the USA which is the largest PAT adopter, was low in 2011, which is an indication that farmers are not still into VRT perhaps due to high investment on the new machinery together with low expectation on the gains from its use. However, it is expected that these rates have been increased since then, taking also into account Figure 12 that shows a continuous increment of all kinds of VRT between 2000 and 2015 in terms of market share in comparison to conventional equipment for the same application (Erichson and Widmar, 2015). In addition, Erichson and Widmar (2015) predicted that VRTs will increase faster until 2018. It is interesting to observe that VRT for lime application is steadily more adopted than the rest of VRTs because the need for pH correction is very important in the USA. If both single and multiple nutrient VRTs for fertiliser application is counted together, then this category is the most usable from US farmers. This could be explained by the fact that fertilisers affect significantly total farm productivity (consequently profit too) and farmers are seeking ways to reduce the total amount of fertilizers applied to their fields. Multiple nutrient VRTs are predicted to overpass single nutrient VRTs because the positive results for farm profitability is expected to grow further with this technology.

Another survey on the adoption of precision agriculture conducted in Ohio in 2010 and the farmers were asked about their motivation to use or plan to use PATs within the next three years. The sample included adopters (farmers that already practice some form of PA) and non-adopters (farmers that are familiar with PA, but do not practice it). This survey indicated that the key motivators for PA users are the reduction in input costs, an increase in profitability, a better understanding of field variability, more information for better decisions, increased yields, improved environmental stewardship, better understanding of farm management practices, improved crop quality and ease of record keeping. All above mentioned motivations were answered by both adopters and non-adopters with the non-adopters always showing less motivation than the adopters, which is an indication that after using some form of PAT the farmers start to understand the benefits and seem more motivated for more PAT applications. The study also indicated that approximately 39% of all surveyed farmers have adopted at least one precision farming component, and 3.6% expect to adopt precision farming technology within the next 3 years (Diekmann and Batte, 2010).

After consulting CEMA on the existing situation of PA equipment in EU, we were informed that agricultural machinery industry in Europe does not share market information in the public domain, like in the USA. CEMA informed us that the percentage of fertiliser spreaders sold today in EU market which incorporate some sort of PA element (able to process parameters from application maps and sensors) is more than 40% of newly sold spreaders. More than 10% of newly sold fertiliser spreaders are sold with licences for section control (which seems to be the most popular fertilising technology). In practice, the percentage of spreaders working with section control is estimated to be around 25-30%, as licences that can be purchased in relation to pesticide and seeding technology can also be used for spreaders. More than 20% of newly sold spreaders are able to document process-related data automatically. Another 20% can record aggregate field-specific data (amount of fertiliser, time), yet not automatically. The uptake/demand for precision fertilising equipment is growing depending on product segment, meaning that upper end products shows strong growth; mid-range products, moderate growth and lower end products are grown slowly.

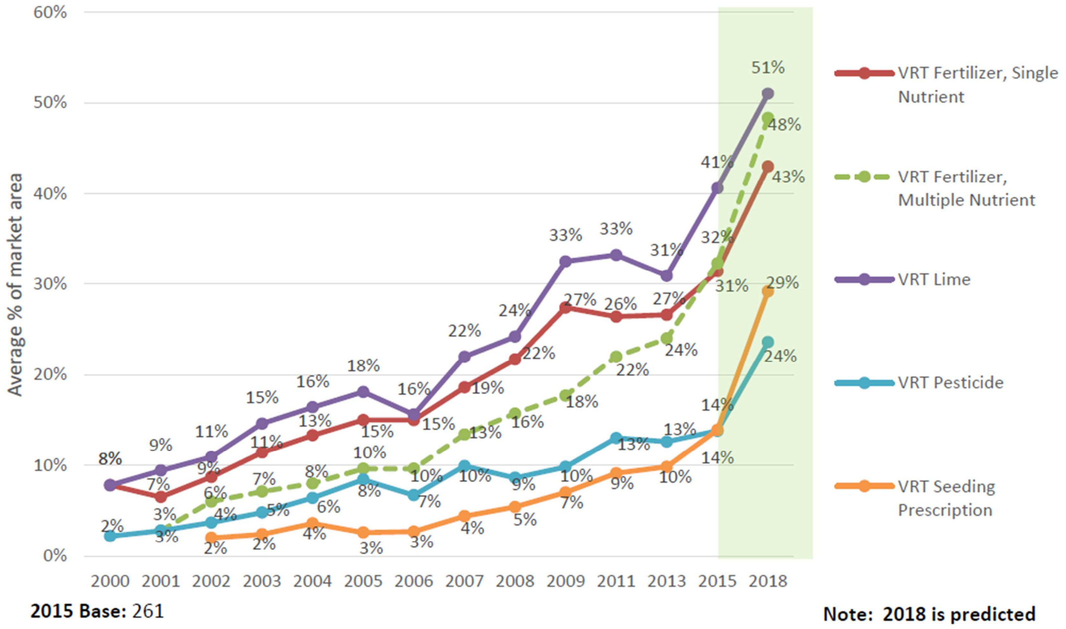


Figure 12: Estimated market area using VRTs over time in the USA (Erickson and Widmar, 2015)

Overall, the GNSS agriculture industry is concentrated in North America, which hosts 63% of the components and receivers market and 46% of the system integrators (Figure 13).

In terms of components and receiver manufacturers, the European companies have a 10% share of the overall market, with the leading players being **Laird**, **Amazonen-Werke** and **Hexagon**. For system integrators, European companies have a market share of 28%, with the top three players being **Hexagon** and its subsidiary **Leica Geosystems**, **Claas** and **CNH**.

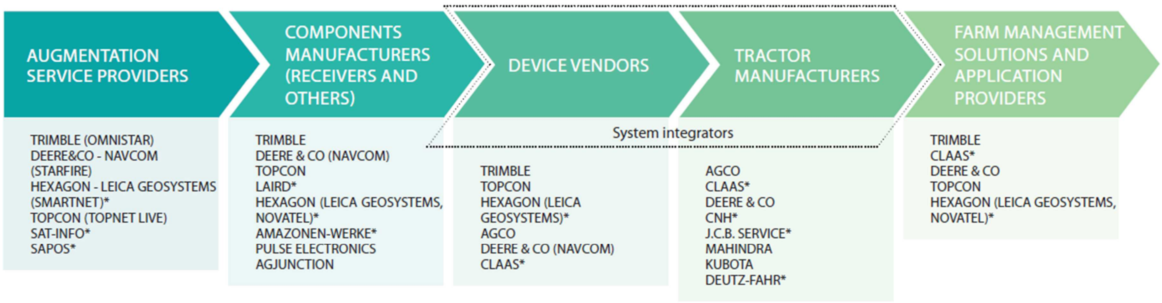


Figure 13: Agricultural Value Chain (GSA, 2016)

4.2 Limitations to PA utilization and ideas to overcome

In Europe, PA technologies are not uniformly applicable due to different environmental, agronomic and cultural reasons. Most notably, EU-28 has a wide range of regions with and cropping systems, farm sizes, farm structures, rural development stages and farm revenues. Thus, the adoption of PA is linked with geographical region, showing differences between EU Northern and Southern countries (Blackmore et al, 2006). This statement was also confirmed by the final report of FP7 FutureFarm project (Blackmore and Apostolidi, 2011), where Southern Europe, with the exception of a part of Spain, showed low to medium potential for PA adoption, in comparison to most Northern regions were the potential was high to very high (Figure 14).

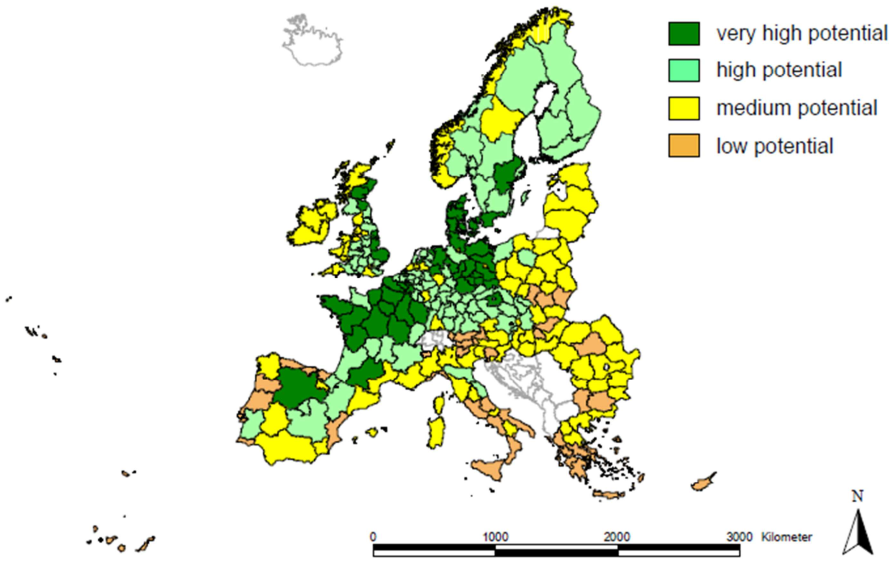


Figure 14: Potential of PA in Europe (Blackmore and Apostolidi, 2011)

PA is mainly adopted in northern countries, due to larger economic farm sizes, higher income (in some extent due to larger size), ease of financing new investments (access to banking with lower interest rates), farmers-entrepreneurship and in some cases state policies. Southern and some eastern countries experience different farming conditions that do not promote PA adoption, such as small farms with segmented property (many parcels in different locations), low profit and difficulty to receive bank financing that complicates investments, low educational levels to receive and digest new agricultural methods based on electronics and traditional thinking (Blackmore, 2006; Blackmore and Apostolidi, 2011).

Physical farm size (i.e. farm surface) is one of the main characteristics that influence PA adoption significantly (Blackmore, 2006; Lawson et al, 2011; Kutter et al., 2011; Pierpaoli et al., 2013). More particularly, as farm size increases, higher PA adoption potential is shown (Polling et al., 2010). Any kind of PA application needs to be assessed according to the field surface to evaluate if it is cost effective (Pierpaoli et al., 2013; Matese, et al., 2015). An example of the importance of farm size in selecting PATs is the work by Matese et al. (2015) where a comparison of UAV, airborne and satellite images to estimate intra-vineyard vegetation spatial variability was executed and it was estimated that the break-even point for using a UAV and receive high accuracy spatial variability data in acceptable cost was at five hectares and that above such a threshold, airborne and satellite have lower imagery cost.

The survey conducted by VFL (Hansen, 2013), pointed out the main reasons why Danish farmers do not invest in GNSS technology (Figure 15). It is obvious that the farm holding size is the most significant reason for non-adoption, especially within small farmers (51% of the interviewees). However, it is very interesting that farmers in a great extent believe that these technologies will not pay off the investment (38% of the interviewees). This is an indication that either the technologies proposed to them are not mature enough to increase farm profit or the cost of adoption is high. The least was also given as the third most important reason for no adoption.

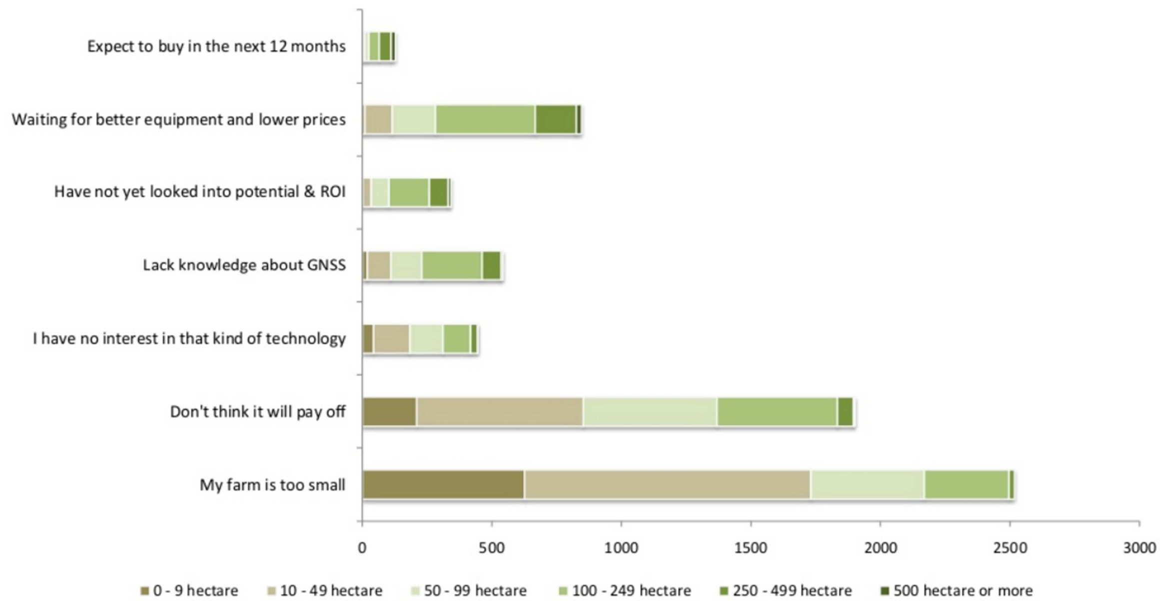


Figure 15: Reasons for not investing in GNSS technology in Denmark (Hansen, 2013)

Education is also an important characteristic determining adoption rates. An example of education importance is a survey from Paxton et al. (2011) among cotton producers which showed that **younger and better educated producers were correlated to the number of PA systems used**, while farmers using computers for management decisions also adopted a larger number of PA technologies.

In Germany, Finland and Denmark, surveys have proved that **farm size** has an impact on farmers' adoption of auto-steering systems and **education** appears to be correlated with adoption of auto-guidance system (Lawson et. al 2011).

The main obstacles for the farmers to adopt PA techniques are (a) **high investment cost** (b) **time consuming** (c) **long learning process in combination with average educational level** (d) **low trust on internet-based data storage** (e) **GPS operation problems** (f) **incompatibility of different PA technologies and software** (Polling et al., 2010). Another survey among Canadian farmers showed that the compatibility of PA technology and the role of farmers' expertise were the main issues for PA technology acceptance and diffusion of innovation (Aubert et al., 2012).There are also a series of other obstacles (McBratney et al., 2005; Adamchuk, 2010). PA has **non-clear economic and environmental benefits** due to lack of appropriate criteria to define them as all aspects of the PA concept should be included, like spatial and temporally induced yield variability, profitability of the agricultural enterprise, sustainability of the resource bas (soil and water), environmental issues and the value of information. In addition, when PA is applied there is **insufficient recognition of temporal variation**, meaning that PA techniques take into account mainly the differences between parts of a certain field based on permanent characteristics without considering temporal features. However, year-to-year variation sometimes overcome spatial variation and it should be included in decision making through PA. The majority of PA research is applied in field basis and there is **lack of farm-level focus**, which is a drawback of PA adoption because farmers consider their farm as a whole and require global solutions. **In-field crop quality** classes together with **product tracking and traceability** of the whole production process are not widely incorporated in the product price and therefore the application of PA techniques that can be auxiliary on both is not so adopted. Finally, there is limited to no environmental auditing that would demonstrate the impact of PA operations and associated fertiliser/agrochemical rates on environment in the product price.

PA technologies have the drawback that for many years, they **offered PA services were incomplete and benefits were very hard to quantify**. As a result, many PATs are, apart from the front runners, hard to be adopted by the regular farmers. As a consequence their development follows the same path as agricultural mechanization (Pedersen et al., 2004). However, it should be noted that if farmers are convinced to adopt them, then they feel the benefits in efficient use of inputs and increased outputs reflected in product quality (Reichardt and Jurgens, 200). The main obstacles in low adoption within PA is a **large knowledge gap between developers and users** and a solution to this will be the development of protocols and realistic performance criteria by technology providers, which will show a positive influence on the rate and breadth of adoption (Lamb et al., 2008).

The environmental benefits, and more specific the GHG mitigation capacity of PA is currently not well assessed. There is a lack of studies of the environmental benefits of using PA, which should go beyond the field and farm scale to wider environmental footprint (Zarco-Tejada et al., 2014). A survey among cotton producers in the USA indicated that the potential for improved environmental quality was a strong adoption motivator across PA technologies (Watcharaanantapong et al., 2014).

A Literature review from Pierpaoli et al. (2013) has used 20 survey papers (mainly from the USA, but also from Europe) and concluded on the main aspects influencing PA adoption that most of them were also identified by other authors as stated above. They separated the PA adoption parameters in three main categories (Competitive and contingent factors, Socio-demographic factors and financial resources). The main parameters included in the first category are farm size, geography and soil quality. As for socio-demographics, age, computer confidence, information availability and education level were identified as limitations for PA adoption. Finally, full time employment of the farm manager, farm income and land ownership and tenure were recognised as the most important financial/economic parameters to promote or delay PA use.

A study among German stakeholders within the PA community explored the barriers in the innovation processes, a gap in the **knowledge transfer between science and practice** and **limited communication and collaboration between farmers and technology providers**. They also pointed out that farmers are not only adopters, but also impose innovation solutions to technology providers (Busse et al., 2014).

In a recent study in Hungary, it was emphasised that PA offers significant benefits to farmers. This is recognised by users and non-users of PA that indicated that PA offers changes in yield quality, chemical usage and income. The PA users indicated that their benefits were high cost savings in fertiliser and herbicide costs (Lencses et al., 2014).

In the USA, Erickson and Widmar, (2015) indicated that on the farmers' perspective the most significant barrier to adopt PA was **farm income**. According to ICF International (2013), PA use was not widespread in the USA for several reasons like lack of information, high capital costs, and time spent on training and data collection. As for the adoption of PA, they concluded that the key factors are fertiliser prices, production acreage, and crop values.

The above mentioned main limitations and obstacles that keep PATs in low adoption rates need to be overcome and there is a series of measures that could be applied in this direction. Average farm size should be either increased in order to increase farm income and allow for investments in PA or cooperation between small farms/advisors/contractors should be increased in order to reduce cost of PA adoption for each individual farm. The role of cooperation among PA stakeholders has been studied by Kutter et al. (2011). They identified as cooperation forms the joint investment to use PATs, contracting of agricultural services to integrate PATs into farming practice, and outsourcing (e.g. data processing and interpretation) when PATs are already implemented on the farm. They found out that cooperation was related to **farm size**, because it affected the attitude of the farm manager. More particularly, large farms employ specialized staff and preferably own their technology, while joint investment in site-specific technologies is an option for smaller farms. In addition, it was assumed that **agricultural contractors will be major driving forces behind the adoption of PA over the next 10 years**, especially in areas with smaller-sized farms.

Contractors, who usually operate with modern technology and due to scale effects, have the possibility to employ specialized staff. There is a tendency towards offering field services and consultancy at the same time. Industry will have to increasingly face the requirements of this group regarding compatibility, software solutions and data management (Kutter et al., 2011). Moreover, data management by service providers is seen acceptable from farmers, but concerns exist regarding data misuse, over-regulation and software compatibility. Before investing in PA tools, interested farmers can evaluate the technology, whilst estimating the degree of variation present in fields and the potential benefits of PA by **engaging contractors and consultants** (Jochinke et al., 2007).

As stated above, PATs are not uniformly applicable throughout Europe and therefore, they should be offered to farmers, crop consultants and technology providers together with specific recommendations for the dedicated field operations and most preferably with a Decision Support System (DSS) (Fountas et al., 2005). Traditional DSS has been upgraded during the years into Farm Management Information Systems (FMIS). The integration of GNSS positioning in FMIS, together with the use of additional information coming from various sensors, has revolutionised PA. FMIS is a system for collecting, processing, storing and providing data in the form needed to manage a farm. GNSS links this data to specific geographical coordinates. As the adoption of PA is closely related to the adoption of FMIS, a survey among European farmers revealed differences in the **weekly hours spent in the office** among the countries and the use of FMIS for different farming activities (Lawson, et al., 2011). More particularly, it was revealed that countries with lower PA adoption rates have also very low time for in-office administrative work, which means that as farmers will adopt FMIS they will also adopt PATs and vice-versa. Such a DSS will be useful not only to carry out the field operations more efficiently, but also pointing out solutions and future directions of PA that may eventually lead to increase PA adoption (Griffin and Lowerberg-Deboer, 2005; Fountas et al., 2005). However, DSS use from farmers is linked to their education level and their computer confidence. Therefore, it is vital that farmers are trained on new technologies in combination with the engagement of younger people with higher education level and familiarity with new technologies.

The above mentioned ideas to overcome the limitations of PA adoption are related to the farmer/farm. However, it is significant that on the side of research and industry the environment of PA will become more clear, easy and cheap to get more appeal for the end users. Regarding research, it is believed that the knowledge gap between scientific findings and farming stakeholders should be shortened and information for PA should be open-access available. Industry should work on making the technology simpler for the user, reduce the cost by applying less expensive technology and try to make different brand systems to be inter-compatible. Combined work between research institutions and industry should also be done to achieve GNSS optimisation in terms of better operation and accuracy, more detailed in-field evaluation of PA benefits in economic and environmental level (involving also temporal variation) and connect crop quality and traceability with the final product price.

To conclude, there is a lack of adoption studies among farmers in Europe. Only in the USA, USDA has incorporated a number of questions in the annual national studies in terms of yield monitors, guidance systems and variable rate applications. In Europe, such national surveys do not exist. As it was mentioned in the above mentioned literature review, the adoption studies carried out in Europe are very few and there were scattered among the countries, which cannot be representative for the different farming cultures in Europe. The Machinery manufacturers have not so far published any statistical data on the sales of PATs supplied with their machinery, but only the percentage of machinery that are equipped with some of these technologies (over 80%). However, it is not certain that these functionalities in the new machinery are used by the farmers. A systematic and well-structured survey among the main climatic and farming conditions in Europe is required to draw conclusions on the adoption trends, drawbacks and perceived benefits. This will help a large number of beneficiaries, such as machinery manufacturers, service providers, policy makers and above all the farmers.

4.3 Future perspective of Precision Agriculture in the EU

According to the GNSS market report (2015), PA in Europe and worldwide will continue to grow, thanks to the expected benefits provided to farmers in terms of increased productivity. It is also expected that the Asia-Pacific region will progressively challenge the role of North America as the largest GNSS market. In addition, it seems that all-around farm management solutions will replace stand-alone use of certain PA technologies, in order to succeed the maximum positive effect. According to a business survey (markets and markets, 2016), the PA market was valued at €2.43 billion in 2015 and is expected to grow at a Compound Annual Growth Rate (CAGR) of 11.7% between 2016 and 2020.In the period 2013 to 2023, it is expected to have an increment in annual shipments of GNSS devices from over 200,000 up to almost 1.2 million units worldwide. Simultaneously, GNSS penetration (the proportion of all high-powered tractors in use that is equipped with GNSS) is foreseen to experience a steady increase over the next decade, reaching 50% of tractors worldwide by 2023 (Figure 16).

Asia-Pacific is projected to take over North America in terms the adoption of GNSS devices, growing from 156,000 units in 2013 to 2.3 million units by 2023. The fact that China and India play a prominent role in the agriculture-related economy (respectively absorbing 35% and 47% of total employment) can be translated to significant room for improvement in terms of production efficiency. Except this, China and India are shifting their agricultural production to practices of sustainability growth in order to confront urbanization, increasing population, land shortage and water scarcity. PA is the opportunity for these countries to improving agricultural productivity in combination with reduced environmental impact, in particular as the trend towards mechanisation continues. Growth in the average size of holdings will also play a major role in boosting the uptake of GNSS.

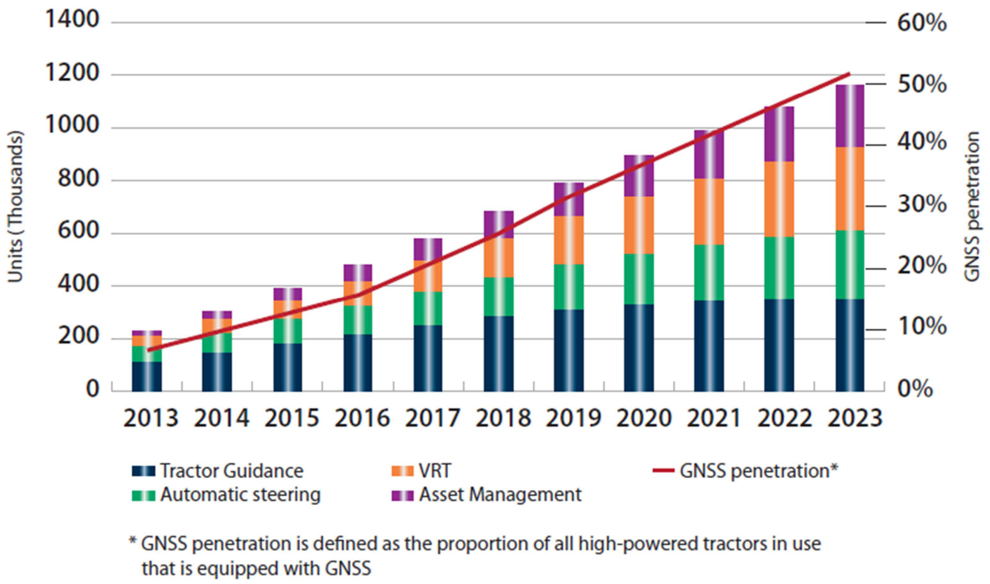


Figure 16: Global Projection of Shipments of GNSS devices by application (2013-2023) (GSA, 2016)

In terms or economics, it is expected that by 2023 the revenues from sales of the GNSS devices producers will increase from over 750 million € to over 2.5 million € (Figure 17). North America and Asia-Pacific will show the largest share of revenues, while Middle East and Africa together with South America and the Caribbean will increase their share significantly. It should be noted that the average price of GNSS devices is expected to decrease from over 3000 € to over 2000€ in the same period (2013-2023), due to increasing competition, increasing needs of end-users and economies of scale.

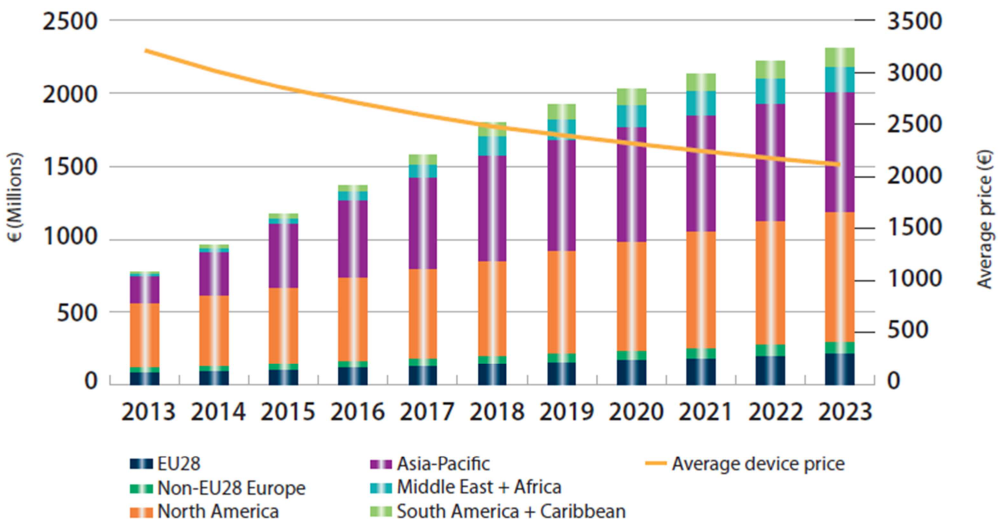


Figure 17: Projection of revenues of GNSS device sales by region (2013-2023) (GSA, 2016)

As for the revenues from different PA technologies based on GNSS devices, Figure 18 shows that automatic steering will keep its position within best-sellers of PA and variable rate technologies will significantly increase (from €135 million in 2013 to €723 million in 2023), while tractor guidance will peak in 2018, at which point they will begin to decline as farmers shift towards more advanced solutions. Revenues from Asset Management will grow from €11 million in 2013 to €102 million in 2023.

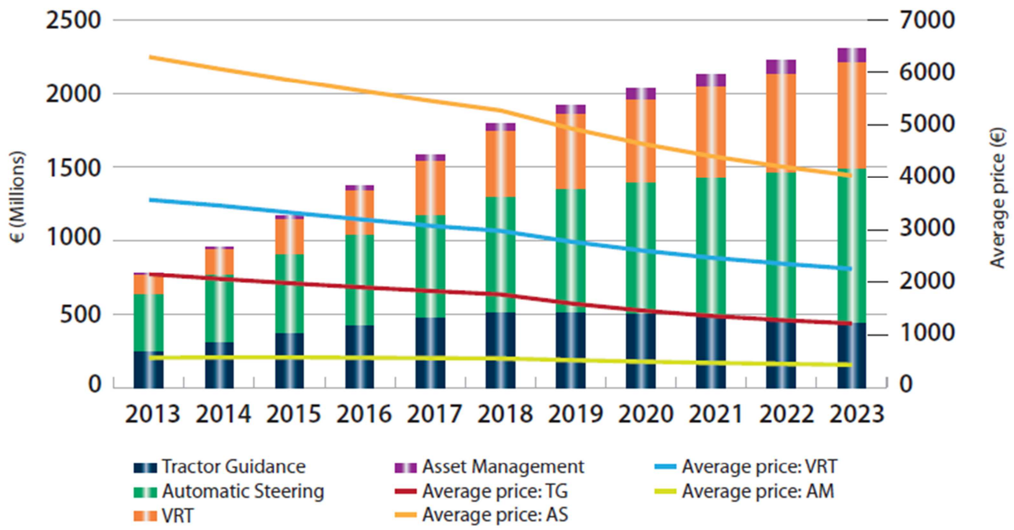


Figure 18: Projection of core revenue of GNSS device sales by application (2013-2023) (GSA, 2016)

5 Precision agriculture technologies affecting greenhouse gas production

In this chapter, the PA technologies that can positively affect the reduction of GHGs for the agricultural sector with positive or neutral impact on farm productivity and farmers economy are specified according to selected criteria and discussed.

5.1 Greenhouse Gases mitigation technologies and practices

Climate change can be mitigated through the **reduction of GHG emissions**, the **enhancement of GHG removals** and the **avoidance or displacement of emissions** (Smith et al., 2008). As mentioned above, the most important agricultural GHGs are CO_2, CH_4 and N_2O, which are produced by mismanagement of carbon (C) and nitrogen (N) flows in the agricultural system. An example of reduction of GHG emissions, specifically N_2O, is the application of nitrogen fertilization at the right amount at the right time (Bouwman, 2001). Regarding enhancing removals, any agricultural practice that increases photosynthetic processes or slows the return of stored C in organic biomass can be considered as C sequestration method (Lal, 2004). GHG emissions can be avoided or displaced by the conversion of residual agricultural biomass into biofuel of any type (Cannell, 2003; Schneider & McCarl, 2003) where in reality this energy source replace fossil fuels of the same energy content.

However, the mechanisms that reduce one GHG can sometimes affect another GHG in a negative way through different mechanisms resulting in combined effects that are unknown (Robertson & Grace, 2004; Schils et al., 2005). For instance, no-tillage practices, which can potentially reduce GHG emissions by 20.6-23.7% compared to conventional tillage (Mangalassery S., et al., 2014) may have unanticipated and unwanted effects on other sources or sinks of greenhouse gases. If, for example, soil water conservation associated with no-till were to provide more moisture for nitrifying and denitrifying bacteria as well as plants, then production of N_2O might increase, offsetting some or all of the mitigation potential of carbon storage (Robertson, 1999).

Smith et al. (2008) listed the GHG emissions mitigation measures in seven categories that include different practices:

1. **cropland management** (nutrient management, tillage/residue management, water management, rise management, agroforestry, set-aside, land-use change)
2. **grazing land management/pasture improvement** (grazing intensity, increased productivity through fertilisation, nutrient management, fire management, species introduction including legumes)
3. **management of organic soils** (avoid drainage of wetlands)
4. **restoration of degraded lands** (erosion control, organic amendments, nutrient amendments)
5. **livestock management** (improved feeding practices, specific agents and dietary additives, longer term structural and management changes and animal breeding)
6. **manure/biosolid management** (improved storage and handling, anaerobic digestion, more efficient use as nutrient source)
7. **bioenergy** (energy crops, solid, liquid, biogas, residues)

PA for crop farming is included in the first category with a special interest on nutrient management and water management. According to Eory and Moran (2012), agricultural GHG emission mitigation focus should be on increasing the efficiency of agriculture in order to reduce future land conversion, and also on reducing N_2O emissions from soil N management and CH_4 emissions from enteric fermentation (though it is much more difficult to achieve high abatement in the latter). Manure management and storage also have to be considered since they offer abatement options, often with a co-benefit of ammonia reductions. They considered 4 mitigation measures connected with PA (improved timing of mineral N application, improved timing of organic N application, full allowance of manure N supply and avoiding N excess). All of them showed considerable abatement rates with "Improved timing of mineral N application" reaching 0.3 tCO_2eq/ha.

Another report (UK government, 2016) indicated some mitigation methods in order to reduce agricultural production emissions by 3 $MtCO_2eq$ until 2020 compared to 2007 and showed that the most promising for GHG reduction (it can reach 1.4 $MtCO_2eq$) in high extend is nutrient management (Figure 19).

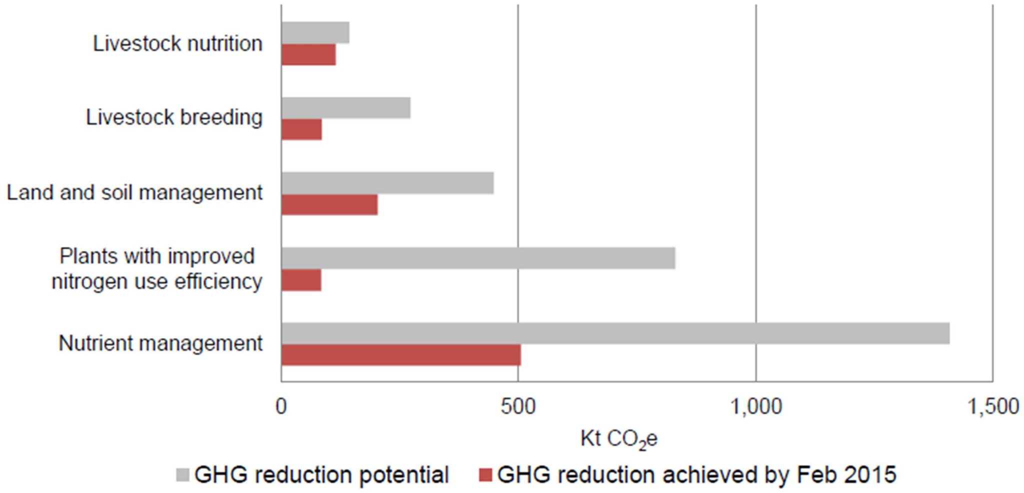


Figure 19: GHG reduction based on uptake of key on-farm mitigation methodsby activity grouping in the UK (UK Government, 2016)

Therefore, they analysed the mitigation methods of the nutrient management activity group and counted that by 2015 the UK have achieved in total 36% of the maximum technical potential reduction. It is obvious that avoidance of high risk areas and fertiliser recommendation systems can play vital role in GHG emission mitigation. If PATs would be included in these mitigation methods, the level of GHG emission reduction could increase further (Figure 20).

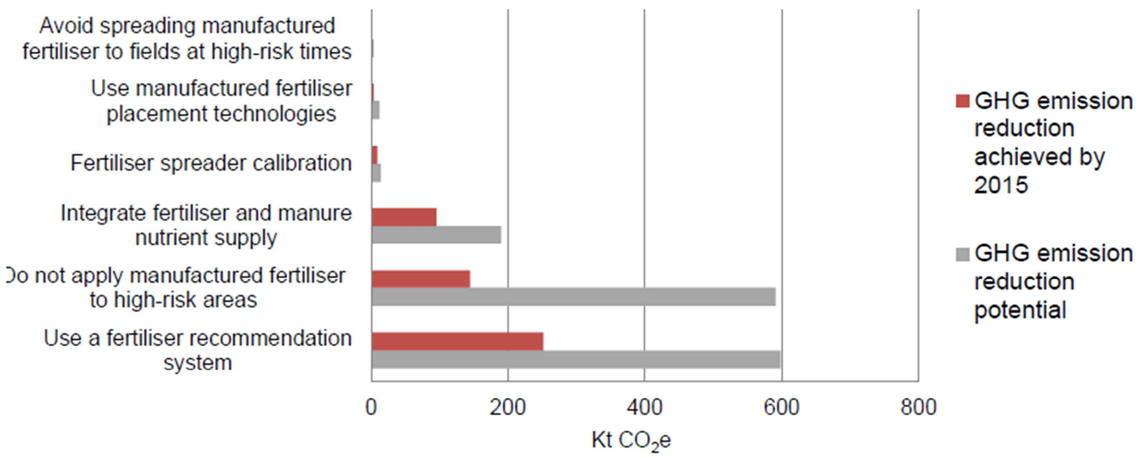


Figure 20: Nutrient management mitigation methods - Potential and achieved GHG emission reduction (UK Government, 2016)

The European Commission Climate Action (http://ec.europa.eu/agriculture/climate-change/factsheet_en.pdf) also proposes GHG mitigation measures related to farming practices, like seeding/planting, harvesting, irrigation and fertilisation of existing crops, use of different varieties, diversify crops, implement management practices. EU seeks for sustainable agricultural schemes through the new Common Agricultural Policy (CAP). Natural resources are depleting and agriculture has to improve its environmental performance. Sustainable management of natural resources and climate action represent one of the three main objectives of the CAP. Improved sustainability will be achieved firstly by covering certain environmental requirements and obligations in order to receive full CAP funding. Secondly, from 2015 onwards, the CAP introduced a new policy instrument, the **Green Direct Payment**, that is granted only when there is simultaneous crop diversification, ecological focus areas and permanent grassland, with environmental benefits on biodiversity, water and soil quality, carbon sequestration and landscapes. It represents 30% of the direct payment budget and it is compulsory. Finally, rural development is vital for achieving the environmental objectives of the CAP and combating climate change as at least 30% of the budget of each rural development programme must be reserved for targeted measures on this direction. All these policy instruments are accompanied by related training measures and other support from the Farm Advisory System, insights gained from the Innovation Partnership and applied research, which would help farmers to implement appropriate solutions for their specific situations. Proposed solutions on the farm level are the adjustment of farm operations timing; the improvement of the effectiveness of pest and disease control through better monitoring, diversified crop rotations, or integrated pest management methods; the use of water more efficiently by reducing water losses, improving irrigation practices, and recycling or storing water; and the improvement of soil management by increasing water retention to conserve soil moisture.

PATs could participate in the achievement of agricultural sustainability as they interfere in most agricultural practices by reducing or redistributing inputs to address the real requirements of the crop. We anticipate that the new CAP will promote further PATs as one of the methods to increase or maintain productivity with simultaneous reduction of environmental impacts, and in specific GHG emissions.

5.2 Criteria of selection

In this section we present the selection criteria of the PATs that have the most promising combination of increased/maintained farm productivity with simultaneous GHG emissions reduction between all the PATs that are presented in Beck et al. (2016).

Precision Farming Technologies can be divided into three main categories (Schwarz et al., 2011):

- **Recording technologies** (soil mapping, soil moisture mapping, canopy mapping).
- **Reacting technologies** (variable rate application of nutrients, pesticides, seeding, irrigation and weeding)
- **Guidance systems**, (driver assistance, machine guidance, controlled traffic farming).
  i)

All the PATs that are included in the above mentioned categories together with their interconnection were analysed in Annex 1. The list divides individual technologies into the three categories described above. All three categories of PATs require the use of Global Navigation Satellite Systems (GNSSs).

Recording technologies are required in order to receive information from the field (before, during and after the crop period) and after processing, extract the data useful for any kind of PA application. On the other hand, guidance technologies can be used for any agricultural practice application (including traditional practices) focusing on precise machinery movement within and between fields with tangible results in reduced overlapping causing lower input use (seeds, fertilisers, pesticides) in parallel with decreased self-propelled machinery fuel consumption. Finally, the reacting technologies are supposed to use the data produced by the recording systems and minimize all inputs (seeds, fertilisers, pesticides, water) in the optimum quantity required by the crop to grow. The right combination of these three categories is expected to increase or at least maintain yield with the advantage of higher quality.

Based on the description above, all PATs contribute in the final quantity and quality of yield due to their interconnections and it is difficult to separate them according to importance. Therefore, the main criterion to select the PATs that have the potential to reduce GHG emissions increasing or maintaining farm productivity was the direct impact on aforementioned both parameters.

As recording technologies remain supportive in the PA process, it was decided not to be analysed in the next section of this report. For the same reasons GNSSs were also excluded from further analysis. The selected PATs are given in the following table 1, according to the expected weight of each one on GHG emission reduction.

Table 1: Selected PATs with direct GHG reduction potential

Ranking of PATs	PAT Type	GHG reduction potential
1	Variable rate nutrient application (VRNT)	5
2	Variable rate irrigation (VRI)	3
3	Controlled Traffic Farming (CTF)	2
4	Machine Guidance (MG)	2
5	Variable rate pesticide application (VRPA)	2
6	Variable rate planting/seeding (VRP/VRS)	1
7	Precision physical weeding (PPW)	1

Scale of importance on GHG reduction potential (Likert-type scale identified by the authors):5: very high potential; 4: high potential; 3: moderate potential; 2: slight potential; 1: low potential

VRNT technologies can reduce GHG emissions significantly as the most influencing agricultural input are the fertilisers and especially nitrogen fertilisers which are the main source of N_2O that is the most influencing GHG derived from agricultural activities (as stated in section 2.3.1.). VRI systems follows in GHG emission reduction potential as its impact is dual; primarily the reduction of irrigated water decrease the energy for water pumping from the aquifer and secondly the optimum irrigation scheduling affect significantly the GHG emissions derived from fertilisers through the soil (mainly N_2O). CTF and MG limit the use of tractors to only the necessary passes through the fields avoiding overlapping with respective decrease in agricultural inputs and fuel (translated into GHG emissions reduction). VRPA is also expected to have GHG reduction potential due to lower pesticide application through lower GHGs coming from pesticide industrial production. In this case, the environmental effect is extremely significant, but in terms of lower chemical substances application that contaminates all natural resources (water, air, soil). VRP/VRS and PPW show lower, but not irrelevant GHG emission mitigation. VRP/VRS is mainly important for optimising plant density in the field that can increase farm productivity, while the reduction in seed/plant population is associated with GHG emissions during their production. PPW reduces pesticide application and fuel used for flame burning of weeds.

5.3 Impacts of the selected precision agriculture technologies

In this section we present the PATs that could increase/maintain farm productivity and simultaneously reduce GHG emissions. At first, a short technical description of each technology is given. More details can be founded in the report entitled "Literature review on the impacts of Precision Agriculture Technologies in agriculture". Then, further analysis of the literature on impacts of PATs (where applicable) that can mitigate GHGs together with discussion on behalf of the authors is given. Prices of the selected PATs, together with the source, are provided in the Appendix A.

5.3.1 Variable rate nutrient application technology

5.3.1.1 Description

Variable rate nutrient application (VRNT) can provide to the field inorganic fertilisers (N, P, K), manure and lime by adjusting the mass flow rate and subsequently the application rate of nutrients according to the specific needs of the crop locally within the field. Inorganic fertiliser is either spread as liquid or solid granules, while manure is spread as slurry or solid manure. VR liquid inorganic fertiliser is spread using VR pesticide sprayer technology (mentioned later).

VRNT is executed by either applying a prescription map that was designed after receiving data from the field using mainly canopy sensors that identify the status of the crop and correlate it with nutrient needs or by combining the recording and reacting procedure on-the-go, meaning simultaneously.

Inorganic fertilizers and lime are distributed in the field using two main technologies; the spinner or centrifugal spreaders that are based on a conveyer belt or chain that transfers the material (granules) from the hopper until it falls on one or more spinning disks throwing the particles into the field and the pneumatic spreaders that use airflow which divides the granules over a piped spreading boom for uniform distribution (Behic Tekin and Okyay Sindir, 2013; Hijazi et al., 2014). VRNT in spinner spreaders the application rate is controlled by adjusting the gate opening and/or changing the speed of the conveyor (and thus the input rate of material). In pneumatic applicators VRNT is executed by spreading the material using an adjustable controlled air stream through a piped boom (Grisso et al., 2011).

As for slurry distribution in the field, the applicators work by either pressuring the slurry tank (by changing the size of the gate that brings slurry to the delivery system) or by pumping the slurry from the tank (by changing pump or valve settings). Solid manure spreaders work with an apron that pushes the manure towards a dispensing system (Calcante et al., 2014; Brambilla et al., 2015). VRNT is based on changing the required slurry flowrate based on an application map or real-time soil sensors, combined with simultaneous measurements of the nitrogen content of the slurry, the ground speed and working width of the vehicle (Calcante et al., 2014; Brambilla et al., 2015).

Trimble (www.trimble.com) offers a crop input control system, named **Field-IQ**, which can be used for seeding, planting, nutrient and pest management operations. The same company provides **Greenseeker** system that effectively and precisely manages N fertilizer inputs on-the-go within the field using NDVI measurements. AgLeader (www.agleader.com) has produced also a system named **OptRX** that measure NDVI from crop canopy and apply real-time variable fertilizer rates. Topcon (www.topconpositioning.com) is the provider of the threat on-the-go system **CropSpec** that uses pulsing laser diodes for sensing chlorophyl content and then manage the exact within field N fertiliser application. Yara (www.yara.co.uk) is the provider of **N-Sensor** which is also a tractor-mounted on-the-go N fertilization system that works on the principle of measuring crop's light reflectance to determine its nitrogen demand. Fritzmeier (www.fritzmeier-umwelttechnik.com) has produced the **ISARIA** system that is based on red edge infection point (REIP) narrow band vegetation index that is highly correlated to the plants' nutrient supply. This company also provide **MiniVeg** system that uses laser-induced chlorophyll fluorescence to obtain crop N needs and determine on-the-go the applied fertilisers.

5.3.1.2 GHG emissions reduction potential

Nitrogen fertilisation is the most significant parameter producing GHG emissions in the agricultural sector, as nitrogen inorganic fertilisers are the cause of CO_2 and N_2O emissions during their production and N_2O emissions after their application in the soil (Fertilisers Europe, 2008; Eory and Moran, 2012; MacLeod et al., 2015).

5.3.1.2.1 GHG emissions from nitrogen fertiliser production

In order to produce N fertilisers, it is required to synthesize ammonia, where CO_2 is produced from the use of fossil energy sources (mainly natural gas) as feedstock and fuel. Methane provides 60% of the required H_2 (together with 40% from water steam) to react with atmospheric N_2 and produce ammonia. A portion of CH_4 is used to heat the process. On the other hand, nitric acid production process is the source of N_2O emissions (Fertilisers Europe, 2008). Ammonium nitrate (AN-N), which is the base of nitrogen fertilisers, can be produced at different levels of technology and the emitted GHGs are different in each case (Figure 21).

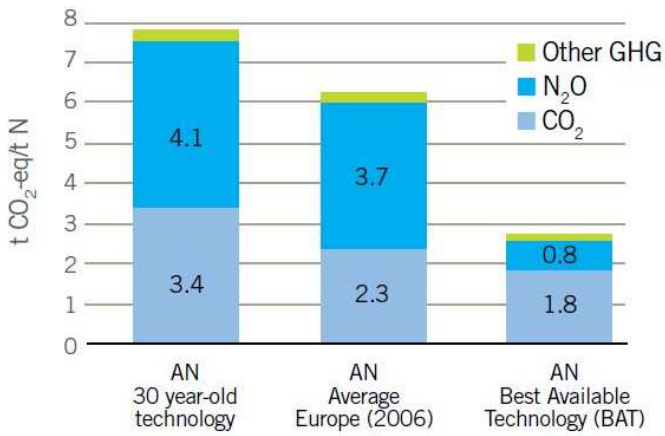


Figure 21: Greenhouse gas emissions of ammonium nitrate production according to technology used (Fertilisers Europe, 2008)

Technology advancement has decreased total GHG emissions from 7.9 t CO_2-eq/t AN-N to a level below 3 t CO_2-eq/t AN-N, which can be achieved by adopting de-N_2O catalyst systems that reduce N_2O emissions from nitric acid production using catalytic systems that break down N_2O under high temperature into harmless nitrogen (N_2) and oxygen (O_2). These systems are being fitted to many nitric acid plants and virtually all operating plants in Europe had abatement systems since the mid-2010s. The respective GHG emissions from wheat production at the economic optimum N fertilizer application rate when de-N_2O technology is applied are significantly reduced by about 40%, from 2.55 t CO_2-eq/ha it was reduced to 1.6 t CO_2-eq/ha (Figure 22).

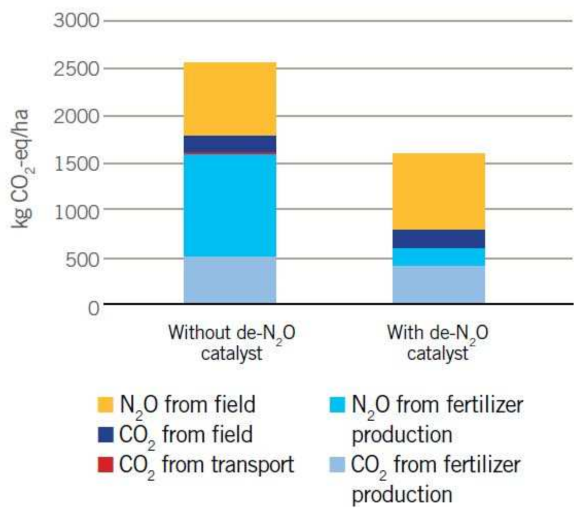


Figure 22: Wheat production GHG emissions at optimum N application rate with or without installation of de-N_2O catalytic system in ammonium nitrate production (Fertilisers Europe, 2008)

Therefore, if variable rate nitrogen fertilization is applied in combination with the fitting of de-N_2O catalytic systems in the production line of N fertilizers, the result in the total GHG emissions derived by N application is expected to be even more positive (Figure 22).

5.3.1.2.2 GHG emissions from nitrogen fertiliser application

Inorganic or organic N within soil is subject to various natural microbial conversion processes, some of which may produce N_2O. The main inorganic forms of N in the soil are ammonium (NH_4^+) and nitrate (NO_3^-). Ammonium originates either directly from mineral fertilisers, from the conversion of manure or crop residues or from urea fertilisers. Nitrate is either directly applied as nitrate mineral fertiliser or results from the microbial oxidation of ammonium. Nitrate is dissolved in the water in the soil and cannot be stored in the soil over the long term. During the period of crop growth, nitrate is taken up at high rates. However, at times of low or zero crop demand, and under certain environmental conditions, nitrate can be lost either to the air via denitrification or to water by leaching. Ammonium is not mobile and most of it has to be converted into nitrate before crops can take it up. Losses of ammonium from the soil occur via volatilisation of ammonia (NH_3).

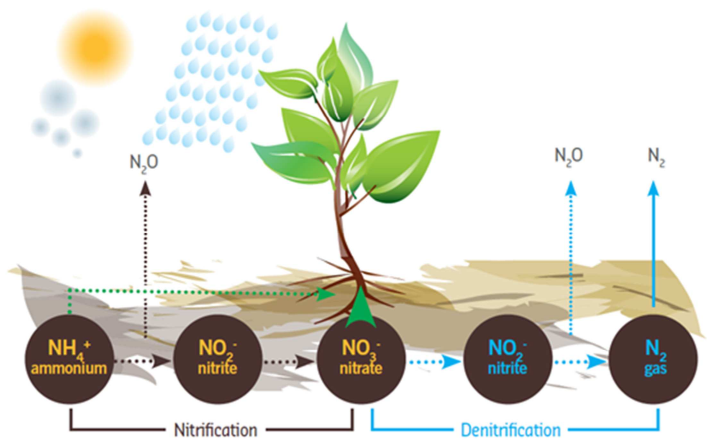


Figure 23: Nitrous oxide production from nitrification and denitrification processes (Fertilisers Europe, 2008)

Nitrification is the oxidation of ammonium to nitrate (Figure 23). This natural process supplies energy to the nitrifying bacteria. During the oxidation of ammonium to nitrite, N_2O is produced as a by-product. Denitrification means the reduction of nitrate to di-nitrogen gas (N_2). During this process N_2O is emitted to the atmosphere. The quantity of N_2O released from denitrification depends on the environmental conditions - more or less N_2O is produced instead of N_2. The more favourable the conditions for denitrification (e.g. completely water-saturated soil), the more N_2 is proportionally produced. Changing the conditions (e.g. from wet to dry soils) favour N_2O release (Fertilisers Europe, 2008). Therefore, when soils start to dry out, more N_2O is emmited.

Therefore, it is obvious that nitrogen fertiliser industrial production and field application contribute significantly to the total GHG emissions of agricultural production. An example of the effect of nitrogen fertilisation is the allocation of the total GHG production from wheat when cultivated in the economic optimum N rate (Figure 24) shows that almost 90% of the total GHGs are associated with N fertilisers (CO_2 and N_2O from production and N_2O from field nitrification and denitrification).

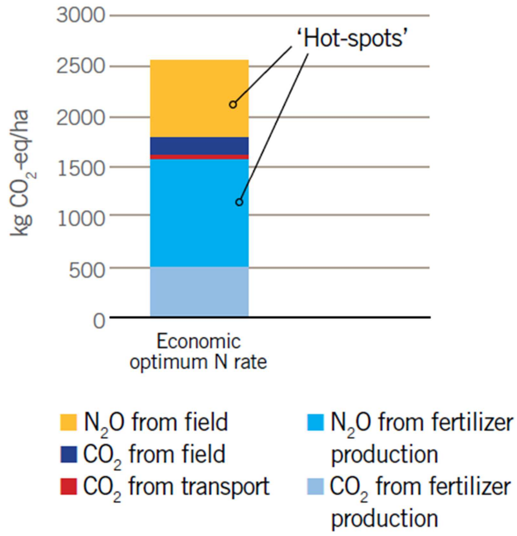
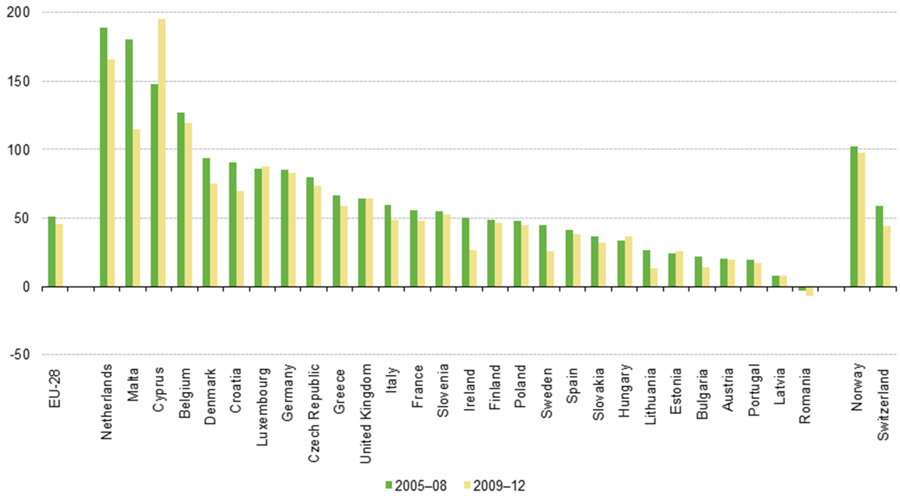


Figure 24: GHG intensity of wheat production (Fertilizers Europe, 2008)

A number of studies have concluded that many farmers apply nitrogen in excess of crop nutrient needs (Bausch and Delgado, 2005; Millar et al., 2010; Ribaudo et al., 2011). According to Eurostat (2016) in the period of 2005-2008 the average nitrogen surplus coming from inorganic and organic fertilizers, manure and other nitrogen inputs, like seeds and planting material, biological fixation by leguminous crops and free living organisms, atmospheric deposition of the EU-28 member states was 51 kg N/ha (Figure 25) that is an indication of the amount of nitrogen fertilisation that could be diminished in EU agricultural production. It can be that there is a trend of nitrogen surplus reduction as in the period 2009-2012 the EU-28 surplus was reduced to 48 kg N/ha.



(1) Eurostat estimates: EU-28, MT, CY, BE, DK, HR, LU, EL, IT, ES, SK, LT, EE, BG, AT, LV and RO.
(2) Average: 2009–11 for EU-28, IE, SE and CH.

Figure 25: Nitrogen surplus (kgN/ha, average 2005-2008 vs 2009-2012, EU-27 (Eurostat, 2016[14])

Therefore, if VR fertiliser application (including manure spreading) is used to provide nitrogen to the crop according to the needs, then the final fertiliser (or manure) quantity will be reduced with significant mitigation of both CO_2 (from fuel reduction timely fertilization and reduced weight of the hopper) and N_2O from N fertiliser production and use (in the case of manure also CH_4 is produced). Especially if the application is selected to be executed in the optimised conditions, then the reduction of GHG emissions will be higher.

All VR nutrient application technologies are interconnected to other PA technologies (GNSS, soil mapping, canopy sensors, on-the-go sensors like YARA, machine guidance) and it should be mentioned that when these technologies are combined in the proper way, the fertiliser quantity applied in the field is the optimum, thus the emitted GHG are reduced. It should be noted that if N fertilisation is combined with weather prediction regarding precipitation or appropriate irrigation scheduling (where applicable), the result can be improved further.

Limited data exist on the GHG mitigation potential of VRT. However, there is significant work on the impact of lower nitrogen field input to N_2O emissions. Bates et al. (2009) identified an abatement potential of 5% reduction in the baseline GHG emission rate that is assigned to mineral fertiliser application. The also pointed out that there is abatement by making effective allowance for manure and residual N with VRA technology and can reach also a 5% GHG emission reduction to the baseline emission rate for mineral fertiliser application. Millar et al., (2010) have found that nitrogen fertilizer application rates correlate well with N_2O emissions. However, the relationship between nitrogen application and N_2O emissions is not necessarily linear (Hoben et al., 2011; McSwiney and Robertson, 2005) and the relationship of N_2O emissions to nitrogen application rate increases proportionally with the application rate (Bouwman et al., 2002). Another study estimated that an average of 1.19% of nitrogen added to soils is released as N_2O (Ogle et al., 2010). Paustian, et al. (2004) pointed out that as cropped soils emit N_2O at a rate of 0.2–3% of their nitrogen inputs, when nitrogen inputs are decreased N_2O emissions

[14] The inputs of the nitrogen balance are: (a) Fertilisers (inorganic fertilisers, organic fertilisers excluding manure); (b) Gross manure input, calculated from manure production (nitrogen excretion; no reductions are made for nitrogen losses due to volatilisation in stables, storages and with the application to the land) and manure withdrawals (manure export, manure processed as industrial waste, non-agricultural use of manure, other withdrawals), change in manure stocks, manure import; (c) Other nitrogen inputs, like seeds and planting material, biological fixation by leguminous crops and free living organisms, atmospheric deposition.

could be reduced directly by approximately 1.25% of nitrogen inputs saved. . Sehy et al. (2003) examined the use of VRT and GPS in field nitrogen application and found out that N_2O emissions decreased by up to 34% in low-yielding areas.

5.3.1.3 Impacts of the use of VRNT on productivity and farm economics

Farm productivity is influenced by nitrogen fertilization rates, as it is one of the most significant parameters for increasing yield, while nitrogen constitutes an essential factor of farm economics. Sogaard and Kierkegaard (1994) described the relation between nitrogen supply and plant yield with a quadratic equation. The parabolic shape reflects that each further added unit of nitrogen causes smaller yield increase of the crop. At a certain point, the benefits of an added unit of nitrogen (i.e. extra crop yield) barely outweigh the costs of this unit, and an economic optimum is reached. This economic optimum is found at lower application rates than the yield optimum. By fertilising each management zone near the economic optimum, higher returns can be achieved. Thus, the highest returns for VRT application are expected on fields with high and spatially variable nutrient requirements (Raun et al., 2001).

Excessive application of nitrogen fertilisation decreases financial returns and increases the potential for nitrogen leaching into the environment. Insufficient application can reduce yields and net farm income (Ribaudo et al., 2011). A landowner who benefits from fertiliser savings and yield gains would not require additional incentives, although yield losses would require additional incentives. Additional revenue gains could be realized with decreased need for fuel, labour, or other chemicals (ICF International, 2013).

Several authors have analysed the impact of VRNT on farm productivity and economics. Tekin (2010) estimated that VRA of nitrogen can increase Turkish wheat production between 1-10% offering savings in nitrogen fertilisation between 4% and 37%. He also made an economic analysis using the prices of the VR equipment, the fertilisers and the price of the wheat seed and found out that the investment cost over a 5-year depreciation period would vary between €11.45 and €115.39 for a 500 ha and 50 ha farm size. Koch et al. (2004) found also similar results (6-46%) in nitrogen savings in corn fields in northeastern Colorado, USA. According to ICF International (2013), VRT in fertilisation was found to produce economic benefits through increased yields, improved crop quality, and decreased fertiliser applications. This report states that 8% increase in wheat yields (for 10% less nitrogen) and 5% increase in corn yield (for 21% less nitrogen) was shown when GreenSeeker technology was used in Maryland. In Virginia, using again GreenSeeker technology in corn fields resulted in nearly 27 kg/ha less nitrogen application than the conventional method with a nearly equivalent yield. GreenSeeker technology costs €17,616-€19,378, depending on whether farmers already have electronic flow control technology on their fertiliser application equipment. Based on the GreenSeeker price, current fertilisers prices and the reduction mentioned above from the results from Maryland, the capital cost per acre for small farms was €77.5, for medium farms €35.23 and for large farms €19.37.

HydroSense project (2013) identified that the simpler form of precision farming in cotton was by using N sensors to estimate uniform application of fertiliser through pre-existing drip irrigation systems resulted in a net benefit of 113 €/ha/year. A variable-rate irrigation system applied in the drip irrigation circuit resulted in a net benefit of 310 €/ha/year, while the net benefit climbs to 480 €/ha/year when deploying the emerging real-time and variable-rate technology for N inputs even though the farmer needs to make significant investment on new equipment. It should be noted that the VR fertigation technique (fertilization + irrigation) can only be applied in crops that are irrigated using drip irrigation systems.

Compared to uniform application, in-season VR application of **granular fertiliser** at 1 m² spatial resolution (based on optical sensing) increased their simple estimate of revenue (grain revenue minus fertiliser cost) by 9.69€/ha when fertiliser was also applied before planting (fixed rate) and more than 24.66€/ha when fertiliser was only applied in-season (Raun et al., 2001; Raun et al., 2002). Mamo et al (2003) found a profit increase of 7 to 20.25 €/ha for corn when using VRT compared to uniform application due to reduction in the use of fertiliser. Koch et al. (2004) found an increase of 25.6 to 38.6 €/ha in net returns for VRT application of N on Colorado corn based on site-specific management zones compared to uniform application rates, both in a farmer and custom applied scenario.

Next to fertiliser costs also other costs can be attributed to VR fertiliser application, such as soil sampling or online sensing, delineation of management zones, fixed or variable costs associated with VRT equipment (GPS receiver, on-board computer, software, VRT system). However, the cost of these equipment or services is not only associated with VR fertiliser application and is interconnected to other PA applications. Larger farm sizes (economics of scale) allow fixed costs associated with VRT equipment to be spread over a larger area, and therefore decrease the expense of VRT equipment per hectare. Variable rate application based on grid soil sampling results in the lowest net return, primarily due to increased fertiliser uses and soil sampling costs (Koch et al., 2004).

Managing **manure** as fertiliser resource for crop production can increase the return for the producer and the overall production efficiency of an animal-crop farming system in much the same way as granular fertiliser management (Huber et al., 1993). Precision management of manure has the potential to further improve farming system production efficiency by applying the exact required manure instead of inorganic fertilizers and increase the return to the farmer and minimizing the pollution potential of animal waste that can be translated in profit as waste management becomes cheaper (Morris et al., 1999). As with VR granular fertiliser application, the key to VR manure application in general is the existence of an application map, which is laborious and time consuming to generate when acquired without sensor technology (Schellberg and Lock, 2009). Although no literature is available considering the economic return of VR manure application, many similarities with VR granular (inorganic) fertiliser applications can be seen. The main difference is the fact that here the applied product is much bulkier, heterogeneous and lower in nutrient content (Morris et al., 1999) and financial value. It should be noted that some VR manure systems can be retrofitted to the tankers that farmers already have (Brambilla et al., 2015), which removes the need for large investments to start with VR manure application.

Variable rate (VR) **lime** (which is primarily $CaCO_3$) application can increase crop yields and the economic return of the farm (Weisz et al., 2003). Lime application increases the soil pH to a desired level and an optimal pH level in the soil is important to achieve optimum yields and consistent quality (Kuang et al., 2014). Also, lime improves the uptake and availability of plant nutrients and can also improve water penetration.

VR lime application can lead to improved adjustment of soil acidity at a lower cost and with a (slightly) better yield response than uniform lime application (Kuang et al., 2014). Under-application of lime can cause large yield losses. Over-application of lime can be as detrimental as under-liming (Weisz et al., 2003), as it is costly and can create problems with availability of some nutrients (for example inhibiting P and Zn, or leading to toxic levels of Mn), disease pressure, reduced herbicide performance and herbicide degradation (Kuang et al., 2014; Weisz et al., 2003). Over- and under-liming cannot be avoided if lime is applied uniformly throughout the field. It should be noted that VR liming appears to be only profitable for high value crops (Swinton and Lowenberg-DeBoer, 1998), because even small effects of liming on yield produce favourable economic results in these crops.

The main cost in a VR lime application is the cost of grid sampling. The actual amount of lime used depends on the soil variability, field acidity, environmental factors, the sampling method and the sampling resolution (Weisz et al., 2003).Weisz et al. (2003) concluded that when performing grid sampling and VR lime for 3 consecutive years in Piedmont no-till soybean fields, the net loss is €11.44/ha compared to uniform lime application. However, when they performed grid sampling only in year 1 and 3, and performed the VR lime in each year (with year 2 based on the PH map of year 1) this turns into a net gain of €4.28/ha over 3 years. Similarly, using the pH map from year 1 to apply lime for 3 years only in the areas were lime was initially required leads to a net gain of €6.44/ha estimated (Weisz et al, 2003).

Field studies have shown that variable rate application of lime, as opposed to uniform application, increases soil pH, reduces in-field variability and increases soybean yield but not corn yield (Pierce and Warncke, 2000). In 75% of the studies (4 in total) reviewed by Lambert and Lowenberg-DeBoer (2000) investigating VR lime, a positive economic effect was found, while in 25%, the articles indicated mixed results. The lime application can be more effective in legumes than in corn and wheat, as the response of the latter is limited to pH 5-5.5, where in legumes this can go up to pH 6 (Weisz et al, 2003). Kuang et al. (2014) found an increase in lime consumption but also an increase in yield and net profit (€3.61/ha) for the VRT approach compared to the traditional approach for Danish spring barley. BonGiovanni and Lowenberg-Deboer (2000) found an increase of €6.51/ha for Indiana corn and soybean production systems.

5.3.2 Variable rate irrigation

5.3.2.1 Description

Variable rate irrigation (VRI) can either be executed using a retrofitted self-propelled irrigation systems or more recently micro-irrigation. The main types of self-propelled irrigation systems are centre pivot and linear move sprinkler systems that apply water above the canopy of the irrigated crop (Berne, 2015). The most used self-propelled irrigation systems are the Mid Elevation Spray Application (MESA) with irrigation efficiency of 85%. New developments are the Low Energy (elevation) Precision Application (LEPA) and Low Energy (elevation) Spray Application (LESA) with irrigation efficiency around 97% (www.csanr.wsu.edu).

VRI systems are commercially available and can easily be retrofitted onto moving sprinkler systems. There are different methodologies available to deliver varying irrigation amounts along a lateral. One approach is to use parallel sprinkler control (McCann et al., 1997; King et al., 1999) or multiple manifolds; each valved separately (Omary et al., 1997, Stone et al., 2006). Another is to regulate the flow of water through each sprinkler drop hose by controlling the “on/off” cycle of a hydraulic valve positioned above the drop hose (Dukes and Perry, 2006; Han et al., 2009; Chavez et al., 2010). A third design changes the cross-sectional area of a sprinkler nozzle by cycling a retractable pin in and out of the nozzle in a controlled manner (King and Kincaid, 2004).

The most common site-specific sprinkler irrigation systems in use today are **speed control systems** (Evans et al., 2013). However, **zone (=boom section) control** systems can achieve the same effects provided by speed control, but with greater flexibility, and provide more management options. In Europe, both centre pivot and linear move sprinkler systems are applied with a preference in the latter, in contrast to USA where centre pivot is the most common. A company providing solutions for both centre pivot and linear moving systems is Valley (www.valleyirrigation.com) that offers VRI speed control, VRI zone control and VRI prescriptions. Zimmatic by Lindsay (www.zimmatic.com) also offer a VRI system named Growsmart precision VRI that works on the principle of loading coordinates of different land parcels within a field with a common centre pivot or linear moving system and then control each nozzle separately to cover the irrigation needs of each parcel. Reinke (www.reinke.com) has in its product range VRI speed control, VRI zone control, and a VRI prescription program software for both centre pivot and lateral move systems. T-L irrigation (www.tlirr.com) has a series of products for advanced irrigation management in collaboration with CropMetrics (www.cropmetrics.com) that include Precision-link for web-based pivot control, T-L precision point control and even manual speed and dierection control for cheaper VRI.

Micro-irrigation, a high-tech type of VRI system, (drip or trickle emitters, micro-sprinkling & microspray, subsurface irrigation) is used in areas with very scarce water supply where high value crops are installed (orchards, vineyards), as they increase crop yield, use more efficiently water, maintain warmer soil temperature and might result in less pesticide use (Camp et al., 1998). This type of VRI is ideal for Mediterranean EU countries, where drip irrigation is already in extensive use due to water scarcity and such systems reduce further irrigation water use. There are limited commercial applications of micro-irrigation. Lindsay offers a system called Multi-Control that is controlled thought FieldNET application and provide flexibility and scalability to control pumps, valves, injectors and other components of micro-irrigation. Hunter (www.hunterindustries.com) has a series of products supporting micro-irrigation in terms of material and control.

5.3.2.2 GHG emission reduction potential

The contribution of VRI in GHG emissions is very important because the reduction in water use combines lower pumping energy needs and proper irrigation scheduling does not allow extreme soil water availability that promote N_2O emissions.

Computer simulation studies comparing conventional and ''optimized'' advanced site-specific zone control by centre pivot irrigation have reported water savings of 0–26% (Evans and King, 2012) that affect also GHG emissions as stated above. However, water savings depend very much on the soil (sandy soil will generate substantial water savings but heavy soils not (compared to surface irrigation systems). Even though, lower quantities of water irrigation is translated to lower pumping needs which is powered by either fossil fuel motors or electricity (indirectly producing GHG emissions if it is provided by fossil energy).

A review by Trost et al. (2013) compared N_2O emissions from irrigated and non-irrigated fields and showed that availability of reactive nitrogen compounds controls increased N_2O emissions under irrigation, in most cases. Increases of about 50% to 140% in N_2O emissions were reported. This shows that VRA irrigation may significantly influence N_2O emission from irrigated soils.

VR irrigation systems are based on reading coming from soil moisture sensing georeferenced using GNSS receivers in order to cover the water needs of the plants (keeping soil moisture between permanent wilting point and field capacity). Meteorological prediction of precipitation does not allow irrigation preceding a rainfall. Therefore, irrigation scheduling can also provide the time window for fertilisation to be executed in order to avoid provoking more GHG emission production through N_2O.

5.3.2.3 Impacts of Variable rate irrigation use on productivity and farm economics

VRI systems have been tested to identify their direct impact on water use reduction and indirect impact on farm productivity and economics. VRI systems can provide 8-20% reduction in irrigation water use (Sadler et al,2005). LaRue and Evans (2012) using centre pivot speed control determined that irrigation efficiency (the ratio between irrigation water actually utilized by growing crops and water diverted from a source) can be increased by more than 5% while if speed control is also combined with zone control then the irrigation efficiency can by further improved by 14%. HydroSense project applied VRI in three experimental fields with cotton in Greece and showed that variable irrigation in cotton cultivation achieved 5 to 34% savings in water consumption with yield impact that was rated between -18% to +31%. As a result, water use efficiency showed variation between -12% to +54%. It should be noted that negative results were only shown in one field that did not affect the total positive impact of VRI. HydroSense project calculated that VRI adoption in drip irrigation may cost up to 40€ per ha (HydroSense final report, 2013).

Few hard figures are available about the economics of variable rate irrigation. LaRue and Evans (2012) reported that speed control in pivot systems is simply activated by changing the control unit of the system with a cost of €1,321-2,202. As for zone control is a more complex system that can reach an investment of €10,570 up to €24,663. Tomasiewicz et al. (2013) indicated that VRI modification of centre pivot with control system may cost between €13,212 and €35,233. They also mentioned that in 2013 200 centre pivot systems (around 0.1% of all installed US pivots) were VRI enabled. However, it may be expected that adoption will be crop-value related: adoption will go faster in high-value crops. Threshold prices can be calculated for specific crops. E.g. for precision irrigation in the Texas High Plains, it was calculated the threshold of cotton price to be set above €1.40/kg to make the use of precision irrigation profitable (Seo et al., 2008).

Lambert and Lowenberg-DeBoer (2000) reported economic benefits of the use of VRI, more specifically on corn yield and on water use efficiency. However, these benefits were not described in numbers. As mentioned above, VRI systems can add significant cost to a farm, but additional benefits have been identified by the installation of such systems, such as possible yield increase, work load reduction, water use reduction and even pesticide use reduction, especially in climatic unfavourable years like in big draughts (Booker et al, 2015; Evans et al, 2012; Sadler et al, 2005). For water use reduction, Hedley and Yule (2009) tested different scenarios for New Zealand and showed significant potential water savings of 21.8–26.3% for VRI. These potential water savings suggest that VRI will become more affordable as irrigation costs increase (Hedley & Yule, 2009).

Daccache et al. (2015) estimated the benefit to the grower in the reduced cost of water and energy to be typically around 30 euro/ha to areas that are over-irrigated in humid climates. These authors also claim that the development and uptake of PI would need to be justified more in terms of the wider benefits to crop quality and reduced environmental impacts.

Currently, no economic data about VR micro-irrigation is available because VRI combined with micro-irrigation is still in its infancy.

5.3.3 Machine guidance

5.3.3.1 Description

Machine guidance refers to the applications of GNSS for steering and guidance though two main systems: driver assistance and machine auto-guidance. Driver assistance helps the driver keep his line in the field through add-ons that are not integrated in the tractor's systems and can be simply installed. The most common driver assistance system is the lightbar guidance system that consists of a horizontal series of Light Emitting Diodes (LEDs) in a plastic case in front of the operator, so he or she can see the accuracy indicator display without taking their eyes off the field. If the light is on the centreline of the lightbar, the machine is on target, while if a bar of light extends to one side, the machine is off the path and needs to be corrected. Auto-guidance is a more advanced navigation systems that have the additional benefit of automatic steer of the tractor, also called auto-steering. Machine auto-guidance systems are integrated in the tractor's hydraulics and can directly take over steering operations. These more advanced systems are coupled to on-board computers that allow for headland steering, section control and that accept drive-maps (routing) and task maps to operate implements. Auto-guidance helps farmers in avoiding gaps and overlaps in multiple passes with the tractor, which is mainly caused by operator error or fatigue. It is the most adopted PAT because the impact on the farm is measurable and accurate. However, farm size matters for the technology to provide tangible results, especially in terms of environment.

5.3.3.2 GHG emissions reduction potential

Guidance technologies improve pass-to-pass efficiency, reduce overlapping and application gaps. Guidance can be used for many field operations such as seeding, tillage, planting, weeding, and harvesting (Abidine et al., 2002) and for enabling autonomous vehicles. Therefore, it is expected that all main agricultural inputs (seeds, fertiliser and pesticides) will be reduced.

Guidance technology saves as standalone fuel of the self-propelled machine and inputs (fertilisers, pesticides) even if implements used are conventional type. In case it is combined with VRA of agricultural inputs, they are also reduced further. An example is the work of Shockley et al. (2011) where machine guidance during planting and fertiliser application led to cost savings of approximately 2.4, 2.2 and 10.4% for seed, fertiliser and tractor fuel, respectively. This savings are also translated to GHG emission mitigation. Guidance systems like lightbar and auto-steering can reduce fuel consumption by 6.32% (Bora et al., 2012).

Machine guidance is based on high accuracy GNSS receivers and can be used with all kind of VRT machinery. As GNSS increases the accuracy of field applications, it will increase the reduction efficiency of the technology itself. As machine guidance is indirectly interconnected with the recording technologies, this combination is expected to reduce GHGs.

5.3.3.3 Impacts on productivity and farm economics

Guidance systems like lightbar and auto-steering can benefit crop growers by reducing working hours as operators in the field) of 6.04% and reducing fuel consumption of 6.32%, respectively (Bora et al., 2012).

In peanut digging operations a study revealed average net returns between 83 and 612 €/ha for the use of auto-steering (Ortiz et al., 2013). More particularly, they identified that increasing the peanut digger efficiency by accurate placement over the target rows could minimize damaged pods and yield losses. Therefore, they studied row deviation between manual driving (90-180 mm) and RTK auto-steering system (0 mm). Data showed that for every 20 mm row deviation, expected yield loss was 186 kg/ha. When RTK auto-steering system was used the expected additional net returns from row deviation of 90 mm was 83 to 356 €/ha and from row deviations of 180 mm was 285 to 612 €/ha.

An economic analysis of farms adopting auto-guidance systems showed that systems with inaccuracies below 2.5 cm are most profitable for larger farms, while systems with less than 10 cm inaccuracy are a better economic alternative for smaller farms (Bergtold, et al., 2009). The accuracy level of these systems is based on the quality of differential correction and internal data processing (as the accuracy improves, the corresponding cost increases).

Farmers identify as the most frequently mentioned disadvantage of machine guidance the up-front cost (Virginia Cooperative Extension, 2016). Machine guidance has scalable cost according to the accuracy obtained from each system. When a GNSS device is already held by the farmer the cost starts from €1,320. Commercial applicators that require a system that combine recording of all operations (to different customers) together with full navigation can reach more than €12,770. A fully automatic navigation system with operator engagement only at field ends could range from €5,284 to €44,040. It is important to select between simple swathing aids like foam-marker systems that cost between €440 and €2,642 and machine guidance systems. As a rule-of-thumb, a navigation system could cost six times more than a foam-marker system, which means that justification for GPS navigation over foam markers must be computed from the benefit side.

Machine guidance can have a variety of indirect economic impacts that are due to the accurate application of different agricultural practices. For example, it is complicated to estimate the economic impact of sprayer skips as influence of weed control on crop yield varies by crop and weed population and long-term weed seed-bank effects have to be evaluated and assessed. When a field is relatively weed-free, the skip impact to yield-loss might be minimal, but in a heavily infested field the yield may drop to almost zero in the skipped area. The most important about pesticide application gaps in economic terms is the creation of a weed seed bank all through the field that will lead to management problems and greatly increased weed control costs in future years. Another case is the impact of application gaps in fertilizer application, because skipping a part of the field is more costly in a high-value crop (fruits and vegetables) than in a bulk commodity such as corn, soybeans, or wheat. Similarly, lime application gap impact in yield in a field at pH 5.8 will probably be low during the first year, but will increase in later years (Virginia Cooperative Extension, 2016).

5.3.4 Controlled Traffic Farming (CTF)

5.3.4.1 Description

Controlled Traffic Farming is a system which confines all machinery loads to the least possible area of **permanent traffic lanes**. It is based on machine guidance, but it keeps record of each field and application in order to follow the same route every year. CTF allows optimised driving patterns, more efficient operations (i.e. reduced overlaps) and targeted input applications. It increases sustainability by reducing soil compaction and allows farming intensification as it prevents yield loss, nutrient and water efficiency reduction, soil degradation and alleviation costs.

5.3.4.2 GHG emission reduction potential

CTF can reduce GHGs emissions as it affects the quantity of agricultural inputs used in field operations (fuel, fertilisers, and pesticides). A study on the potential impact of site-specific application and controlled traffic systems implemented on larger farms in Denmark (300 ha and above) has stressed how a reduction of fuel costs by 25-27% in cereals can be traced back to a lesser overlap, but also how 3-5% savings in fertiliser and pesticide in cereals can be obtained (when fertilizers and pesticides are applied in a conventional manner) (Jensen et al., 2012). In the same work, fuel reduction is mainly due to ease of cultivation (loose soil due to minimum compaction) and of course due to minimum overpassing. Better soil structure means that conditions will be more favourable for gases that are absorbed into the soil (e.g. CH_4) and to prevent harmful gases being produced through anaerobic conditions, such as N_2O and CH_4, both of which are particularly damaging to the environment. The greater number and larger size of pores in a non-trafficked soil means that more water infiltrates and is captured within the profile. This means that not only is there less potential for run-off and erosion but also that there will be more plant available water that will probably increase yield. Higher yields can be translated into increased carbon stock in the crop itself, but also will reduce GHG emission intensity as even if all agricultural inputs remain constant their ration with yield will decrease.

Tullberg, 2016 has analysed the impact of CTF in GHG emissions directly and indirectly, by reducing energy inputs, facilitating zero tillage and increasing fertiliser efficiency. Primarily, he referred to **fuel** energy that in comparison to conventional, tillage, tractor fuel requirements of uncontrolled traffic zero tillage and controlled traffic zero tillage farming are reduced by approximately 40% and 70% respectively. The CTF effect is a result of improved tractive efficiency and reduced draft at planting, reduced rolling resistance at harvest and spraying operations, and the total elimination of tillage. Then, he went through **herbicide** energy, where he explained that there is work in literature about how zero tillage affect herbicide energy requirements, but not about how CTF reduce herbicide requirement. According to this author, the reduction is due to more timely spraying from permanent lanes and the overall mean reduction can reach 25%. **Fertilizers** were also referred, as in CTF they are not applied to permanent wheel tracks, which is translated to fertilizer cost reduction of 10-15% for narrow-spaced crops, while yield increases by about the same amount. CTF will also increase **nitrogen efficiency** (40-80%) due to reduced soil compaction and improved soil biological activity when CTF is applied. In addition, as nitrogen fertilisers are applied at seeding time in a moist compacted seed zone with limited drainage, it is expected that denitrification is increased and as a consequence N_2O will also increase. However, CTF will minimise this problem because it reduces seed zone compaction and waterlogging and allows the farmer to split fertilizer applications with denitrification reduction as a side effect. Finally, it was explained that CTF increase **soil carbon stock** as it reduces soil disturbance and improves the potential for cropping to mimic natural vegetation in maximising dry matter production (and water use) by double cropping or cover cropping.

5.3.4.3 Impacts of the use of CTFC on productivity and farm economics

Heavy machinery passing on soil causes damage mainly due to compaction especially in wet conditions. If traffic is reduced or stopped, soil becomes more friable, it requires little or no tillage and its structure gets better year after year. CTF reduces compaction by confining wheels or tracks to the least possible area of permanent traffic lanes. CTF is used to create and maintain healthy soils and crops in combination with sustainable farm profit. According to CTF Europe (2016), CTF typically releases 57-115 €/ha extra profit including the required investment, cost savings and increased yields. **Investment** has to do with the machine guidance installed in the agricultural machinery in use (tractors, self-propelled sprayers, harvesters) and it was analysed in machine guidance section. Cost savings include improved **field efficiency**, **less tillage** and significant capital **savings on machinery** due to lower powered tractors needed.

Field efficiency is increased by reducing agricultural inputs and simultaneously increase yield. Using CTF can decrease fertiliser use by 10-15% for narrow-spaced crops and pesticide reduction can reach 25% (Tullberg, 2016). Horsch (2016) pointed out that fuel use for crop establishment with CTF is reduced by at least 35%, while Jensen et al. (2012) estimated that it may be possible to reduce costs of fuel by 25-27% in cereals due to less overlap. Horsch (2016) also mentioned that time and energy for crop establishment can even be reduced by 70%. Horsch (2016) mentioned that CTF increase yield about 15% more (averaged across 15 crops) than randomly trafficked soils as a result of improved root growth that uses water and fertiliser more efficiently. CTF is focused on the compaction where the system in Australia already is showing yield gains of 15% in sandy soils and 5% in heavier soils. CTF Europe (2016) studied a 1400 ha wheat/oilseed rape rotation farm converted from minimum tillage farming to CTF no tillage and they found out that yield was increased by 4% in wheat and 7.5% in oilseed rape.

In addition, machinery costs are reduced as lighter machines with less power are needed. According to CTF Europe (2016), some farmers in Australia have cut their machinery costs by as much as 75% while their crop yields have risen. Horsch (2016) explains that CTF planning can lower the costs, because on the one hand existing equipment may be enough for the new farming system and on the other farmers converting to CTF can sell a lot of their equipment and invest in lower powered tractors (15% more profit and 20% reduction in machinery costs have been recorded).

Blackwell et al. (2013) reported that the total cost for adopting CTF varies significantly from farm to farm due to farm's equipment level. It ranges between €21,140 and €52,850, while 21% of the Australian farmers used CTF in 2011. CTF Europe (2016) studied a 1400 ha wheat/oilseed rape rotation farm converted from minimum tillage farming to CTF no tillage and they found out that farm profit was increased by 8% and the return on capital investment was 14%. They also got €290,000 savings on machinery investment. CTF Europe (2016) identified the cost of UK consultants (€927 plus expense and VAT) for providing farm survey to the farmer, including the present production constraints, the machinery and equipment requirements to apply CTF and an estimation of increase in profit. If the farmer requires a full action plan to install CTF the service cost is increased to €1,390 plus expense and VAT.

5.3.5 Variable rate pesticide application

5.3.5.1 Description

Variable rate pesticide application (VRPA) technologies enable changes in the application rate to match actual or potential pest stress in the field and avoid application to undesired areas of the field or plant canopies (Karkee et al., 2013). In some cases, they can also be used to apply fertiliser at variable rates (Ess et al., 2001).

There are two types of VR pesticide application technology. The **map-based VR pesticide application** adjusts the application rate based on a prescription map, using a GPS receiver to identify the field position and the input concentration is changed as the applicator moves through the field (Grisso et al., 2011). The **real-time sensor-based VR pesticide application** changes the application rate using the current situation of pest stress or canopy characteristics that is identified by the difference on colour, shape, size, texture, reflectance, and temperatures of pests that is detected by different sensor types (colour cameras, photodetectors, laser scanners, multispectral and hyperspectral cameras, thermal cameras, and ultrasonic sensors). The sensor input can also be used to control the direction and rate of chemical application (Karkee et al., 2013). VR pesticide application technologies use other PATs (GNSS, machine guidance, crop sensing, and leaf wetness sensors) to apply the optimum pesticide quantity site-specifically.

One example of a commercial unit is the **WeedSeeker®**, which is equipped with a reflectance sensor that identifies chlorophyll. Finally, Rometron (www.rometron.nl) has produced WEEDit that is based on fluorescence. By emitting red light by the sensor, the chlorophyll of the plants shifts this into infrared light, which is then detected by the WEEDit detection sensor. With this information the position of the weed is been determined and a solenoid valve will be activated to spray just the weed.

5.3.5.2 GHG emission reduction potential

Pesticide application using variable rate technologies have the advantage of applying reduced quantities of pesticides, not exceeding the application rate indicated for the diagnosed disease (e.g. fungicides), or enemy (e.g. insecticides) or weed type (e.g. herbicide).

This means that the crop yield will not be affect negatively, as the enemy or rival will be treated at lease as efficiently as before. At the same time, the reduction of chemical application will affect the quality of the final product that could increase farm profitability due to increase product prices.

The environmental benefits from pesticide application reduction are numerous as ground and water contamination is reduced and the influence on biodiversity becomes lower (Timmermann et al., 2003). In addition, limiting insecticide use and precision application of pesticides to only infested spots, provide floral resources and shelter habitats that can increase the abundance, diversity and fitness of natural enemies, decrease pest damage, increase crop yield and the farmer's profit (Vasileiadis et al., 2013). As shown in Beck et al. (2016) there is significant work on the saved pesticide quantity that ranges from 11 to 90% for herbicide use in different arable crop types (Gerhards et al., 1999; Heisel et al., 1999; Timmermann et al., 2003; Dammer and Wartenberg, 2007). Other work recorded pesticide use in perennial crops between 28- 70% (Solanelles et al., 2006; Gil et al., 2007; Llorens et al., 2010; Chen et al., 2013). VR pesticide application can also cause reductions in insecticide use by 13.4% in winter wheat (Dammer and Adamek, 2012). They also reduce significantly spray overlap that can also reduce the total pesticide use (Batte and Ehsani, 2006).

The impact of the high pesticide reduction shown from the literature is environmentally significant, but in terms of GHG emission reduction the contribution of this technology to the total agricultural effect is slight. The reason is that in this case GHG emissions are mitigated only during the industrial production of the pesticide. Even if the index of GHG emission production for every kg of pesticide is very high in comparison to other agricultural inputs (seed, fertilisers, fuel), the total applied quantity is very low mirroring in a low total impact on GHGs (IPCC, 2007).

5.3.5.3 Impacts of the use of variable rate pesticide technologies on productivity and farm economics

Benefits of variable rate pesticide spraying are mainly associated with savings on pesticide use. Since most research has been done in the area of herbicide application (vide supra), the focus of this section lies on the economic impact of VR herbicide application.

Oriade et al. (1996) suggest that weed patchiness is the most important factor economically justifying the use of site-specific weed control. Using simulation, they show that economic and environmental benefits are almost zero at low weed pressures, particularly if weeds are evenly spread. The benefits were larger as weed populations and level of patchiness increased. At high weed patchiness, return values of 17 €/ha to 33 €/ha were found in corn and soybean. The authors concluded that returns from site-specific management of less than 14 €/ha are not sufficient to warrant the practice. The costs of information collection, time application effects, and human capital were not considered in this model.

Besides pesticide saving, more savings are possible from shorter times per hectare for filling the tank and carrying the spray mixture to the field by reducing the volume that is needed per hectare (Timmermann et al., 2003).

Swinton (2003) states that research results on the profitability of site-specific weed management are very variable, because certain studies focus only on potential reduced cost from less herbicide spraying while ignoring the increased capital cost of variable rate application equipment and the increased variable cost of information processing. Other studies do take these last two factors into account, which results in more realistic numbers on profitability. Timmermann et al. (2003) found that the monetary savings resulting from the reduction in herbicide use varied between crops, depending on the amount of herbicides saved and the price of herbicide. In maize, winter wheat, winter barley and sugar beet, savings of respectively 42 €/ha, 32 €/ha, 27 €/ha, and 20 €/ha were realised. In this regard, savings also depend on the different economic thresholds for pest control and the different competitive power of the crops. Batte and Ehsani (2006) estimated spray material savings of about 4 €/ha for a map-based spraying system compared to a self-propelled sprayer without any form of GPS for guidance assistance or sprayer control. The magnitude of input savings further increased as waterways were added to the field. Those authors also calculated the costs of the map-based spraying system: 2911 €, 3004 € and 3096 € per year in extra costs for sprayers with a boom width of 18.3, 27.4 and 36.6 meter, respectively. Most of the costs are related to the fixed investment which diminishes per hectare as farm size increases. They also conclude that the benefits increase proportionally to the cost of the pesticide being applied, the number of annual applications, and to the driver error-rate of the non-precision spraying system.

Gerhards and Sökefeld (2003) evaluated the economic benefits of a real-time, automatic, site-specific weed control system compared to conventional field spraying. They found that although the costs (fixed + variable) for the VRA technology were larger (9.56 €/ha vs. 5.20 €/ha), the average costs for weed control were lower due to herbicide savings (32 €/ha vs. 68 €/ha in winter wheat and winter barley, 69 €/ha vs. 148 €/ha in sugar beet, and 96 €/ha vs. 103 €/ha in maize). Based on these economic calculations, Dammer and Wartenberg (2007) comment that if sensors were available on the market, it would be profitable for farmers to invest in variable rate technologies.

Costs of map-based VRA are attributed to mapping, data processing, decision making and site-specific application technology. Commercial mapping services typically charge 4.5 – 9.0 €/ha to map field boundaries including waterways and other physical features (Batte and Ehsani, 2006). Gerhards and Sökefeld (2003) estimated the costs of a direct injection system at 3.9 €/ha (in addition to the costs of the sprayer) for weed control in sugar beet, maize, winter wheat and winter barley in a German study. Batte and Ehsani (2006) state that the extra cost of a precision sprayer equipped with individually controlled nozzles based on GNSS information would be about €8,000. However, Timmermann et al. (2003) comment that several components of variable rate technology, including GNSS, board computer and GIS, can also be used for other precision farming activities such as planting, fertilisation and harvest, and can therefore not be considered as a cost that is solely related to VRA pesticide application.

In contrast to map-based VRA, an additional step of generating an application map with the help of GIS is not necessary. Therefore, there are no additional costs for computers, GIS software or DGPS. However, the sensor technology can be very expensive, although cheap sensors are available as well. Gerhards and Sökefeld (2003) estimated the cost of a camera system for weed detection at 40,000 Euro, whereas Dammer and Wartenberg (2007) used an optoelectronic weed sensor of about 2,000 Euro. The latter could however not distinguish between crops and weeds and was therefore limited in its operations.

In a study of Vasileiadis et al. (2011) on maize-based cropping systems, experts within Europe evaluated that precision spraying using GPS spray maps can result in a net profit within a time frame of 3-4 years.

5.3.6 Variable rate planting/seeding

5.3.6.1 Description

Variable rate planting/seeding (VRP/VRS) is the method of varying the rate of plants or seeds according to local soil potential. Regular planters/seeders are based on the constant rate of plants or seeds through a ground drive wheel, while VR systems is equipped with independent gear box or hydraulic drive that is controlled according to the needs of the certain part of the field (Grisso, 2011). More advanced systems have independent planting/seeding elements that can also differentiate the application rate on-the-go per row (Trimble, 2015). A prescription map is required. VRP/VRS eliminate double planting in headlands and point rows and in very heterogeneous fields redistribute within field seeds in the optimum quantity. VRP/VRS can perform better in heterogeneous fields because seed rate differentiation will affect the yield in low crop performance zones and the final output will be in favour of the farmer.

5.3.6.2 GHG emission reduction potential

When applying VRP/VRS tt is possible that the total plant/seed quantity used in the field will be lower (less GHG emissions coming from the production of the plant or the seed) or the same as in conventional seeding. Nevertheless, an effect of VRP/VRS on GHG emissions can be expected through the increased yield reported by Hörbe et al. (2013). Another means of GHG reduction is the decreased fuel required for generating the same amount of harvest, since through VRP/VRS more harvest can be produced on a given soil surface.

5.3.6.3 Impacts of the use of Variable rate planting/seeding on productivity and farm economics

The main benefit from VR planting/seeding is an increase in yield (vide infra). The main factor driving the economic performance of variable-rate seeding is soil variability. In very uniform fields, the return on investment of VRA planting/seeding will be low, while in heterogeneous fields with differentiated performance zones, the return on investment will be much higher. In the early years of VRA planting/seeding development, its economic impact was unclear.

Variable seeding rate of winter wheat can offer increase in yield from 3% compared to uniform seeding (Decisive Farming, 2016). Another research showed that farmers using variable rate seed have achieved an average winter wheat yield benefit of 4.6% over and above farmers drilling at a flat rate. This makes the average winter wheat yield benefit over the four years of study (2011-2014) to be 6.45% (IPF, 2016). Corn yields can be increased by 6% using variable rate seeding (AgPhD, 2016). Although VRA seeding dates back at the first years of precision agriculture movement it is now the time that its importance was acknowledged by farmers. Specifically, 10-12% climb in acquisition of VRA drills and planters was noticed in USA in 2007 (Cotton Growers, 2007).

Bullock et al. (1998) observed differences in economically optimal plant densities for different field qualities: they estimated that areas of the field with higher yield potential could benefit from a higher plant density. At the time, they concluded that variable rate seeding would be infeasible, because of the high cost associated with characterizing site variability. In the same year Lowenberg-DeBoer (1998) stated that the investments necessary for adopting variable rate corn seeding would only be economically justifiable for farmers with some low yield potential land, where significant seeds savings and yield gains can be made, but not for farmers with a mix of solely medium and high potential land. Taylor and Staggenborg (2000) concluded that variable rate seeding was only economically feasible on their fields of study if less expensive ways to generate the prescription map were available or if corn showed a greater yield response to seeding rate. In 2004, Shanahan et al. stated that "site-specific management of plant densities may be [ed: economically] feasible", most likely due to technological advances. Dillon et al. (2009) performed sensitivity analysis with respect to alternative soils, seed price, wheat price and cost of variable rate seeding technology to determine the economic feasibility of variable rate seeding and concluded that the practice of VRA seeding of wheat in France is economically feasible.

In more recent years, Hörbe et al. (2013) performed two experiments that tested the economic returns of VRA seeding maize according to a prescription map with three management zones, i.e. a low crop performance zone (LZ), receiving 31% less seeds/ha, a medium crop performance zone (MZ), receiving the normal seeding rate, and a high crop performance zone (HZ) receiving 13% more seeds/ha. This resulted in a yield increase of 1.20 and 1.90 tons/ha in the LZ of the two experiments, and 0.89 and 0.94 tons/ha in the HZ. In the second experiment, carried out one year after the first, in growing season 2010-2011, this resulted a partial net income (excluding extra costs for the VRA seeder) that was around 7% higher than in the same field seeded with a flat rate over the entire field. 71.5% of this higher net income was gained in the LZ, although the LZ area was smaller than the HZ area (22% vs 28% of the total field area, respectively).

A study of automatic section control systems in planters among 52 fields showed a percentage of double-planted area to reach up to 15.5% and the savings from the use of PA planters ranged from €3.5 to €22.9 per ha depending on the farming operation and the field type (Velandia et al., 2013).

No independent scientific research on the economic impact of multi-hybrid planting/seeding is currently available, because this technology has been developed very recently.

5.3.7 Precision physical weeding technology

5.3.7.1 Description

Precision physical weeding technology is the method of weed control through burning, mechanical weed control with knives, discs, hoes or harrows with minimum crop damage and no chemical herbicide use. The technology is still in its infancy, with some prototypes that use precise guidance and detection systems being available.

The most promising approach for weed detection is a continuous ground-based image analysis system that locate crop row in the field (Martelloni, 2015). In this work is reported the design and development of an automatic machines able to perform, at the same time, mechanical and thermal weed control on maize. The equipment is coupled to an autonomous ground mobile unit equipped with a row and a weed detection system to remove weeds mechanically from the inter-row spaces of the crop and perform selective and targeted cross flaming, in the rows of the crop. The precision of the treatment is ensured by specific vision based perception system for weed detection and crop row detection. Mechanical treatment (inter-row cultivation) is performed in a continuous way, even without weed presence. The machine is provided with a guidance system managed by a crop row detection system in order to avoid damaging the maize plants with the rigid tools used for mechanical weed removal. On the contrary cross flaming on the rows of the crop is actuated only if weed patches are detected. The thermal weed control is applied by LPG fed rod burners, able to treat 25 cm wide strips with the crop row in the middle. The biological selectivity is ensured by maize high tolerance and weeds sensitivity to flame exposure for few tenths of seconds. Moreover, the LPG working pressure can be adjusted according to the level of weed cover detected by the weed detection system (low LPG working pressure, if weed cover is lower than 25%; high LPG working pressure, if weed cover is higher than 25%). Each unit for thermal weed control is provided with an ignition system able to properly switch on the burners at the selected LPG working pressure.

Other detection system would be ultrasonic sensors that detect plant density that when it is increased the harrow treats this part more aggressively (Peteinatos et al. 2015). In this work, a system for online weed control was developed. It automatically adjusts the tine angle of a harrow and creates different levels of intensity (gentle to aggressive). Discriminant capabilities of an ultrasonic sensor were used to determine the crop and weed variability of the field. A controlling unit used ultrasonic readings to adjust the tine angle, producing an appropriate harrowing intensity. Thus, areas with high crop and weed densities were more aggressively harrowed, while areas with lower densities were cultivated with a gentler treatment. Experimental filed work showed that weed control achieved by the system reached an average of 51% (20%–91%), without causing significant crop damage as a result of harrowing. This system is proposed as a relatively low cost, online, and real-time automatic harrow that improves the weed control efficacy, reduces energy consumption, and avoids the usage of herbicide.

A hybrid physical/chemical weeding system is mentioned by Norremark (2010). A robotic physical weeding system is applied in sugar beet that execute real-time weed infestation survey and apply 4 row intra-row precision weed control implement combined with 4 row precision spraying (10% of normal herbicide dose rate). It can also combine an inter-row weed control implement that increase its efficiency.

5.3.7.2 GHG emission reduction potential

Precision physical weeding technology might have an effect on reducing GHG emissions through the production of the avoided pesticides. In the case of mechanical precision weeding, fuel consumption will also be reduced (and the respective GHGs) because the tractor pulling the weeding implement will confront lower draught forces coming from soil tilling when the angle of the harrow tines will be less aggressive than with the conventional tillers (Peteinatos et al., 2015). In the case of precision thermal weed control, the fuel for weed burning is expected to be lowered reflecting in GHG emissions in comparison to conventional weed burning implements that have continuous flame covering all field surface. However, if thermal weed control is applied in fields that the conventional weeding is based in mechanical tillage then the GHGs from burning weeds will contribute negatively in climate change. In addition, when conventional chemical weeding is substituted from precision thermal weeding, the GHG emissions coming from pesticides reduction will be partially compensated from the emissions emitted from weed burning. As in the case of VR pesticide application, the impact on the avoided GHG emissions of the total agricultural system is expected to be very low.

5.3.7.3 Impacts on productivity and farm economics

The hybrid mechanical/chemical system showed total estimated cost reduction for 10-year depreciation and 5% interest rate was 12% (in particular 260 euros/ha, while conventional weeding cost 297 euros/ha) in a 80 ha field size working 667 hours per year. When the inter-row weed control implement is added to the system, the cost reduction can reach 24%. This is due to the reduction in total weed management costs compared to the conventional (Norremark, 2010). Peruzzi et al. (2008) worked on physical weed control in open field tomatoes by applying a rolling harrow and a flaming machine in pre-transplanting together with precision hoeing in post-transplanting. It was noticed that yield increased by 15-20% due to better weed management which resulted in 400-700 euros/ha on top of the normal harvest.

6 Skills requirements for the use of the selected precision agriculture technologies

Precision Farming Technologies are complex equipment which, as a prerequisite for their correct application need adequate knowledge and skills by the user regarding their operational system. However, traditionally "researchers invent things that are not picked up sufficiently and they often do not deal with issues that matter to farmers" (Rural Review, 2013). At the time being, the knowledge gap between research institutions/industries and every day users (advisors and farmers) is still wide and there is a need of bridging this innovation gap by increasing the skills of end-users.

Regarding farm advisers and farm advisory system staff, their training on PATs use and impact is a key issue to increase PATs benefits on farm productivity and GHG mitigation at farm level. As for farmers, informing and supporting them on PATs use is vital because awareness of the use complexity and of the benefits that could occur to their farm will be given to the ones that real-time implementation is on their hands. In addition, farmers will be informed about the important role they play or the parallel (non-personal) benefits behind PATs use.

Robert (2001) identified the existence of three challenges that farmers face in order to adopt PATs. These challenges include the socio-economic barriers, the agronomic barriers and the technological barriers. The socio-economic barriers refer to the costs and skills that are needed by farmers in order to adopt PATs. Specifically, surveys suggest that age, attitude and education level are highly correlated with the adoption of PATs by producers. On the other hand, the agronomic barriers are related with having basic terrain information, having knowledge on soil texture and nutrients, having sufficient crop monitoring, applying site-specific recommendations, applying efficient management and use of agronomic information and having PA specialized agro-consultants. Finally, the technological barriers are connected with the farm equipment level, the existence of GNSS, the GIS software and the remote sensing equipment.

Kitcen et al (2002) found out that the optimal value of information on PA will be best achieved by producers, agribusinesses and educators as they improve their agronomic knowledge and skills, their computer and information management skills and understanding PA as a system for increasing knowledge. The authors identified six steps to learn about PA: (1) spatial data management, (2) proper use of sensors like GNSS devices, yield monitors, remote sensors, VRTs (3) computer and software use, especially on GIS, (4) map analysis and prescription map production (5) site-specific management planning, (6) strategic sampling and on-farm trials.

CAP 2014-2020 Article 14 refers to knowledge transfer and information actions and requires from member states to take action to use funds for vocational training and skills development in the form of workshops, training courses, coaching, information actions and farm visits to foster the uptake of PA. It could facilitate, for instance, the sharing of relevant PA experiences on decision practices and impact measurements.

7 Conclusions

Climate change is a real fact and anthropogenic activities are one of the parameters accelerating the phenomenon. Through the years, agriculture did not receive the attention it should in terms of GHG emission production. In the recent past, detailed analysis of the impact of this sector has been executed and several mitigation measures were proposed.

PA has several positive impacts on agricultural systems and recently there is interest on the possible GHG emission mitigation through such techniques. However, literature is limited on data regarding the effect of PA in climate change.

According to the fact that most PATs have impact on the agricultural inputs (seed, fertilisers, pesticides, water and fuel) of a farm, it is expected that respective GHG emissions will also decline in some extend. An important comment would be that in extensive agriculture, where acceptable yield is based on the application of inorganic or organic N fertilisation, regular farm GHG emissions are mainly coming from this sector. Therefore, specific interest on VRA of N fertilisers has to be given in order to apply the least N required for optimum crop growth. If this is combined with meteorological projection and appropriate irrigation scheduling, then the right amount of N application could be executed at the right time and avoid extreme N_2O emission. The second most important PAT to reduce GHGs would be all kinds of machine guidance and especially CTF.

It is required that more research is conducted on GHG emission impact of PATs, as it seems that there is an opportunity to gain more from these technologies. Adoption rates of PATs could increase rapidly if such impact would be justified numerically.

Appendix A: List of PATs and PATs services indicative costs

PAT type	Description	Source	Price range for PAT (€)
Machine Guidance			
Guidance systems (GPS)	Guidance systems refer to the systems that are used for the tractor guidance. Lightbar guidance is an entry level guidance system that indicates to the tractor driver how to steer the tractor for following the most effective route during field operations. Mechanical steering is a system that aids to steering the tractor. Autopilot is a system that has the ability to fully control the steering system of the tractor without having any help by the tractor driver. There are different levels of accuracy according to the GPS equipment used such as WAAS (30cm), Radio Beacon (10cm), RTK (3cm).	Groover (2009)[15]	Lightbar Guidance System – 30cm Accuracy **1735 €** Lightbar Guidance System – 10cm Accuracy **4500 €** Mechanical Steering Systems - 10cm Accuracy **5800€** Auto Pilot Systems – 3cm Accuracy **36640 €**
		Price (2011)[16]	Lightbar **1830 €**, WAAS (Wide Area Augmentation System) **5500 €**, Omnistar **7330 €**, Radio Beacon **11910 €**, RTK (Real Time Kinematik) **19240 €**
VRA Seeding			
VRA seed drill (with GPS)	VRA seed drills are seed drills that have the ability to apply seeds in different densities. They use a field computer that computes the seed doses that must be applied by site specific needs (through sensor or map based prescription maps), by a GPS	Farm Industry News (2007)[17]	**16490-93420 €**

[15] https://pubs.ext.vt.edu/448/448-076/448-076_pdf.pdf
[16] http://www.bookstore.ksre.ksu.edu/pubs/MF2942.pdf
[17] http://farmindustrynews.com/high-performing-grain-drills

	unit that understands the tractor position on the field, by a microcontroller that receives information from the field computer and adjusts the seed doses accordingly and sometimes by sensor(s) that instantly measure the organic matter for applying seeds.		
VRA seed drill kit	VRA seed drill kit is a group of components that is implemented in a conventional seed drill for enabling it in precision agriculture. The key components of the system are microcontrollers for controlling the seed doses, a field computer that sends data to the microcontroller based on prescription maps and a GPS unit for the tractor.	Farm Industry News (2013)[18]	**12500-25500 €**
VRA Fertilization			
VRA spreaders (with GPS)	VRA spreaders have the ability to apply fertilizers in different doses to the site specific needs. These systems are consisted by field computer that computes the doses that must be applied by site specific needs (through sensor or map based prescription maps), by a GPS unit that understands the tractor position on the field, by a microcontroller that receives information from the field computer and adjusts the fertilizer doses accordingly and sometimes by sensor(s) that instantly measures the crop needs for fertilizers.	Cochran et al. (2004)[19]	**16030-35720 €**
VRA spreader kit	VRA spreader kit is a group of components that is implemented in a conventional spreader for enabling it in precision agriculture. The key components of the system are microcontrollers for controlling the fertilizer doses, a field computer that sends data to the microcontroller based on prescription maps and a GPS unit for the tractor.	The Daugherty Companies (2015)[20]	**4580-9160 €**
VRA Spraying			
VRA sprayer	VRA sprayers have the ability to apply different doses of spraying products.	Farmers Classified[21]	**30000-100000 €**

[18] http://farmindustrynews.com/planters/electric-variable-rate-planting-entrepreneur
[19] http://ageconsearch.umn.edu/bitstream/34678/1/sp04co01.pdf
[20] http://www.ag-electronics.com/2015_inside_pages.pdf
[21] http://classified.fwi.co.uk/browse/sprayers-and-spreaders

	VRA sprayers can be boom sprayers or orchard sprayers according to the crop type. These systems are consisted by field computer that computes the doses that must be applied by site specific needs (through sensor or map based prescription maps), by a GPS unit that understands the tractor position on the field, by a microcontroller that receives information from the field computer and adjusts the fertilizer doses accordingly and sometimes by sensor(s) that instantly measures the crop needs for spraying doses.	Silvan[22]	**53100 €**
		Gerhards and Sökefeld (2003) (The cost includes together the VRA sprayer, the weed detection system and the direct injection system)	**107000 €**
VRA sprayer kit	VRA sprayer kit is a group of components that is implemented in a conventional sprayer for enabling it in precision agriculture. The key components of the system are microcontrollers for controlling the spraying doses, a field computer that sends data to the microcontroller based on prescription maps and a GPS unit for the tractor.	TeeJet[23]	**9160-27470 €**
		Downey et al. (2011)[24]	**13740 €**
VRA Irrigation			
VRA Irrigation Equipment Adoption	VRA irrigation equipment is the equipment that is needed for applying variable rate irrigation. This equipment consists of sensors that detect crop water needs such as weather station, soil moisture sensors and actuators for applying accurate water doses such as solenoid valves.	HydroSense[25]	**<40 €/ha**
		Kim et al. (2008)[26]	**915 €**
PATs Services			
On the Go Soil Sensing	On the go soil sensing is a mapping service that collects soil samples for measuring soil parameters according to precision agriculture methods. Also,	Hurst et al. (2015)[27]	**6.5 €/ha**

[22] http://www.silvannz.co.nz/documents/catalogues/20121115112122_9.pdf
[23] http://www.teejet.com/media/463685/98-15014-r2%20eu-electronic%20teejet%20price%20book_final%20hi-res%202014-2015.pdf
[24] http://californiaagriculture.ucanr.org/landingpage.cfm?article=ca.v065n02p85&fulltext=yes
[25] http://www.hydrosense.org/eDocuments/annexes/Annex%207.2.13%20Minimum%20dataset_April14-2.docx
[26] http://pubag.nal.usda.gov/pubag/downloadPDF.xhtml?id=53900&content=PDF
[27] http://www.massey.ac.nz/~flrc/workshops/15/Manuscripts/Paper_Hurst_2015.pdf

	non-destructive methods for estimating these parameters can be used. Aim of this service is to produce prescription maps for variable rate fertilization and variable rate seeding in order to achieve the highest economic profit by managing in field variability.		
EO Crop Scouting and Services	Earth Observation based crop scouting services offer added value services to farmers by exploiting satellite data. These data are used for assessing crop status, providing yield estimation, delineating management zones and as a result producing prescription maps for variable rate applications (seeding, fertilization, spraying).	Space-tec (2012)[28]	**6-10 €/ha**
UAV Crop Scouting and Services	UAV based crop scouting services offer added value services to farmers by exploiting high resolution data collected from drones. These data are used for assessing crop status, providing yield estimation, delineating management zones and as a result producing prescription maps for variable rate applications (seeding, fertilization, spraying).	Wilkes (2015)[29]	**10-25 €/ha**

[28] http://www.copernicus.eu/sites/default/files/library/GMES_GIO_LOT3_Sector_Summary_Agriculture_final.pdf
[29] http://www.cornucopia.org/2015/02/uavs-awaiting-take-off-us-agriculture/

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ANNEX 3. Definition of relevant case studies and survey design

Definition of relevant case studies and Survey Design

Deliverable 3

PRECISION AGRICULTURE project

contract no. 199163-2015 A08-NL

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1 Introduction

A part of Task 3 is to propose relevant case studies (task 3.1). The aim of Task 3.1 is to identify a combination of regions in the EU, Precision Agriculture Techniques (PATs) and arable crop types that could realise the maximum potential economic and environmental benefits of adopting PATs. This report is the result of Task 3.1 of the project.

To achieve this task the consortium conducted a review of the relevant existing studies on the impacts of **Precision Agriculture Technologies (PATs)** regarding economic, social and environmental elements of agriculture.

The report aims to support the selection of relevant PATs that contribute to the reduction of greenhouse gas (GHG) emissions.

2 Case study selection

The aim of Task 3.1 is to identify a combination of regions in the EU, Precision Agriculture Techniques (PATs) and types of farms that could realize the maximum potential GHG emission savings of adopting PATs. Informed by the results obtained in Tasks 1 and 2 with respect to the appropriate typology of PA technologies, case studies are defined in terms of countries, appropriate PATs and arable crop types. In consultation with JRC staff members, a set of case studies are chosen. These cases are selected based on their PAT adoption potential as well as on the GHG emission potential savings through its use. .

In order to select the case studies for the evaluation of the application of PATs, several steps were undertaken to identify the robust and representative combinations of PAT x Country x Crop. Criteria were established for selection of the case studies. The selection criteria used are:

1. PATs that are available and adopted at present and that have the potential to reduce GHG emissions
2. EU regions where the PAT adoption potential is great focusing on
    2.1. Regions with large farms
    2.2. Regions with appropriate farm income
3. Selection of countries with high greenhouse gas emissions, particularly N_2O
4. Selection of relevant crops in the EU focusing on areal coverage and economic value of the crop

3 PATs that are available at present

To identify the case studies, PATs described in Deliverable 1 (Beck *et al.* 2016a) and selected in Deliverable 2 (Balafoutis, *et al.* 2016b) are summarised in Table 1. This table includes all the PATs that are available at present in the EU or have the potential to be available in the near future or by the year 2030. Because they reduce N_2O emissions and because they can be adopted in the EU context, Variable Rate Nutrient Application, Variable Rate Irrigation and Machine Guidance were identified in Deliverable 1 and 2 as the most promising PATs. For practical reasons these broad categories of PATs are used to define relevant case studies and not the subdivision of PATs in Table 1.

Table 1: Promising PATs resulting from work under de deliverables 1 and 2

Variable rate nutrient application (N, P, K, lime, manure)	
Inorganic, solid granules	Spinner spreader
	Pneumatic spreaders (airflow)
	Fertilizer drills
Inorganic, Liquid	VR pesticide sprayer technology
Organic, Slurry	Flow rate regulated by map information
	Flow rate regulated by map information and by online measurement of nutrient content
Organic, Solid	Solid manure spreaders
Variable rate irrigation	
Centre Pivot	Speed controlled
	Zone controlled
	Combination speed/zone controlled
Linear Move	Speed controlled
	Zone controlled
	Parallel sprinkler lines
	On / off cycling of nozzles
	Nozzle size regulation
Micro Irrigation (drip)	Zone controlled
	On / off cycling of nozzles
Machine Guidance	
Driver assistance	Light bar
	Auto steer
Machine auto guidance	Machine integrated
Controlled traffic farming	
Permanent traffic lanes	Permanent traffic lanes
Variable rate pesticide application	
Input system	Map based
	Real-time Sensor Based
Output system	Flow based control
	Direct chemical injection
	Chemical injector with carrier control
	Spraying nozzle control
Variable rate seeding	
Output system	Independent engine/gear box/hydraulic drive
	Independent planting/seeding elements per row
Precision physical weeding	
Input system	Image analysis systems
	Various other sensorsUltrasonic sensors
Output system	Guided harrowing, guded hoeing, guided flaming

4 EU regions where the PAT adoption potential is great

The likelihood of a PAT to be adopted increases when the PAT is able to fit into the farming systems and in turn provides a benefit from its application (Robertson et al., 2007). As a consequence, Eurostat data sources have been investigated to identify the following number of logical but not exhaustive routes for PAT adoption namely:

1. Farm size
2. Farm income

In the case of large farms, the application of a PAT is likely to be beneficial because its effect, even when it would be relatively minimal, becomes clear when it is applied over many hectares. Also application of a PAT requires initial investments which are most likely available in regions with an appropriate farm income.

Adoption of PAT requires a level of knowledge and ability to implement technology at the farm level (Robertson et al., 2007). The use of Global Navigation Satellite System (GNSS-navigation) on machinery is an important enabler to implement PATs. Nowadays, farming equipment is increasingly equipped with a GNSS receiver. Moving from Machine Guidance with GNSS to Variable Rate Application (VRA) requires additional expertise in preparing and utilising different data sources like for instance soil maps, yield maps and satellite imagery. Preparing these maps requires knowledge, software products for interpretation and GIS-mapping. At a more basic level, farmers must be aware that the technology exists and they must be convinced of its added value. The early adopters of PATs could therefore be large farms which are according to Eurostat farms greater than 50 ha, as well as farms with an appropriate farm income.

4.1 Regions with large farms

Figures 1 and 2 show the farm size distribution in hectares of Utilized Agricultural Area (UAA) at NUTS2 level across Europe. Large farms are classified as farms above 50 ha, medium farms between 5 and 50 ha and small farms below 5 ha (Eurostat, 2015).

Large farms are predominantly situated in France, UK and Germany (Figure 1). In order to realize the maximum potential economic and environmental benefits of adopting PATs we will focus on the predominantly large (>50 ha) farms (Figure 2). Thus the countries of interest are France, Belgium, the Netherlands, UK, Ireland, Germany, Poland, Denmark, Sweden, and Finland.

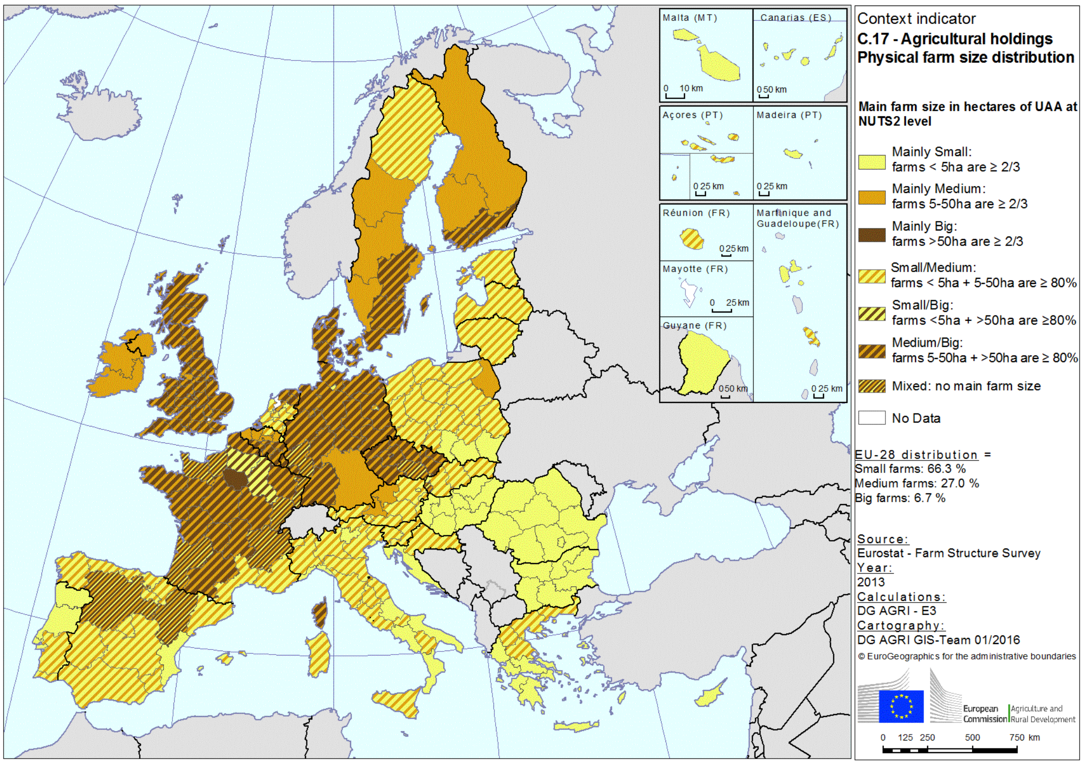

Figure 1: Main farm size in hectares of UAA at NUTS2 level (Eurostat 2015a)

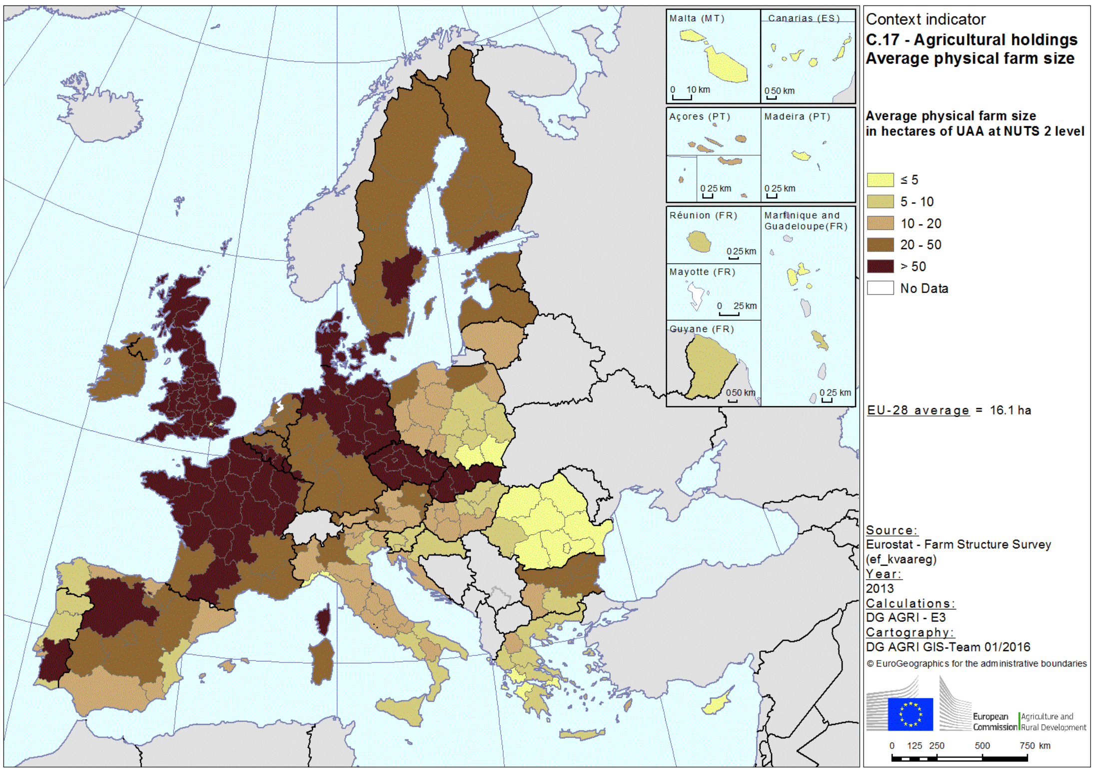

Figure 2: Average physical farm size in hectares of UAA at NUTS2 level (Eurostat 2015a)

4.2 Regions with appropriate farm income

Initial investments for adopting PATs are high and utilising high-tech equipment is intrinsic to application of PATs. The risk-return for small scale farmers will be too high, therefore early adopters of PATs are more likely to be farmers and farms which generate a relatively high income (Fountas et al., 2005). Figure 3 shows regions with economically big farms in terms of a high agricultural factor income (which is the amount of money generated by a farm to pay for land, labour and capital) per annual work unit. One annual work unit (AWU) corresponds to the work performed by one person who is occupied on an agricultural holding on a full-time basis. Full-time means the minimum hours required by the relevant national provisions governing contracts of employment (http://ec.europa.eu/eurostat/statisticsexplained/index.php/Glossary:Annual_work_unit_(AWU)

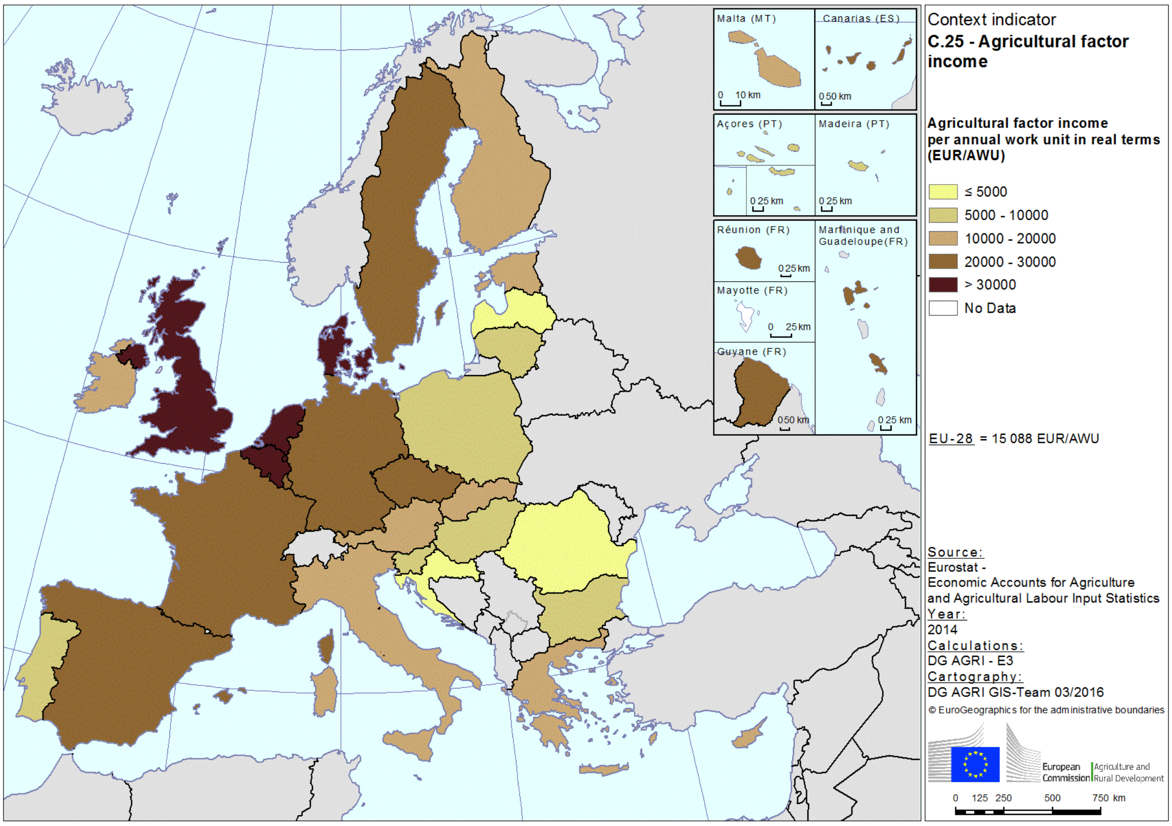

Figure 3: Agricultural factor income per annual work unit (Eur / AWU) per country (Eurostat, 2015a)

Based on Figure 3 it is concluded that the major areas where sufficient farm income is generated to pay for the application of PATs are the Netherlands, Denmark, UK, Belgium, France and Germany.

5 Selection of countries with high greenhouse gas emissions from agriculture

This project's rationale is concerned with the contribution of PATs to farm productivity and the mitigation of greenhouse gas emissions in the EU. Consequently, it is reasonable to focus the case study selection on regions with high nitrous oxide (N2O) emissions, as N2O is the most important GHG arising from crop production activities. For example, 93% of crop-production related GHG emissions in Europe were in the form of N2O in 2013 (Leip et al., 2014; personal communication dr. G.L. Velthof). In addition, as N2O emissions mainly arise from fertiliser, the reduction of fertiliser through PAT adoption, especially the adoption of Variable Rate Nutrient Application (VRNT), is improving the economics of the farmer. Where PATs contribute to a more efficient use of the applied N, it may also increase yield. Hence, areas with large N2O emissions provide a substantiated potential for PAT adoption.

Miterra (Oenema et al., 2007) modelling results are used for information on N2O emission rates (kg N/ha/year) at the NUTS2 level (Figure 4).

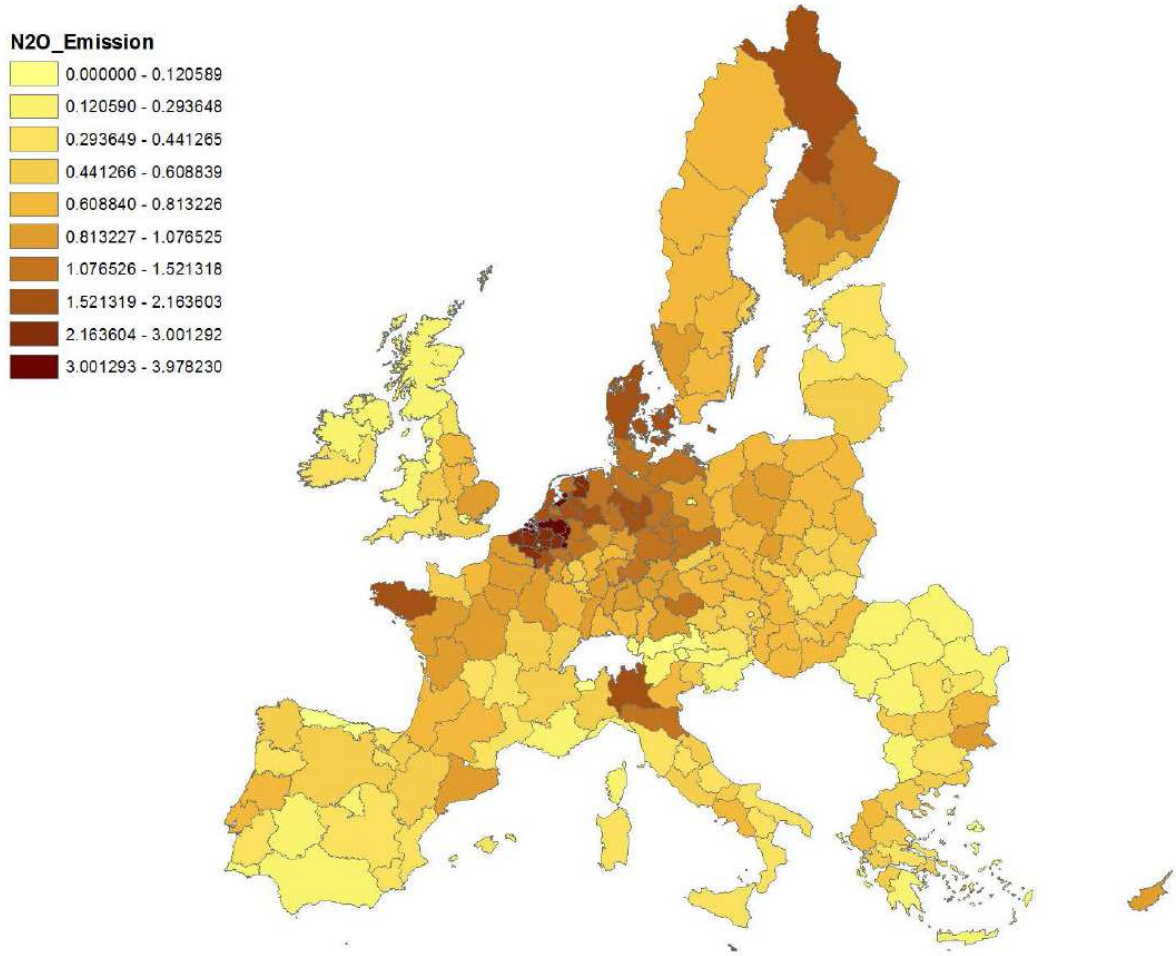

Figure 4: N_2O emissions (kg N / ha / year) resulting from mineral fertilizer application in Europe at NUTS2 level (Source MITERRA)

As one of the criteria of case studies selection is the EU country where the survey will be conducted, the NUTS2 level N2O emission (kg N / ha / year) results calculated by Miterra (Figure 4) were also aggregated at the country level (Table 2). The amount of N applied to the crop as mineral fertilizer is indicated by N-application in Table 2. Miterra is used to calculate N-surplus in Table 2 being the difference between N-application and N uptake by the crop. Next Miterra calculates the partitioning of N-surplus in emissions of N towards atmosphere and towards ground water. Miterra also calculates which part of the N emission to the atmosphere is N2O (Table 2). All values are in kg N / ha / year.

Table 2: N2O emissions (kg N / ha / year) in Europe per country (source MITERRA, Oenema et al., 2007).

	Napplication	N-surplus	N2Oemission
Austria	36	7	0.37
Bulgaria	59	29	0.59
Belgium	175	103	2.19
Cyprus	86	80	0.86
Czech.Rep	67	12	0.67
Germany	107	38	1.14
Denmark	124	36	1.70
Estonia	35	10	0.35
Greece	41	29	0.42
Spain	40	24	0.41
Finland	116	78	1.27
France	77	19	0.77
Hungary	64	25	0.65
Ireland	29	4	0.30
Italy	54	17	0.58
Lithuania	46	21	0.46
Luxembourgh	67	26	0.67
Latvia	35	10	0.35
Malta	160	143	1.60
Netherlands	162	93	2.46
Poland	69	34	0.75
Portugal	42	26	0.42
Romania	24	4	0.24
Sweden	68	-5	0.73
Slovenia	25	-7	0.25
Slovakia	50	16	0.50
UnitedKingdom	42	11	0.43
Europe	**62**	**23**	**0.66**

Table 2 shows that countries with the highest N2O emissions are Belgium, Germany, Denmark, Finland, Malta and the Netherlands (all dark green). These countries are potential case study candidates because application of PATs could have a large impact on emissions. Caution should be taken by solely basing the selection on a country basis, because for instance Brittany in France and Lombardy and Emilia-Romagna in Italy are NUTS2 regions with significant N2O emissions (as shown in Figure 4). Similarly, NUTS2 region areas will have a high N2O field emission rate, due to a high N field application rate. This 'dilution effect' at the coarser scale from field to region to country will be most prominent in countries with large extensively managed areas, such as for instance Scotland and Greece. For example, N field application rates to cereals in the UK are around 150 - 200 kg N / ha / year, and for grass 200 – 300 kg N/ha/year but this is not clear from Figure 4 and Table 2 due to this dilution of emissions.

6 Selection of relevant crops in the EU

Innovations like PATs are most likely adopted when a new technique has the potential to increase yield or farm income. Therefore, as costs can be reduced and/or yields can be increased with variable rates of fertiliser application, accrued profit must be higher than initial investment. Consequently, selection of relevant crops can be based on the large area the crop covers while the price per unit of crop is not maximal (medium or less value crops) as well as on a high price per unit of crop (high value crops) while the area the crop covers is not necessarily large. If these criteria are met it is likely that the cost of uptake can be paid back through accrued income from these crops. Furthermore, adoption within these large area or high value cropping categories could also lead to a follow up effect for application into other crops by the same farmer.

Eurostat data (Eurostat 2015a) were used to identify different land uses which occupy a sizeable area within the EU. Figures 5 and 6 show the major land uses, based on the Utilised Agricultural Area (UAA), per NUTS2 (Figure 5) and country level proportions (Figure 6) respectively.

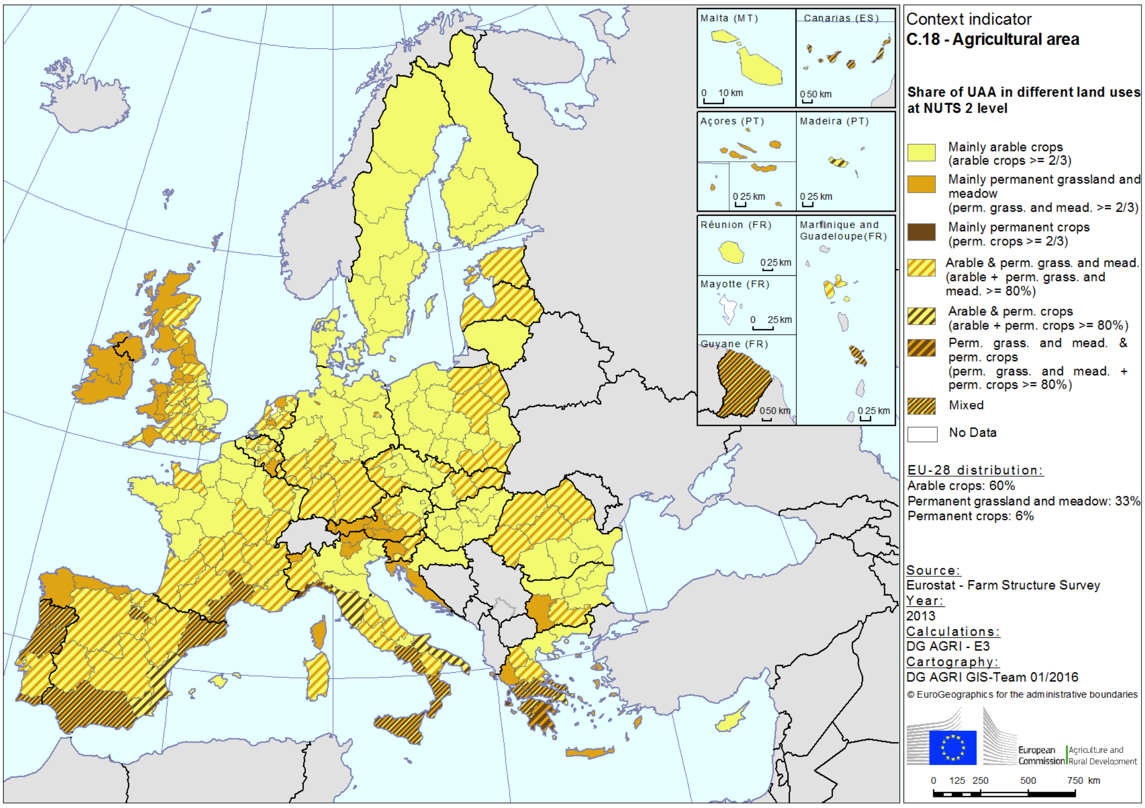

Figure 5: Share of UAA in different land uses (Eurostat, 2015a)

In addition, a more detailed analysis at crop level of Eurostat data for the year 2015 (Eurostat 2015a) per member state was performed (detailed results are presented in Annex II). Grassland and fallow land, which together add up to 39% of the arable production area in the EU, are not taken into account. Crops account for the remaining 61% of arable production area. These crops are shown below, where brackets identify the area share of the different crops in EU, as well as the number of countries where the crop share is more than 10% of the UAA of arable land:

- Common wheat and spelt (24%, 28 countries);
- Plants harvested green from arable land (Fodder) (17%, 25 countries);
- Barley (12%, 19 countries);
- Oilseeds (9%, 11 countries);
- Grain Maize and corn-cob-mix (8%, 9 countries);
- Olives (5%, 5 countries);
- Durum wheat (3%, 2 countries);
- Fruits, berries and nuts (excluding citrus fruits, grapes and strawberries) (3%, 1 country);
- Grapes (3%, 1 country);

- Oats and spring cereal mixtures (mixed grain) (3%, 2 countries);
- Triticale (2%, 1 country);
- Fresh vegetables (including melons) and strawberries (2%, 1 country);
- Rye and winter cereal mixtures (2%, 1 country);
- Potatoes (including seed potatoes) (1%, 2 countries);
- Sugar beet (excluding seed) (1%, 2 countries).

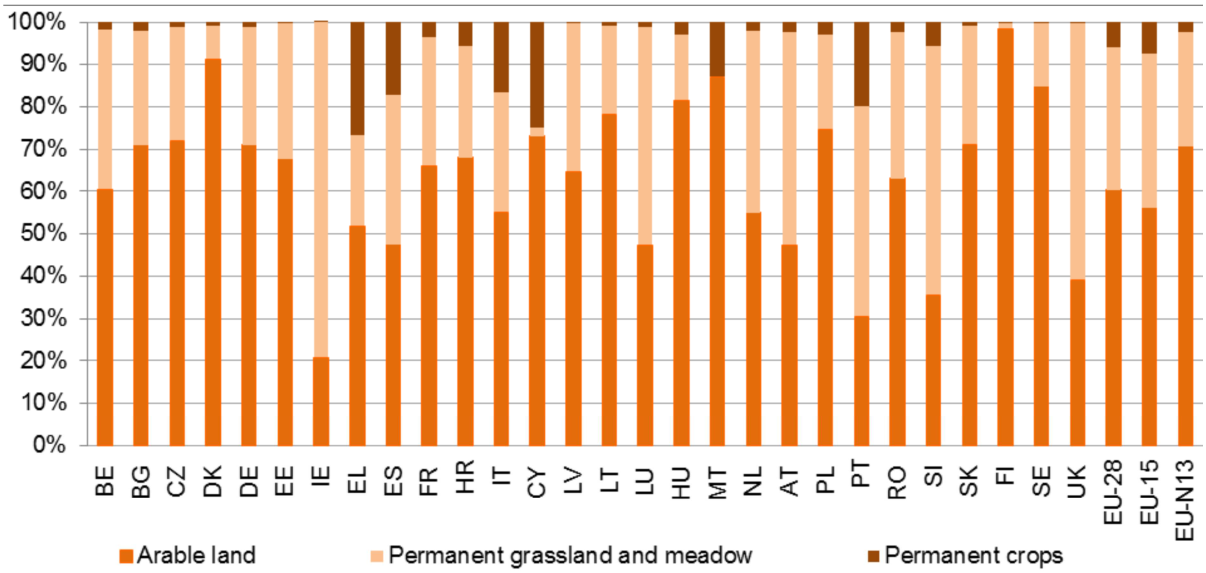

Figure 6: Share of UAA in different categories of land use in the EU (Eurostat 2015a).

Figures 5 and 6 indicated that regions with mainly arable crops are to be found in central Europe, as well as in Sweden and Finland. In general, fertiliser demand of arable crops is high compared to the demand of grassland. The above list of crops shows that within the regions with arable crops, wheat is the arable crop most widely cultivated in Europe.

The harvested production of cereals (including rice) in the EU-28 was estimated to be around 334.2 million tonnes in 2014. This represented about 13 % of global cereal production (based on estimates made by the United Nations' Food and Agriculture Organization), making the EU one of the world's biggest producer of cereals.

Figure 7 indicates that 44.8% of the total cereal production in the EU is wheat. Figure 8 indicates that the total wheat production over the period 2007 – 2014 is relatively constant at 150 million tonnes per year. Nearly two-thirds of the EU's cereals are used for animal feed, with around one-third for human consumption and only 3% is used for biofuels (Eurostat, 2015b).

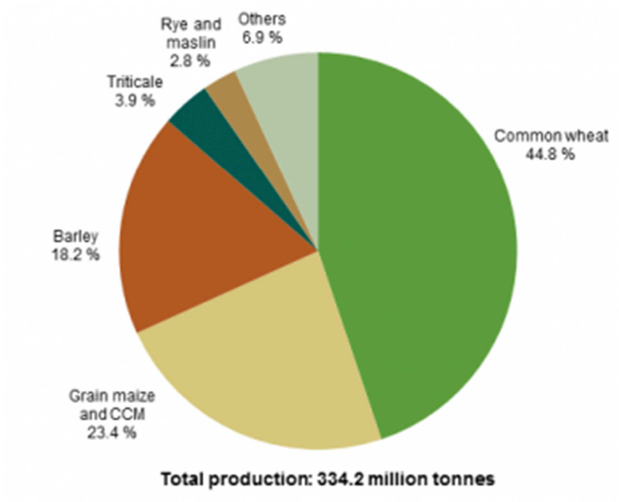

Figure 7: Production of cereals (% of total production of cereals) in the EU-28 for the year 2014.(Eurostat, 2015b).

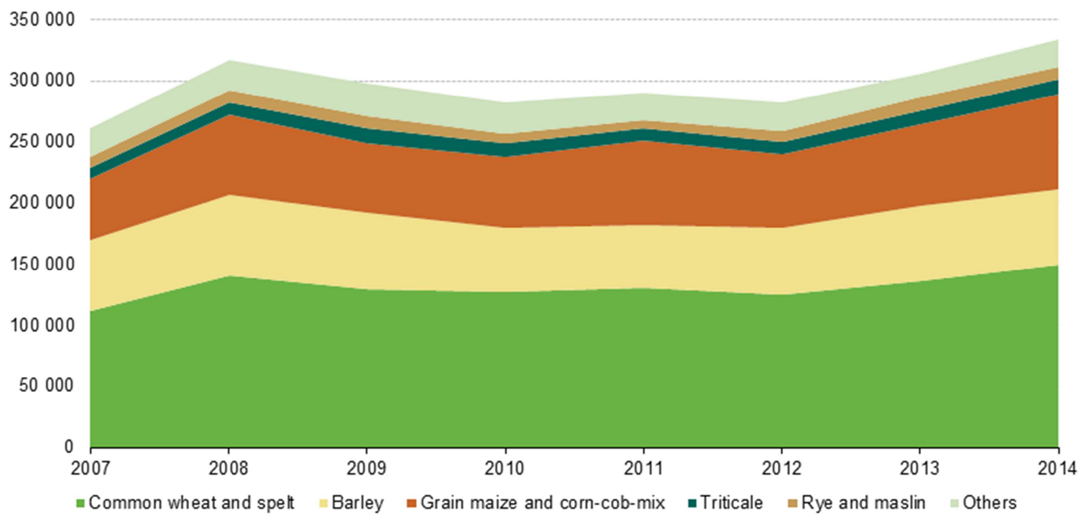

Figure 8: Production of cereal types, in the EU-28 for the period 2007–2014 (1 000 tonnes) (Eurostat, 2015b).

Hence, in summary wheat covers 24% of the UAA of arable land and accounts for 44.8% of the total cereal production in the EU, thereby making wheat an economically important crop.

In order to establish the economic importance of the previous list of crops for which the share is more than 10% of the UAA of arable land, we used reported yields (in 100 kg/ha) and reported selling prices of crop products (absolute prices in Euros) from the Eurostat (2015b) crop statistics for the year 2015 (http://ec.europa.eu/eurostat/statistics-explained/index.php/Agricultural_production_-_crops#Cereals). Per member state, yields per ha were multiplied by prices in order to obtain Euros per hectare. This indicates the relative economic importance of the crop. When no prices were available for one of the member states we used the EU average price.

It was not possible to obtain the figures for all crops because some crops are grouped in crop categories with different prices. For instance, a category 'other industrial crops' containing crops like peas, cauliflower etc. with different prices (See Annex II). The category group 'potato' is not uniform as it contains the range of potato production commodities: main crop potato, seed potato, and other potato which each carry different prices. In this case we used the price of the main crop potato. Although due to categorisation, values are not absolutely accurate, it does provide insight into the economic importance of the main crops grown in the European Union.

Results (presented in Annex III) identify that root crops (i.e. potatoes and sugar beet) are examples of high value crops, with a high economic output per ha per year. For example, compared to common wheat (which on average over all member states where wheat is grown, is € 945/ha/year) the yield of common potato is 6 times higher (which on average over all member states where common potato is grown, is € 5,676/ha/year). This high output is also related to high input, meaning that there are significant gains in reducing inefficiencies with PATs. Also, any small effect on yield has a significant impact too. This high economic output per ha per year for potato is likely to be able to compensate for the costs associated with adopting PATs in this crop.

As a result, wheat (because of its large share in utilised area) and potato (because of its high economic output per ha per year) are the crops to be considered in the selection of case studies.

7 Selection of case studies

7.1 Countries

The maximum potential for environmental benefits of PATs takes place when PATs are introduced in regions with high N2O emission. In addition, it is worthwhile investigating PATs used on major and high potential crops. Successful application under these circumstances may offer greater potential for encouraging adoption in other crops. The reasoning is that if a PAT is successfully introduced in one crop, farmers are more likely to adopt the PAT for other crops as well.

In the sections 3, 4, 5 and 6 several criteria for selecting case studies have been described and investigated using existing data sources. The corresponding data sets of these criteria were used to make an unbiased ranking in order to select the most important countries. We used the following ranking:

Figure 1: main farm size in hectares of UAA

1. Total UAA of big farms (>50 ha) is more than $^{2}/_{3}$ of total UAA or the total UAA area of medium and big farms (>5 ha) is more than 80% of the UAA
2. all other options

Figure 2: average physical farm size (UAA)

1. average physical farm size is bigger than 50 ha/holding
2. average physical farm size is bigger than 20 ha/holding and smaller than 50 ha/holding
3. average physical farm size is smaller than 20 ha/holding

Figure 3: factor income per annual work unit (EUR/AWU)

1. factor income per annual work unit is bigger than €30.000
2. factor income per annual work unit is bigger than €10.000 and less than €30.000
3. factor income per annual work unit is less than €10.000

Table 2: N-application

1. N-application is bigger than 100
2. N-application is less than 100

Table 2: N-surplus

1. N-surplus is bigger than 75
2. N-surplus is less than 75

Table 2: N_2O-emission

1. N_2O-emission is bigger than 1
2. N_2O-emission is less than 1

The results are shown in table 3 and leads in a first identification of interesting countries were the case studies can be carried out: Belgium, Denmark, Germany, the Netherlands, Finland and United Kingdom.

It is remarkable that there are no Mediterranean countries in this list with 40% of the UAA area is situated in the Mediterranean countries. In addition, this area is identified by the FAO (2016) as one of the most prominent hotspots in future climate-change projections. It is challenging to investigate if adoption of PATs can make the agricultural system more resilient.

Table 3: Ranking of potential countries

Reference	figure 1: main farm size in hectares of UAA	figure 2: average phusical farm size	figure 3: factor income per annual work unit (2014)	table 2: N2O emissions			Ranking
	farms 5-50 ha + > 50 ha are > 80%	ha UAA/ holding	EUR/AWU	N-application	N-surplus	N_2O-emission	total sum
Belgium	1	2	1	1	1	1	7
Bulgaria	2	2	3	2	2	2	13
Czech Republic	1	1	2	2	2	2	10
Denmark	1	1	1	1	2	1	7
Germany	1	1	2	1	2	1	8
Estonia	2	2	2	2	2	2	12
Ireland	1	2	2	2	2	2	11
Greece	2	2	2	2	2	2	12
Spain	2	2	2	2	2	2	12
France	2	1	2	2	2	2	11
Croatia	2	2	3	2	2	2	13
Italy	2	2	2	2	2	2	12
Cyprus	2	3	2	2	1	2	12
Latvia	2	2	3	2	2	2	13
Lithuania	2	2	3	2	2	2	13
Luxembourg	1	1	2	2	2	2	10
Hungary	2	2	3	2	2	2	13
Malta	2	3	2	1	1	1	10
Netherlands	2	2	1	1	1	1	8
Austria	2	2	2	2	2	2	12
Poland	2	2	3	2	2	2	13
Portugal	2	2	3	2	2	2	13
Romania	2	3	3	2	2	2	14
Slovenia	2	2	3	2	2	2	13
Slovakia	2	1	2	2	2	2	11
Finland	1	2	2	1	1	1	8
Sweden	1	2	2	2	2	2	11
United Kingdom	1	1	1	2	2	2	9

Based on this information the selected countries are: Belgium, United Kingdom, the Netherlands, Germany and Greece.

7.2 Crops

Using the Eurostat 2015 data (Eurostat 2015a) as presented in Annex II, Table 4 shows the crops grown in the list of selected countries and it is clear that in all countries, wheat is the main arable crop, except for the Netherlands where potatoes dominate.

Table 4: Crops per selected country(Eurostat, 2015).

	Denmark	Netherlands	United Kingdom	Germany	Finland	Belgium	Greece
Common wheat and spelt	43%	35%	31%	28%	13%	24%	5%
Plants harvested green from arable land			25%	24%	38%	37%	27%
Barley	43%	8%	19%	14%	24%	5%	4%
Oilseeds			11%	12%	3%	1%	1%
Grain maize and corn-cob-mix	0,5%	4%	0,1%	4%	0%	6%	4%
Olives				0%	0%	0%	25%
Durum wheat	0%	0%	0%	0,2%	0%	0%	10%
Rye and winter cereal mixtures (maslin)	8%	0,4%	0,4%	5%	2%	0,1%	0,6%
Potatoes (including seed potatoes)	3%	38%	2%	2%	1%	9%	0,7%
Sugar beet (excluding seed)	2%	14%	2%	3%	0,7%	6%	0,2%

7.3 Precision Agriculture Technique combinations

Including also the PATs as described in section 2, results in Table 4 with the different selection criteria in the order of: appropriate PAT, crop and country. PATs are also selected based on their ability to be fitted into existing farming procedures. This is considered necessary in order to identify reasons for adoption and non-adoption. As a result, Table 5 gives a gross list of potential case studies. From this list the case studies were selected in consultation with JRC (Table 5).

Table 5: Gross list of potential case studies

Technique	Crop	Country
VRA nutrient application Inorganic, solid granules	Potato / wheat	Belgium / France / Denmark / Germany / Netherlands / UK / Greece
VRA nutrient application, Inorganic, liquid	Potato / wheat	UK
VRA nutrient application Inorganic, solid granules	Barley	UK
VRA nutrient application Inorganic, solid granules	Grassland	Netherlands
VRA Organic nutrient application, slurry	Grassland	Netherlands
VRA Organic nutrient application, slurry	Fodder maize	Belgium
VRA nutrient application Inorganic, solid granules	Sugar beet	Netherlands
Machine Guidance, Controlled traffic farming	Potato / wheat	Belgium / France / Denmark / Germany / Netherlands / UK / Greece
VRA nutrient application Inorganic, solid granules	Cotton	Greece

As agreed upon with JRC, in order to get representative numbers of both adopters and non-adopters it is proposed to administer a similar survey across 5 regions (with approximately 200 farms per region).

As **techniques**, we propose to look at Machine Guidance and at Variable Rate Nutrient Application. Deliverables 1 and 2 have shown that these two techniques are the most prominent techniques. Currently, Machine Guidance is the most applied PAT technique whilst Variable Rate Application has not yet mainstreamed, but offers major GHG mitigation potential within the next decade.

As **crops,** we propose to look at wheat as this crop is grown in all countries in the EU. In addition, we propose to look into a high value crop. Potatoes are an economic intensive crop and therefore potato growers have a larger incentive to invest in precision technology and are among the early adopters that achieve an economic benefit from applying PATs. In terms of quantity produced and acreage, wheat is by far the most popular cereal crop grown in the EU, making up nearly half the total of all cereals grown. In practice potatoes, as a root crop, and wheat, as a cereal, are combined in a crop rotation system within the same farm. Accordingly, we will focus surveys on arable farmers, specializing in wheat (monoculture) production and potato-wheat crop rotation. In Greece, as representative of the Mediterranean region, potato is not much grown. Here we propose to select cotton as a high value crop where investments in PATs take place.

As **countries**, we propose to select the UK, Netherlands, Belgium, Greece and Germany. The four partner countries match criteria on diversity in farming systems and throughout Europe have relevant populations of adopters and non-adopters. Adding Germany will include large agricultural farms. These countries do represent the major agricultural regions in Europe and contain sufficient differences for the primary data collection and analysis.

Given the above we therefore propose the following case studies (Table 6):

Table 6: Proposed case studies

Country	**Technique**	**Crop**
Netherlands	Machine Guidance/ VRNT	Wheat / Potato
Belgium	Machine Guidance/ VRNT	Wheat / Potato
UK	Machine Guidance/ VRNT	Wheat / Potato
Greece	Machine Guidance/ VRNT	Wheat / Cotton
Germany	Machine Guidance/ VRNT	Wheat / Potato

8 Survey Protocol

8.1 Purpose

The purpose of the survey is to assess the impacts, uptake levels and reasons behind uptake of identified PAT options.

In the previous section, two PATs have been identified as the most likely candidates for investigation: i) machine guidance technology and vii) variable rate technology (VRT). This will guide the construction of the questionnaire and choice of variables selected for analysis.

8.2 Target population

The population of study will be farmers and contractors who have adopted the technology and applied it within the last cropping season. In addition, the survey will be targeted on farmers and contractors who grow wheat and/or potatoes within the rotation. A filter question will be asked before the interview begins.

Within these respondents there will be three populations we will survey, namely

- Non-adopters – those who have not adopted machine guidance or VRT technology;
- Partial adopters – those who have adopted machine guidance alone;
- Full adopters – adoption of VRT requires machine guidance, so therefore are deemed to be full adopters.

8.3 Piloting

The survey will be piloted to at least 12 participants within each region. The questionnaire will be modified to provide open comments to be completed within the survey. The purpose will be to test the validity and coherence of the questions. In addition, the flow of the questionnaire will be tested in terms of the order of the sections, alongside identifying the most valid statements related to uptake of PAT before the administration of the full survey.

8.4 Administration

The survey will be administered through an electronic questionnaire across 5 regions, namely UK, Netherlands, Belgium, Greece and Germany.

The response for each region will be 200 completed questionnaires. The response profile will be stratified in terms of the following numbers:

- 60 full adopters, that is farmers and contractors who have adopted VRT
- At least 70 partial adopters, that is farmers and contractors who have adopted Machine Guidance and not VRT
- The remainder to make up the 200 will be non-adopters, which are farmers who have not adopted Machine Guidance or VRT.

8.5 Recruitment

Principal recruitment will be through specialist fairs, as well as related events specific to each region, namely demonstration days, farmer discussion and study groups, monitor farm networks and operation groups which exist on a commodity level within the candidate countries. These events are focused at the commodity or the technology level. This will enable us to target those most likely to have adopted machine guidance and VRT.

If specialist fairs do not provide sufficient responses along the stratification proposed then other opportunities will be explored utilising our networks within the agricultural community. This will principally affect the requirement to have 60 completed questionnaires for full adopters. Specifically, our advisors will be in contact with farmers and will be aware of farmers adopting VRT. In addition, companies supplying equipment for VRT, e.g. Yaris, have and will be contacted to identify potential adopters. VRT, representing full adoption, may be the province of contractors and, in most regions, we will be able to identify these through our advisory networks.

8.6 Data Collection

The questionnaire will be prepared as an electronic version, preferably administered through a tablet or a laptop at these events for efficient data collection. The questionnaire will be constructed in SNAP survey software which offers the opportunity for routing questions according to type of adoption and circumstances. Where, for some reason, the administration of the survey is not able to be administered electronically, paper versions will be provided for completion by interviewers in a face to face interview.

The base questionnaire will be prepared in English and, once approved by the funders, will be translated into native languages of the five regions through the consortium partners and then tested through the pilot before full roll out of the survey.

The survey will be administered through the core team with associated research assistants within each region. A training event is timetabled with surveyors and will be conducted as a remote question and answer session to explain the logic of the survey, demonstrate the survey operation and clarify any issues with interviewers. A similar session will be held with the interviewers post-piloting to feedback any issues and inform the report on the piloting of the survey.

8.7 Data Preparation and Analysis

The data, collected electronically, will be collated on a central server and downloadable for analysis as a csv file. This will be imported into STATA 14 for analysis. Throughout the running of the survey update tables will be provided by the consortium to the funders which highlight numbers within each strata of full, partial and non-adoption and by region.

Analysis will be conducted in Stata, this will principally consist of analysis of frequencies for level of adoption and perceived impacts. This will allow the research team to calculate partial budgets for each region. In addition, drivers of adoption and non-adoption will be assessed using probit or logistic regression type approaches.

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Appendix A: Crop shares on arable land

The table shows per country the crop share (UAA) of the different crops (%). Numbers are obtained from Eurostat for the year 2015. In green are the crop/country combinations where the crop share is over 10 % (dark green) or 8 % (light green).

	Common wheat and spelt	Plants harvested green from arable land	Barley	Oilseeds	Grain maize and corn-cob-mix	Olives	Durum wheat	Fruits, berries and nuts (excluding citrus fruits, grapes and strawberries)	Grapes	Oats and spring cereal mixtures (mixed grain other than maslin)	Triticale	Fresh vegetables (including melons) and strawberries
Denmark	43%		43%		0.5%		0%				1%	
Latvia	39%	30%	9%	8%	0%	0%	0%	0.4%	0%	6%	0.9%	0.3%
Lithuania	37%	24%	9%	8%	0.5%	0%	0%	0.9%	0%	4%	5%	0.5%
Netherlands	35%		8%		4%		0%			0.4%	0.3%	
Bulgaria	35%	3%	6%	33%	16%	0%	0.3%	1%	1%	0.4%	0.4%	0.8%
Czech Republic	34%	19%	15%	18%	3%	0%	0%	0.6%	0.6%	2%	2%	0.4%
Turkey	32%	9%	14%	4%	3%	4%	6%	8%	2%	0.5%	0.2%	4%
Poland	32%		11%		9%		0%			16%	20%	
United Kingdom	31%	25%	19%	11%	0.1%		0%			2%	0.2%	2%
Germany (until 1990 former territory of the FRG)	28%	24%	14%	12%	4%	0%	0.2%	0.5%		1%	3%	1%
Estonia	28%	24%	22%	12%	0%		0%		0%	4%	1%	0.4%
Slovakia	28%	19%	11%	19%	15%	0%	2%	0.3%	0.7%	1%	0.8%	0.6%
France	27%	26%	9%	12%	9%	0.1%	2%	0.8%	4%	0.8%	2%	1%
Former Yugoslav Republic of Macedonia, the	27%	13%	15%	3%	12%		0%		8%	1%	0.7%	
Hungary	24%	7%	7%	22%	28%		0.5%		2%	1%	3%	2%
Romania	24%	10%	6%	18%	31%	0%	0.0%	2%	2%	2%	1.0%	2%
Belgium	24%	37%	5%	1%	6%	0%	0%	2%	0%	0.4%	0.6%	7%
Luxembourg	23%	44%	12%	6%	0.2%		0%			2%	7%	
Switzerland	21%	41%	7%	7%	3%	0%	0%	0.8%	4%	0.4%	2%	4%
Austria	21%	19%	11%	11%	14%	0%	1%	0.7%	3%	2%	4%	1%
Sweden	20%	47%	14%	4%	0.1%	0%	0%	0.1%	0.0%	8%	2%	0.9%
Croatia	17%	11%	5%	18%	31%	2%	0.2%	3%	3%	3%	1%	1%
Slovenia	17%	32%	11%		21%		0%		8%		2%	3%
Ireland	14%	25%	45%	2%	0%	0%	0%	0.2%	0%	5%	0%	1.0%
Spain	13%	8%	19%	6%	3%	18%	3%	6%	7%	4%	2%	3%
Finland	13%	38%	24%	3%	0%	0%	0%	0.1%	0%	16%	0%	0.7%
Bosnia and Herzegovina	12%	26%	4%		38%		0%		0.9%		2%	6%
Norway	11%	62%	16%	0.4%	0%		0%		0%	8%	0%	
Italy	6%	25%	3%	5%	8%	13%	15%	4%	8%			5%
Greece	5%	27%	4%	1%	4%	25%	10%	4%	3%	2%	0.3%	3%
Portugal	2%	30%	1%	1%	6%	22%	0.2%	11%	11%	3%	1%	3%
Malta	0%	61%	0%	0%	0%	0%	0%	0%	8%	0%	0%	23%
Iceland	0%		77%		0%	0%	0%	0%	0%	0%	0%	0%
Cyprus	0%	35%	18%	0.1%	0%	12%	11%	6%	6%	0.3%	0%	3%
Europe	**24%**	**17%**	**12%**	**9%**	**8%**	**5%**	**3%**	**3%**	**3%**	**3%**	**2%**	**2%**

	Rye and winter cereal mixtures (maslin)	Potatoes (including seed potatoes)	Sugar beet (excluding seed)	Dry pulses and protein crops for the production of grain (including seed and mixtures of cereals and pulses)	Fibre crops	Citrus fruits	Rice	Other cereals n.e.c. (buckwheat, millet, canary seed, etc.)	Other permanent crops for human consumption n.e.c.	Aromatic, medicinal and culinary plants	Tobacco	Sorghum	Other root crops n.e.c.	Other industrial crops n.e.c.	Energy crops n.e.c.	Hops
Denmark	8%	3%	2%		0%		0%	0%		0%	0%	0%		0%	0%	0%
Latvia	3%	0.9%	0%	3%	0.0%	0%	0%	0.9%	0%	0.1%	0%	0%	0.0%			
Lithuania	2%	1%	0.5%	7%	0.1%	0%	0%	2%	0%	0.2%	0%	0%	0.1%	0.0%	0.0%	0%
Netherlands	0.4%	38%	14%	0%			0%	0%			0%	0.3%	0%			0%
Bulgaria	0.2%	0.3%	0%	0.6%	0.1%	0%	0.4%	0.2%		2%	0.4%	0.2%	0.0%	0.0%	0%	
Czech Republic	0.9%	0.9%	2%	1%	0.0%	0%	0%	0.2%	0%	0.2%	0%	0%	0.0%	0.0%	0.1%	0.2%
Turkey	0.6%	0.8%	1%	3%	2%	0.7%	0.6%	0.0%	0.9%	0.3%	0.5%	0%	0%	0%	0%	0%
Poland	11%						0%	1%				0%		0%		
United Kingdom	0.4%	2%	2%	4%	0%		0%	0.6%		0.1%	0%	0%	0.7%	0%	0.1%	0%
Germany (until 1990 former territory of the FRG)	5%	2%	3%	1%	0.0%	0%	0%		0%	0.1%			0.0%		0.1%	0.2%
Estonia	2%	0.6%	0%	5%	0%	0%	0%	0.2%		0.1%	0%	0%	0%	0%	0%	0%
Slovakia	0.9%	0.2%	2%	0.8%	0%	0%	0%	0.1%	0%	0.2%	0%	0.1%	0.0%	0%	0%	0.0%
France	0.1%	0.9%	2%	1%	0.4%	0.0%	0.1%	0.2%		0.2%	0.0%	0.3%	0.1%	0.2%	0%	0.0%
Former Yugoslav Republic of Macedonia, the	1%	5%	0%	5%	0%		2%	0.7%		0.1%	6%	0%		0.0%	0%	0%
Hungary	0.9%	0.4%	0.4%	0.6%	0%		0.1%	0.3%		0.1%	0.1%	0.1%	0.0%	0.0%	0.2%	0%
Romania	0.1%	2%	0.3%	0.6%	0.0%	0%	0.1%	0.0%	0%	0.0%	0.0%	0.2%	0.2%	0.0%	0.0%	0.0%
Belgium	0.1%	9%	6%	0.3%	2%	0%	0%	0.3%	0%	0.0%	0.0%	0%	0.5%	0.0%	0%	0.0%
Luxembourg	2%	0.9%	0%	0.9%	0%		0%	0.1%		0.0%	0%	0%	0.2%	0.3%	0.1%	0%
Switzerland	0.5%	3%	5%	1%	0%	0%	0.0%	0.0%	0%	0.1%	0.1%	0%	0.1%	0%	0.0%	0.0%
Austria	3%	2%	3%	2%	0.1%	0%	0%	0.8%	0.1%	0.2%	0%	0.2%	0.0%	0.0%	0.1%	0.0%
Sweden	1%	1.0%	0.8%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.0%	0%
Croatia	0.1%	1%	2%	0.3%	0%	0.3%	0%	0.1%	0%	0.5%	0.6%	0.0%	0.1%	0%	0%	0%
Slovenia	0.7%	2%	0%	0.5%	0%	0%	0%	2%		0.0%	0%	0.0%	0.5%	0%	0%	0.8%
Ireland	0%	2%	0%	2%	0.0%	0%	0%	0%	0%	0.0%	0%	0%	3%	0%	0.3%	0%
Spain	1%	0.5%	0.3%	4%	0.5%	2%	0.8%	0.1%	0.3%	0.1%	0.1%	0.1%	0.1%	0.1%	0%	0.0%
Finland	2%	1%	0.7%	1%	0%	0%	0%	0.1%	0%	0.5%	0%	0%	0%	0%	0.2%	0%
Bosnia and Herzegovina	0.8%	7%	0%	2%			0%	0.2%		0.1%	0.3%	0.0%	0.2%		0%	0%
Norway	1%	2%	0%	0%	0%	0%	0%	0%		0%	0%	0%		0%	0%	0%
Italy	0.0%	0.6%	0.4%	0.8%	0.0%	2%	3%	0.4%	0.1%		0.2%	0.5%	0.0%			
Greece	0.6%	0.7%	0.2%	0.7%	7%	1%	0.8%	0.0%	0%	0.1%	0.6%	0.0%	0%	0%	0.1%	0%
Portugal	1%	2%	0.0%	0.8%	0%	1%	2%	0.1%	0.9%	0%	0.0%	0%	0.1%	0.1%	0%	0%
Malta	0%	8%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Iceland	0%	23%	0%			0%	0%	0%	0%			0%				
Cyprus	0%	5%	0%	0.4%	0%	3%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%
Europe	**2%**	**1%**	**1%**	**2%**	**0.7%**	**0.5%**	**0.4%**	**0.2%**	**0.2%**	**0.2%**	**0.2%**	**0.1%**	**0.1%**	**0.0%**	**0.0%**	**0.0%**

Appendix B: Prices per hectare per year for different crops

From the Eurostat crop statistics over the year 2015 we used reported yield (100 kg / ha) and reported selling prices of crop products (absolute prices) in Euros. Reported yields and prices were multiplied in order to obtain the price per hectare per year, thereby indicating the economic importance of the crop. When no prices were available for one of the member states we used the average price. Source data are from Eurostat (2015b) crop statistics for the year 2015. (http://ec.europa.eu/eurostat/statistics-explained/index.php/Agricultural_production_-_crops#Cereals).

CROPS	€/ha												
	Common wheat and spelt	Durum wheat	Rye and winter cereal mixtures (maslin)	Barley	Oats and spring cereal mixtures (mixed grain other than maslin)	Grain maize and corn-cob-mix	Triticale	Sorghum	Rice	Potatoes (including seed potatoes)	Sugar beet (excluding seed)	Tobacco	Hops
Ireland	€ 1,703	€ 0	€ 0	€ 1,349	€ 1,096	€ 0	€ 0	€ 0	€ 0	€ 8,762	€ 0	€ 0	€ 0
United Kingdom	€ 1,497	€ 0	€ 0	€ 951	€ 0	€ 0	€ 0	€ 0	€ 0	€ 7,879	€ 1,705	€ 0	€ 0
Belgium	€ 1,445	€ 0	€ 489	€ 1,276	€ 376	€ 1,779	€ 531	€ 0	€ 0	€ 4,639	€ 2,241	€ 0	€ 0
Netherlands	€ 1,410	€ 0	€ 0	€ 1,058	€ 0	€ 1,621	€ 719	€ 0	€ 0	€ 4,909	€ 3,187	€ 0	€ 0
Germany (until 1990 former territory of the FRG)	€ 1,296	€ 1,115	€ 765	€ 1,098	€ 647	€ 1,331	€ 857	€ 0	€ 0	€ 9,082	€ 1,851	€ 0	€ 0
France	€ 1,265	€ 1,347	€ 637	€ 1,085	€ 648	€ 1,282	€ 717	€ 725	€ 1,248	€ 0	€ 0	€ 0	€ 0
Denmark	€ 1,240	€ 0	€ 832	€ 986	€ 0	€ 929	€ 766	€ 0	€ 0	€ 10,769	€ 270	€ 0	€ 0
Sweden	€ 1,088	€ 0	€ 766	€ 696	€ 528	€ 863	€ 727	€ 0	€ 0	€ 9,454	€ 1,606	€ 0	€ 0
Czech Republic	€ 1,007	€ 0	€ 700	€ 904	€ 825	€ 768	€ 609	€ 0	€ 0	€ 3,688	€ 1,854	€ 0	€ 7,330
Luxembourg	€ 980	€ 0	€ 818	€ 818	€ 570	€ 1,017	€ 820	€ 0	€ 0	€ 7,098	€ 0	€ 0	€ 0
Italy	€ 882	€ 789	€ 414	€ 595	€ 0	€ 1,566	€ 0	€ 972	€ 1,745	€ 5,711	€ 0	€ 0	€ 0
Lithuania	€ 850	€ 0	€ 317	€ 575	€ 306	€ 690	€ 477	€ 0	€ 0	€ 1,958	€ 1,539	€ 0	€ 0
Croatia	€ 821	€ 1,791	€ 458	€ 676	€ 420	€ 829	€ 524	€ 281	€ 0	€ 2,456	€ 1,512	€ 2,228	€ 0
Slovakia	€ 807	€ 1,237	€ 474	€ 730	€ 455	€ 764	€ 502	€ 0	€ 0	€ 4,432	€ 1,827	€ 2,152	€ 3,422
Hungary	€ 800	€ 1,091	€ 352	€ 651	€ 397	€ 780	€ 521	€ 335	€ 694	€ 0	€ 0	€ 0	€ 0
Estonia	€ 765	€ 0	€ 516	€ 649	€ 408	€ 0	€ 656	€ 0	€ 0	€ 4,378	€ 0	€ 0	€ 0
Latvia	€ 742	€ 0	€ 502	€ 509	€ 310	€ 0	€ 488	€ 0	€ 0	€ 2,740	€ 0	€ 0	€ 0
Austria	€ 733	€ 1,133	€ 473	€ 848	€ 434	€ 1,267	€ 609	€ 996	€ 0	€ 4,965	€ 1,684	€ 0	€ 7,656
Poland	€ 731	€ 0	€ 347	€ 516	€ 316	€ 639	€ 475	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
Bulgaria	€ 708	€ 589	€ 237	€ 615	€ 365	€ 757	€ 462	€ 386	€ 1,843	€ 2,953	€ 1,073	€ 3,536	€ 0
Finland	€ 692	€ 0	€ 645	€ 531	€ 468	€ 0	€ 0	€ 0	€ 0	€ 4,313	€ 1,017	€ 0	€ 0
Greece	€ 640	€ 689	€ 252	€ 435	€ 238	€ 2,339	€ 502	€ 1,045	€ 1,722	€ 12,086	€ 1,747	€ 4,989	€ 0
Romania	€ 636	€ 623	€ 354	€ 669	€ 404	€ 545	€ 461	€ 355	€ 1,265	€ 3,877	€ 142	€ 2,816	€ 5,041
Spain	€ 477	€ 621	€ 250	€ 377	€ 228	€ 1,693	€ 852	€ 293	€ 2,082	€ 6,454	€ 2,444	€ 6,338	€ 8,675
Portugal	€ 397	€ 719	€ 166	€ 453	€ 227	€ 1,448	€ 306	€ 0	€ 1,756	€ 3,458	€ 664	€ 4,781	€ 7,426
Cyprus	€ 0	€ 697	€ 0	€ 382	€ 274	€ 0	€ 0	€ 0	€ 0	€ 4,485	€ 0	€ 0	€ 0
Malta	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
Slovenia	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0

Appendix C: Yield per 100 kg/ha

Yield source data derived from Eurostat (2015b) crop statistics for the year 2015 (http://ec.europa.eu/eurostat/statistics-explained/index.php/Agricultural_production_-_crops#Cereals).

Last update 10.05.16. Extracted on 11.05.16.

	Common wheat and spelt	Durum wheat	Rye and winter cereal mixtures (maslin)	Barley	Oats and spring cereal mixtures (mixed grain other than maslin)	Grain maize and corn-cob-mix	Triticale	Sorghum	Rice	Potatoes (including seed potatoes)	Sugar beet (excluding seed)	Tobacco	Hops
Belgium	93.6		45.5	89.7	56.4	118.7	73.2			465.8	850.8		
Bulgaria	45.4	33.0	17.8	39.7	19.8	54.1	30.2	25.0	54.9	149.5	418.5	17.6	
Czech Republic	63.6		48.7	54.4	34.9	55.4	47.2			222.6	593.8		10.5
Denmark	80.0		63.0	61.0		62.0	53.0			421.0	669.0		
Germany	81.1	46.5	56.6	71.7	44.9	88.8	64.7			438.1	721.7		
Estonia	47.9	0.0	38.2	42.4	28.3	0.0	49.5	0.0	0.0	211.2			
Ireland	106.6			85.8	84.4		0.0	0.0	0.0	422.7			
Greece	33.0	28.8	20.4	26.0	14.1	111.2	37.9	74.4	75.1	252.4	663.7	15.9	0.0
Spain	29.9	25.9	18.5	24.6	15.8	113.0	64.3	20.9	77.0	311.4	953.0	31.9	17.1
France	79.2	56.2	47.2	70.9	44.9	85.6	54.1	51.7	46.1				
Croatia	53.9	66.0	30.0	43.0	30.0	65.0	38.0	20.0	0.0	170.6	544.9	20.0	0.0
Italy	55.2	32.9	30.6	38.9		104.5		69.2	64.5	275.5			

	Common wheat and spelt	Durum wheat	Rye and winter cereal mixtures (maslin)	Barley	Oats and spring cereal mixtures (mixed grain other than maslin)	Grain maize and corn-cob-mix	Triticale	Sorghum	Rice	Potatoes (including seed potatoes)	Sugar beet (excluding seed)	Tobacco	Hops
Cyprus	0.0	29.1	0.0	24.9	19.0				0.0	216.4	0.0	0.0	0.0
Latvia	50.3		42.8	38.8	26.9		40.0			201.2			
Lithuania	52.4		27.8	40.1	25.3	48.1	38.4			170.0	506.1		
Luxembourg	62.8		62.8	57.6	48.6	65.8	59.5			227.5			
Hungary	51.4	48.3	27.9	48.2	28.8	56.9	39.9	26.5	28.6				
Malta													
Netherlands	90.4			69.1		108.2	50.3			426.9	833.0		
Austria	57.7	46.4	43.7	55.4	41.0	86.8	52.9	70.9		263.4	628.0		12.0
Poland	45.7	0.0	28.2	35.3	26.9	47.1	35.2	0.0	0.0				
Portugal	21.6	25.8	8.4	23.2	12.7	83.9	17.2		64.0	186.2	258.9	24.1	17.3
Romania	38.2	26.0	26.2	34.6	19.7	31.9	34.8	25.3	46.7	143.7	394.0	14.2	10.0
Slovenia													
Slovakia	55.2	51.6	36.3	48.2	26.4	54.7	37.9		0.0	179.3	560.1	10.8	6.8
Finland	41.0	0.0	34.2	34.7	34.7	0.0	0.0	0.0	0.0	243.1	327.4		
Sweden	72.2	0.0	63.4	52.5	45.3	57.6	58.1	0.0	0.0	347.3	608.0		
United Kingdom	88.0	0.0	0.0	66.0			0.0	0.0	0.0	402.0	665.0		

Appendix D: Prices per 100 kg crop

Price source data derived from Eurostat (2015b) crop statistics for the year 2015 (http://ec.europa.eu/eurostat/statistics-explained/index.php/Agricultural_production_-_crops#Cereals).

Last update 04.05.16. Extracted on 11.05.16

	Common wheat and spelt	Durum wheat	Rye and winter cereal mixtures (maslin)	Barley	Oats and spring cereal mixtures (mixed grain other than maslin)	Grain maize and corn-cob-mix	Triticale	Sorghum	Rice	Potatoes (including seed potatoes)	Sugar beet (excluding seed)	Tobacco	Hops
Belgium	€ 15		€ 11	€ 14	€ 7		€ 7			€ 10	€ 26	€ 177	€ 461
Bulgaria	€ 16	€ 18	€ 13	€ 16	€ 18	€ 14	€ 15	€ 15	€ 34	€ 20		€ 201	€ 406
Czech Republic	€ 16		€ 14	€ 17	€ 24	€ 14	€ 13			€ 17	€ 31		€ 698
Denmark	€ 16		€ 13	€ 16	€ 14		€ 14			€ 26	€ 4		
Germany													
Estonia													
Ireland				€ 16	€ 13								
Greece	€ 19	€ 24	€ 12	€ 17	€ 17	€ 21			€ 23	€ 48	€ 26	€ 314	
Spain													
France													
Croatia	€ 15	€ 27	€ 15	€ 16	€ 14	€ 13	€ 14			€ 14	€ 28	€ 111	

	Common wheat and spelt	Durum wheat	Rye and winter cereal mixtures (maslin)	Barley	Oats and spring cereal mixtures (mixed grain other than maslin)	Grain maize and corn-cob-mix	Triticale	Sorghum	Rice	Potatoes (including seed potatoes)	Sugar beet (excluding seed)	Tobacco	Hops
Italy													
Cyprus													
Latvia	€ 15		€ 12	€ 13	€ 12		€ 12			€ 14			
Lithuania	€ 16		€ 11	€ 14	€ 12	€ 14	€ 12			€ 12	€ 30		
Luxembourg	€ 16		€ 13	€ 14	€ 12	€ 15	€ 14			€ 31			
Hungary	€ 16	€ 23	€ 13	€ 14	€ 14	€ 14	€ 13	€ 13	€ 24	€ 22			
Malta										€ 33			
Netherlands	€ 16						€ 14			€ 12	€ 38		
Austria	€ 13	€ 24	€ 11		€ 11	€ 15	€ 12			€ 19	€ 27		€ 638
Poland	€ 16		€ 12	€ 15	€ 12	€ 14	€ 14			€ 12	€ 29	€ 190	€ 347
Portugal	€ 18	€ 28	€ 20	€ 20	€ 18	€ 17	€ 18		€ 27	€ 19			€ 430
Romania	€ 17			€ 19	€ 20	€ 17				€ 27	€ 4		
Slovenia	€ 17		€ 15	€ 13		€ 13	€ 14			€ 13			€ 562
Slovakia	€ 15		€ 13	€ 15	€ 17	€ 14				€ 25	€ 33		
Finland	€ 17		€ 19		€ 13					€ 18	€ 31		
Sweden	€ 15		€ 12	€ 13	€ 12		€ 13			€ 27	€ 26		
United Kingdom	€ 17			€ 14	€ 15					€ 20			
Average price	**16.0**	**24.0**	**13.5**	**15.3**	**14.4**	**15.0**	**13.3**	**14.0**	**27.1**	**20.7**	**25.6**	**198.7**	**506.1**

ANNEX 4. Pilot survey results and final questionnaire

Pilot Survey Results and Final Questionnaire

Deliverable 4

PRECISION AGRICULTURE project

contract no. 199163-2015 A08-NL

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Table of Contents

1 Introduction

The purpose of this report is to present the results of a pilot survey on the uptake of precision agricultural technologies. In so doing we will outline the data analysis strategy proposed for the main survey.

A set of criteria were agreed as Deliverable 3 (D3) for the technologies, commodities and the regional dispersion of case studies. The purpose of the survey is to assess the impacts, uptake levels and reasons behind uptake of identified PAT options. Two PATs have been identified (outlined in D3) as the most promising mitigation technologies for investigation in this study: i) machine guidance technology and ii) Variable rate nitrogen application technologies (VRNT).

Machine guidance is defined as: "*Guidance technologies are systems that pilot machinery using GPS. They enable farm machinery to follow straight lines to reduce overlaps and avoid gaps of the tractor and equipment passes. In order to use machine guidance systems, one needs a GPS receiver in the tractor or mounted on the machinery and a lightbar or a display on-board to provide driving direction. A more advanced option is to use machine auto-guidance systems, which are integrated in the tractor's hydraulics and can directly take over steering operations*".

Variable rate nitrogen application technology (VRNT) is defined as:"T*echnologies which enable changes in the application rate to match actual need for fertiliser in that precise location within the field. The basic idea is that, according to an electronic map or sensors, a control system calculates the input needs of the soil or plants and transfers the information to a controller, which delivers the input to the location*".

The majority of the pilot study was conducted throughout July to August 2016, with a final case study (Germany) conducted in December 2016. The purpose of the pilot survey was to test the validity and coherence of the proposed questionnaire (delivered report D3). In addition, the flow of the questionnaire was tested and the pilot aimed to identify the most valid statements related to reasons and incentives for adoption or non-adoption of precision agriculture before the administration of the full survey.

Twelve farmers were selected for each of the five regions, namely United Kingdom (herewith UK), Greece (herewith GR), Belgium (herewith BE), Netherlands (herewith NE) and Germany (herewith DE). In the UK and the Netherlands a farmer's meeting was chosen to pilot the survey, whereas for Greece, Belgium and Germany researchers used their links to farmer groups or specialist meetings to interview farmers.

The target population were wheat and/or potato producers. In the case of Greece, potato producers were substituted with cotton producers, as the most representative of that region's agricultural production and the most likely to adopt these technologies.

2 Methods for testing the pilot surveys

2.1 Data collection

For the pilot stage the data were entered into an excel spreadsheet from the paper copies of the pilot. This was set up with drop down boxes to maintain consistency of entered fields. However, entry for some countries was in the region's native language. Consequently, some reformatting was needed to harmonise fields across the regions to ensure they were recognised within the analysis software. As a consequence, a web survey data collection platform was established for the main survey to ensure archiving of data which followed an agreed format.

Once harmonised regions were merged into one excel file and then imported into STATA software. Recoding of value labels and categories was conducted to convert text values into numeric values for these data. Data were also imported into SPSS to produce a (.sav) file. An excel file is provided identifying categories and values for the numeric data set.

2.2 Data analysis

The analysis strategy for the main survey aims to follow three key steps;

1) Data validity and checking, through production of frequency graphs and summary statistics to understand the presence of outliers.

2) Analysis of characteristics of adopters and non-adopters, through i) frequency tables and chi-square statistics to examine relationships between regions, and ii) probit or logit regression approaches to understand the significance of drivers behind non-adoption, machine guidance only and MG with VRNT precision agricultural technologies, and

3) Compilation of partial budgets. These will be constructed for small, medium and large cereal, potato and cotton farms (in the case of Greece) in order to examine the effect on yield, input use and operating costs on the overall farm account.

The purpose of what follows is to illustrate some of the outputs and analysis strategy specified above on the pilot responses. As the sample is small, at 12 respondents per region, these are not expected to be illustrative of final results but merely used to understand the approach proposed by the consortium.

3 Results of the pilot surveys and questionnaire validation

3.1. Awareness and Adoption of PA technologies

Table 1 shows the responses to the questions "Are you aware of Variable Rate Nitrogen Application" (Q14) and "Are you aware of Machinery Guidance?" (Q17). This was a simple yes or no question and the table shows the percentage (of the 12 per region) who responded yes to each question. As would be expected the bulk of respondents were aware of machine guidance technology, with lower levels of awareness related to variable rate nitrogen application technology (VRNT). Awareness of VRNT varied from 58%, in Greece, to 92% in Belgium.

Table 1. Awareness of precision agriculture technologies by region, percentage

		Aware of VRNT		Aware of Machine Guidance	
	N	No	Yes	No	Yes
BE	12	8%	92%	0%	100%
DE	12	17%	83%	0%	100%
GR	12	42%	58%	8%	92%
NL	12	17%	83%	0%	100%
UK	12	0%	100%	0%	100%

The farmers were given a range of choices related to adoption, namely:

- Yes, I own a variable rate technology/machine guidance (option 1)
- Yes I rented the variable rate technology/machine guidance (option 2)
- Yes I have used/tried variable rate technology/machine guidance (option 3)
- No I haven't but I'm planning to adopt variable rate technology/machine guidance (option 4)
- No, I haven't and I do not plan to adopt variable rate technology/machine guidance (option 5)

Adopters were identified as those who own or rent (options 1 or 2) as oppose to those who did not adopt (options 3, 4 or 5). The table 2 shows the overall adoption profile against regions and the type of technology.

Table 2. Level of adoption and non-adoption of precision agricultural technologies, percentage per region (numbers in brackets and technology

	N	Non-Adoption	MG Only	MG+VRNT
BE	12	(10) 83%	(2) 17%	(0) 0%
DE	12	(8) 67%	(2) 17%	(2) 17%
GR	12	(8) 67%	(4) 33%	(0) 0%
NL	12	(2) 17%	(10) 83%	(0) 0%
UK	12	(4) 33%	(7) 58%	(1) 8%

The bulk of adopters within the pilots were found in relation to machine guidance only, as would be expected as it is a more common technology. VRNT was less common in the pilot, though 2 farmers in Germany (17%) and 1 farmer in the UK (8%) had adopted VRNT.

3.2 Descriptive Statistics

This section shows the general descriptors of the pilot responses to illustrate the distribution across each region. Tables 3, 4 and 5 show the number of respondents who were growing wheat, potatoes/cotton or both crops categorised by their level of adoption. Clearly, this is determined by the sample of 12 farmers per country but the bulk of respondents were growing wheat in the last cropping season, whereas fewer farmers had cropped potatoes or cotton.

Table 3. Numbers of respondents growing wheat, potatoes/cotton or both, percentage distribution across each region, non-adopters

	Wheat Only		Potatoes/Cotton Only		Wheat and Potatoes	
	n	%	n	%	n	%
Belgium	5	42%	2	17%	3	25%
Germany	8	67%		0%		0%
Greece	2	17%	1	8%	5	42%
The Netherlands		0%		0%	2	17%
UK	3	25%	1	8%		0%

Table 4. Numbers of respondents growing wheat, potatoes/cotton or both, percentage distribution across each region, machine guidance only

	Wheat Only		Potatoes/Cotton Only		Wheat and Potatoes	
	n	%	n	%	n	%
Belgium		0%		0%	2	17%
Germany	2	17%		0%		0%
Greece	3	25%		0%	1	8%
The Netherlands		0%		0%	10	83%
UK	5	42%	1	8%	1	8%

Table 5. Numbers of respondents growing wheat, potatoes/cotton or both, percentage distribution across each region, MG + VRNT

	Wheat Only		Potatoes/Cotton Only		Wheat and Potatoes	
	n	%	n	%	n	%
Belgium		0%		0%		0%
Germany	2	17%		0%		0%
Greece		0%		0%		0%
The Netherlands		0%		0%		0%
UK		0%		0%	1	8%

3.3 Characteristics of Adopters versus Non-Adopters

Table 6 shows the characteristics of adopters and non-adopters. Where continuous variables were used, such as land area and staff numbers, the mean is given. For categorical responses, such as membership of a co-operative, the median was taken.

For ease of illustration the table represents all 60 responses and does not discriminate by region30. Whilst these results only represent the pilot responses there are some differences between adopters and non-adopters. A larger average utilised agricultural area, arable area and more full-time labour indicates, perhaps, that larger farmers are more likely to be machine guidance only adopters, compared to smaller farmers and this agrees with most of the technology adoption literature. Similarly, another finding that matches the bulk of literature on technology adoption is that adopters tend to be younger, are more educated and members of a co-operative group. Whilst offering spreading of risk and sharing of investment, this latter finding may also indicate a higher level of social capital as farmers are more embedded within their social networks for a source of information and support. Notably, income did not vary between adopters and non-adopters, where we would expect those with high household incomes to be more likely to invest in these technologies it may be a result of the restrictive upper limit imposed on income categories in the pilot. As noted above, these categories were extended to accommodate greater variance in incomes in the main survey.

Only three farmers were MG + VRNT adopters. Nevertheless there are still some differences, as these tend to have a larger utilised agricultural area and arable area than non-adopters. Similarly they are more likely to be members of co-operatives. This matches to the literature on technology adoption, outlined above. Conversely, they are, on average older. As the sample is small and biased this may be an abnormal result, or may indicate that MG + VRNT adopters are older.

[30] Once the full survey is complete it is intended to present these results by each region.

Table 6. Characteristics of adoption across all regions

	Non-Adoption (n=32)	MG Only (n=25)	MG+VRNT (n=3)
Winter Wheat (Ha), Mean	18.2	54.4	34.3
Spring Wheat (Ha), Mean	1.2	6.9	0.0
Ware Potato (Ha), Mean	7.1	25.0	2.7
Seed Potato (Ha), Mean	3.1	6.7	0.0
Utilised Agricultural Area (Ha), Mean	83	228	212
Arable Area, Ha (mean)	76	204	182
Full-Time Regular Labour, numbers (mean)	1	2	1
Age (mean)	48	43	50
Role in the farm (Median)	Owner	Owner	Owner
Education and Training (median)	HNC/Diploma in agriculture or related subject	HBO (Agricultural)	Degree in agriculture or related subject
Are you a member of a co-operative? (median)	No	Marketing co-op	Machinery collective
Gross income category (median)	>72.000	>72.000	No answer
Percentage of farm income from wheat (median)	1-20%	1-20%	1-20%
Percentage of farm income from potatoes (median)	0%	21-40%	0%

3.4 Multinomial logistic modelling[31]

In order to understand the causality of drivers towards adoption a logistic model is proposed. This is because the responses will be assessed in terms of non-adoption (0), MG Only (1) and MG+VRNT (2).

A series of explanatory variables on characteristics of adoption will be assessed, some of these will be continuous variables, such as age and land area, but others will be handled as categorical variables, such as ownership status and education. In this case a reference value will be taken as the comparator, e.g. ownership status, and the odds of adoption will be examined relative to this reference value, e.g. tenanted farming. Explanatory variables will be chosen with respect to previous reviews of literature on adoption (D1) and wider literature on adoption. Generally, these will be either farmer specific variables, such as age and education, but also farm specific variables, such as size and level of specialisation.

The output will be a behavioural model which indicates the main drivers and the magnitude of their impact on adoption. As the sample size is expected to be around 200 responses per region, with an even distribution between adopters and non-adopters, it is hoped that this will provide a reasonable fit within the regressions of adoption and non-adoption.

As a contingency, probit models may be explored comparing each separate technology, e.g. adoption of machine guidance, and adoption of VRNT. These will also give an understanding of the main drivers of uptake of technologies and may be less restrictive than the proposed logistic model, as they rely on a binary response variable, as oppose to a multi-nominal variable in the case of the logistic model.

3.5 Perceived Impacts

Farmers who were adopters were asked to estimate the effects of adoption on a range of farm level variables, such as yield, nitrogen use and other variable or fixed costs. Farmers were asked for a response along a range of categories for each variable from over minus 40% to more than plus 40%, including a 'no effect' category. This is only illustrated for those who were growing wheat and had adopted machine guidance, the largest response group within the pilot, in order to show the potential variance in response per region and farm level variable. Table 7 shows median values, in terms of the perceived effects for wheat enterprises from adoption of machine guidance.

[31] The 60 responses from the pilot were insufficient to run an example probit that could produce a satisfactory solution. Hence this section aims to simply describe the approach proposed.

Table 7 Median values for perceived effects on the wheat enterprise for machine guidance effects, category by region

	BE (n=2)	DE (n=2)	GR (n=4)	NL (n=10)	UK (n=6)
Yield (Kg per ha)	5-10% increase	No perceived effect	No perceived effect	No perceived effect	No perceived effect
Fuel quantity (litres per ha)	5-10% reduction	5-10% reduction	11-20% reduction	No perceived effect	5-10% reduction
Nitrogen fertiliser quantity applied (N Kg/ ha)	5-10% reduction	5-10% reduction	21-30% reduction	No perceived effect	No perceived effect
Cost of hired labour (euro)	No perceived effect	5-10% reduction	No perceived effect	No perceived effect	No perceived effect
Labour Training Time (hrs)	No perceived effect	5-10% increase	No perceived effect	No perceived effect	No perceived effect
Management Time (hrs)	5-10% increase	5-10% increase	No perceived effect	No perceived effect	No perceived effect
Time spent in field (hrs)	5-10% reduction	5-10% reduction	11-20% reduction	No perceived effect	5-10% reduction
Machinery costs (euro) *	No perceived effect	-	5-10% increase	5-10% increase	No perceived effect
Repairs and Spares (euro)	5-10% increase	No perceived effect	No perceived effect	No perceived effect	No perceived effect
Contractor costs (euro)	No perceived effect	No perceived effect	No perceived effect	No perceived effect	No perceived effect

* As the German pilot was conducted later, machinery costs had already been dropped from the effect variables.

Overall impacts on the outputs and inputs for the farm business were either small (between 5 to 10%) or were perceived to have no effect. This is a small sample, with only limited responses to uptake of the technology per region, and it would be expected there are few effects which are common across each country, aside from contractor costs where no perceived effect were identified. Only Belgium noticed a positive effect on yield, whereas the other regions saw no effect. The focus of these technologies has been mainly on inputs, so we would expect little effect from yield. For Fuel and Nitrogen there were more visible positive effects from adopting the technology, with Greece noting the highest levels of improvement. The Netherlands, as with the majority of other variables, identified no perceived effect on these inputs. Though it would be expected that some reduction in these inputs would be noticed through fuel saving from the guidance technology used. Management time and repairs and spares were identified as having increased due to the adoption of machine guidance tools.

3.6 Partial Budgets

Table 8 shows an example of a partial budget for a wheat enterprise in the UK32. A partial budget offers the opportunity to compare a typical farm budget against potential impacts of the adoption of a technology, or changes in prices and costs.

The impact categories in the survey will be matched with relevant FADN financial data categories related to enterprise outputs, costs and labour usage33. The net farm financial impact is then simply the difference between the impact on wheat and potato and cotton yield and the impact on costs. The relative impact on the net margin and gross margin can be calculated for both the typical farm budget and an adjusted farm budget, once effects of adoption are accounted.

As bands were used in the survey, for ease of respondent completion, the partial budgets are presented at the median for each effect. Notably for the UK the only effect on inputs was a reduction in fuel quantity which reduced other crop costs. Whilst time spent in the field was also noted, this could not be directly accounted within the partial budget, as average estimates are not available for this factor, but should be highlighted as an ancillary benefit to adoption.

[32] This is for illustrative purposes. Once the survey is complete partial budgets will be presented for wheat, cotton and potato enterprises and by size, namely small, medium and large.
[33] FADN data had not been received when the pilot analysis was been completed. Hence, we have used the SAC Farm Management Handbook (2016) to calculate values for a typical wheat enterprise.

Table 8. Example partial budget for a typical medium sized specialist wheat farm in the UK with and without expected effects of machine guidance technologies, € per annum

	Current Annual Budget (€ per annum)	Effect of Adoption of Machine Guidance (€ per annum)	Median Perceived Effect
Output			
Sales of crop products	239,727	239,727	No perceived effect
Income from agri-environment payments	10,455	10,455	No perceived effect
Other income	25,338	25,338	No perceived effect
	275,520	**275,520**	
Variable Costs			
Fertiliser costs	39,926	39,926	No perceived effect
Seed costs	15,990	15,990	No perceived effect
Other crop costs (e.g. insurance)	23,911	22,237	5-10% reduction
Contractor costs	21,156	21,156	No perceived effect
Cost of causal labour	20,910	20,910	No perceived effect
Other variable costs	22,140	22,140	No perceived effect
Total Variable Cost (VC)	**144,033**	**142,359**	
Gross Margin (Output - VC)	**131,487**	**133,161**	
Fixed Costs			
Labour costs	12,405	12,405	No perceived effect
Fuel and energy costs	49,194	49,194	No perceived effect
Overheads	67,395	67,395	No perceived effect
Total Fixed Costs (FC)	**128,994**	**128,994**	
Farm Income (Output – (VC+FC))	2,493	4,167	
Overall Effect on Farm Business Inc.		**1,674**	

Source: SRUC Farm Management Handbook (2016)

Accordingly, the adoption of machine guidance could improve the farm business income of a medium sized cereal enterprise in the UK by around €1,674 per annum.

3.7 Intentions for Adoption

Respondents were asked their intentions towards adopting a range of precision agriculture technologies in the next 5 to 10 years. These are split into categories of non-adoption, MG Only or MG+VRNT.

Table 9. Intentions to adopt precision agricultural technologies by region, non-adopters, median

	Non-Adoption				
	BE (n=10)	DE (n=8)	GR (n=8)	NL (n=2)	UK (n=4)
Machine Guidance (+/-2cm)	No Intention to Adopt	No Intention to Adopt	Already adopted	Yes in 5-10 years	No Intention to Adopt
Machine Guidance (+/-40cm)	No Intention to Adopt	No Intention to Adopt	No Intention to Adopt	No Intention to Adopt	No Intention to Adopt
Variable Rate technology for nitrogen	Yes in 5-10 years	No Intention to Adopt	Already adopted	Yes in 5-10 years	No Intention to Adopt
Controlled traffic farming	Already adopted	Already adopted	No Intention to Adopt	Already adopted	No Intention to Adopt
Variable rate Irrigation	No Intention to Adopt	No Intention to Adopt	No Intention to Adopt	No Intention to Adopt	No Intention to Adopt
Variable rate pesticide application	Yes in 5-10 years	No Intention to Adopt	No Intention to Adopt	Already adopted	No Intention to Adopt
Variable rate seeding/planting	Yes in 5-10 years	No Intention to Adopt	No Intention to Adopt	Yes in 5-10 years	Yes in 5-10 years
Precision physical weeding	No Intention to Adopt	No Intention to Adopt	No Intention to Adopt	Yes in 5-10 years	No Intention to Adopt

For those who were non-adopters, there were no consistent findings across the regions. Principally, most respondents were likely to not adopt other technologies, aside from region specific intentions related to a number of technologies. However, what does emerge is that non-adopters claimed to have already adopted controlled traffic farming, in Belgium, Germany and Netherlands.

Table 10. Intentions to adopt precision agricultural technologies by region, machine guidance only, median

	MG Only				
	BE (n=2)	DE (n=2)	GR (n=4)	NL (n=10)	UK (n=7)
Machine Guidance (+/-2 cm)	No Intention to Adopt	No Intention to Adopt	Yes in 5-10 years	Already adopted	Already adopted
Machine Guidance (+/-40 cm)	Already adopted	Already adopted	Already adopted	No Intention to Adopt	No Intention to Adopt
Variable Rate technology for nitrogen	Yes in 5-10 years	Already adopted	Yes in 5-10 years	Yes in 5-10 years	Yes in 5-10 years
Controlled traffic farming	Already adopted	Already adopted	No Intention to Adopt	Already adopted	No Intention to Adopt
Variable rate Irrigation	No Intention to Adopt	No Intention to Adopt	No Intention to Adopt	No Intention to Adopt	No Intention to Adopt
Variable rate pesticide application	Already adopted	Already adopted	Yes in 5-10 years	Yes in 5-10 years	Yes in 5-10 years
Variable rate seeding/planting	No Intention to Adopt	Already adopted	Already adopted	Already adopted	Yes in 5-10 years
Precision physical weeding	Already adopted	No Intention to Adopt	No Intention to Adopt	No Intention to Adopt	Yes in 5-10 years

A more positive picture of adoption emerges for the machine guidance adopters as a number of technologies are either already adopted or are intended to be adopted in the next 5 to 10 years.

Table 11. Intentions to adopt precision agricultural technologies by region, MG+VRNT, median

MG+VRNT					
	BE (n=0)	DE (n=2)	GR (n=0)	NL (n=0)	UK (n=1)
Machine Guidance (+/-2 cm)		Already adopted			Yes in 5-10 years
Machine Guidance (+/-40 cm)		Already adopted			No Intention to Adopt
Variable Rate technology for nitrogen		Already adopted			Yes in 5-10 years
Controlled traffic farming		Yes in 5-10 years			No Intention to Adopt
Variable rate Irrigation		Already adopted			No Intention to Adopt
Variable rate pesticide application		Already adopted			Already adopted
Variable rate seeding/planting		Already adopted			Yes in 5-10 years
Precision physical weeding		Already adopted			No Intention to Adopt

The full adopters represent only 3 farmers and consequently indicate significant bias and no conclusions can be drawn from these responses.

3.8 Reasons for adoption

Influences on adoptions

The farmers who had either adopted machine guidance or VRNT farmers were asked who influenced their adoption decision. Responses are shown in Table 12 and 13 as a distribution of total responses per region for machine guidance and MG +VRNT adopters.

Table 12. Influences on adoption, median response

	MG Only				
	BE (n=2)	DE (n=2)	GR (n=4)	NL (n=10)	UK (n=7)
Local farm advisor or extension agent	Some Effect	Some Effect	No Effect	No Effect	No Effect
Industry salesperson or machinery dealer	Some Effect	Some Effect	Some Effect	Some Effect	Some Effect
Input-supplier	No Effect	No Effect	No Effect	No Effect	No Effect
Other farmers	Some Effect	Some Effect	No Effect	Some Effect	Some Effect
Co-operative	No Effect	No Effect	No Effect	No Effect	No Effect
Machinery collective/machinery ring	No Effect	No Effect	No Effect	No Effect	No Effect
Contractor	Some Effect	No Effect	No Effect	No Effect	No Effect
Visit to a trade fair	Some Effect	Some Effect	No Effect	Some Effect	Some Effect
Researchers	No Effect	Some Effect	Some Effect	No Effect	No Effect
College/ University open days	No Effect	No Effect	No Effect	No Effect	No Effect
Farmer's Union	No Effect	No Effect	No Effect	No Effect	No Effect

Clearly, for machine guidance adopters a number of influences emerge as having an effect, though very few have a strong influence on the decision. Clearly, industry salespeople, other farmers and visits to trade fairs seem to emerge as the main influences on uptake of machine guidance.

Table 13. Influences on adoption, median response

	MG+VRNT				
	BE (n=0)	DE (n=2)	GR (n=0)	NL (n=0)	UK (n=1)
Local farm advisor or extension agent		Some Effect			Strong Influence
Industry salesperson or machinery dealer		Some Effect			Some Effect
Input-supplier		No Effect			Some Effect
Other farmers		Some Effect			Some Effect
Co-operative		Some Effect			No Effect
Machinery collective/machinery ring		No Effect			No Effect
Contractor		No Effect			No Effect
Visit to a trade fair		Some Effect			Some Effect
Researchers		Some Effect			No Effect
College/ University open days		Some Effect			No Effect
Farmer's Union		No Effect			No Effect

For MG+VRNT adopters, there may be some strong influences on uptake with local farm advisors and extension agents. However, only 3 farmers within the pilot were MG+VRNT adopters, consequently these results indicate significant bias and no conclusions can be drawn from these responses.

3.9 Incentives to adopt

All Farmers were asked "Could you indicate what incentives would encourage you to increase your use and adoption of precision agriculture technology?" They were given a range of potential incentives and asked to indicate how it would affect their decision to adopt precision agricultural technologies (PATS). The tables below show the range of responses for each incentive divided by the categories of non-adoption, MG only and MG+VRNT.

Table 14. Potential incentives on adoption of precision agricultural technologies, non-adopters, median values

	Non-Adoption				
	BE (n=10)	DE (n=8)	GR (n=8)	NL (n=2)	UK (n=4)
More support for training of my staff	This would have no effect on my decision	This would have no effect on my decision	This would most definitely increase use of PATS	This would probably not affect my decision for more PATS	This would most probably increase my use of PATS
Confidence that yields would increase	This would most definitely increase use of PATS	This would have no effect on my decision	This would most definitely increase use of PATS	This would most definitely increase use of PATS	This would most definitely increase use of PATS
Confidence that my costs would reduce	This would most definitely increase use of PATS	This would have no effect on my decision	This would most definitely increase use of PATS	This would most definitely increase use of PATS	This would most definitely increase use of PATS
More support for training for myself and family	This would most probably increase my use of PATS	This would have no effect on my decision	This would most definitely increase use of PATS	This would probably not affect my decision for more PATS	This would most probably increase my use of PATS
More technical support from sales people	This would most definitely increase use of PATS	This would have no effect on my decision	This would most definitely increase use of PATS	This would most probably increase my use of PATS	This would most probably increase my use of PATS
Directed subsidy support for uptake of PATS	This would most definitely increase use of PATS	This would most probably increase my use of PATS	This would most definitely increase use of PATS	This would most definitely increase use of PATS	This would most probably increase my use of PATS
Financial support from tax breaks	This would most definitely increase use of PATS	This would have no effect on my decision	This would most definitely increase use of PATS	This would most probably increase my use of PATS	This would most definitely increase use of PATS
A 10% reduction in the present cost of the technology	This would most definitely increase use of PATS	This would have no effect on my decision	This would most probably increase my use of PATS	This would have no effect on my decision	This would most probably increase my use of PATS

In terms of non-adoption, the most common positive responses were related to directed subsidies for support of uptake of PATs. German non-adopters expressed that most other incentives would have no effect on their decisions to uptake the PAT. Disregarding German farmer responses, it seems most of the incentives would encourage uptake at a regional level.

Table 15. Potential incentives on adoption of precision agricultural technologies, MG only adopters, median values

	MG Only				
	BE (n=2)	DE (n=2)	GR (n=4)	NL (n=10)	UK (n=7)
More support for training of my staff	This would probably not affect my decision for more PATS	This would most probably increase my use of PATS	This would most definitely increase use of PATS	This would most probably increase my use of PATS	This would have no effect on my decision
Confidence that yields would increase	This would most definitely increase use of PATS	This would most probably increase my use of PATS	This would most definitely increase use of PATS	This would most probably increase my use of PATS	This would most definitely increase use of PATS
Confidence that my costs would reduce	This would most definitely increase use of PATS	This would most probably increase my use of PATS	This would most definitely increase use of PATS	This would most probably increase my use of PATS	This would most definitely increase use of PATS
More support for training for myself and family	This would most definitely increase use of PATS	This would most probably increase my use of PATS	This would most definitely increase use of PATS	This would most probably increase my use of PATS	This would most probably increase my use of PATS
More technical support from sales people	This would most probably increase my use of PATS	This would most probably increase my use of PATS	This would most definitely increase use of PATS	This would most probably increase my use of PATS	This would have no effect on my decision
Directed subsidy support for uptake of PATS	This would most definitely increase use of PATS	This would most probably increase my use of PATS	This would most definitely increase use of PATS	This would most probably increase my use of PATS	This would most definitely increase use of PATS
Financial support from tax breaks	This would most definitely increase use of PATS	This would most probably increase my use of PATS	This would most definitely increase use of PATS	This would most probably increase my use of PATS	This would most definitely increase use of PATS
A 10% reduction in the present cost of the technology	This would most definitely increase use of PATS	This would most probably increase my use of PATS	This would most definitely increase use of PATS	This would most probably increase my use of PATS	This would most definitely increase use of PATS

In terms of MG Only-adoption, most incentives were seen as potentially useful for encouraging uptake. Greek farmers seemed the most positive towards these incentives, whereas Dutch and UK farmers were slightly less enthusiastic towards these incentives.

Table 16. Potential incentives on adoption of precision agricultural technologies, MG + VRNT, median values

	MG+VRNT				
	BE (n=0)	DE (n=2)	GR (n=0)	NL (n=0)	UK (n=1)
More support for training of my staff		This would have no effect on my decision			This would most probably increase my use of PATS
Confidence that yields would increase		This would most probably increase my use of PATS			This would most definitely increase use of PATS
Confidence that my costs would reduce		This would most definitely increase use of PATS			This would most definitely increase use of PATS
More support for training for myself and family		This would have no effect on my decision			This would most probably increase my use of PATS
More technical support from sales people		This would have no effect on my decision			This would most probably increase my use of PATS
Directed subsidy support for uptake of PATS		This would most probably increase my use of PATS			This would most probably increase my use of PATS
Financial support from tax breaks		This would most definitely increase use of PATS			This would most probably increase my use of PATS
A 10% reduction in the present cost of the technology		This would most probably increase my use of PATS			This would most probably increase my use of PATS

The MG + VRNT adopters identify a number of incentives that would increase uptake. Very few incentives were seen as a disincentive and these were only pertinent to the German farmers. However, as only 3 farmers were MG + VRNT adopters in the pilot these are not representative of the wider industry.

Other incentives

An open question was asked "Are there other incentives that would encourage you to increase your use and adoption of precision agriculture?". It is proposed to analyse these in the main survey through a frequency analysis of individual words. This allows us to identify the key themes emerging from these qualitative questions. For the pilot, the sample was too small to conduct a meaningful analysis, hence the key statements were categorised against themes emerging from the statements themselves.

Whilst several respondents mentioned financial reasons, e.g. "We need to be achieving a higher price for the products we sell", others focused on the need for ease of use and reliability, e.g. "Reliability, compatibility between VRT", "Less stress when operating" "More training by dealers". Several mentioned regulation and Government incentives "More stringent laws on pesticide and nitrogen application" "Environmental Protection", whereas others focused on the knowledge around the technologies themselves, "Insight into the effects of soil on production and translation to PA-maps", "PA-maps with good sound justification dependent on development, especially on spraying techniques".

3.10 Reasons for adopting or not adopting PATs

Farmers were asked an open question contingent on whether they were adopters or non-adopters. This sought to identify the main reasons farmers decided to either adopt or not adopt precision farming techniques.

Reasons for adoption were classified into financial reasons – "financial gain", "financial reasons", less costs", "Money/return on investment"; physical efficiencies "need to gain time" "Less time needed", "increase of yield and cost reduction"; and ease of use of the technology, "ease of working in the field", "user friendliness, to be able to work after sunset, work more precise". "The increase in efficiency and soil conservation".

Reasons for non-adoption were also based on financial reasons "financial difficulty, no subsidy," "Cost of the technology", "The cost factor". Related to this several farmers highlighted structural and farm related factors "Farm size is too small for PFT to be economically viable". "Arable land too small", "Because it does not make sense for our operation our enterprise is too small" and "Will run the farm for 5 years and then lease".

In addition, lack of knowledge and learning around the technology and uncertainty whether the technology would have an effect on the enterprise was raised, "Don't know it very well, too new technology", "lack of information about PAT, not many working PAT of other farmers or sellers so that I could see the technology working", "Not enough proof of the effects". In addition, some technological concerns were raised by one German farmer "The signal cover of RTK and GPS does not fit with us. Neighbors have already tried it, but it has not worked at my adjacent areas”.

Summary

This report was prepared to outline the main analysis methodology and present results of the piloting of the survey across the five targeted European regions. The regions showed variable rates of adoption of machine guidance and only three farmers were MG+VRNT adopters. Consequently, results are only for illustrative purposes and do not reflect any conclusions on uptake of PATs.

Appendix A: Pilot Questionnaire

Precision Agriculture Uptake Survey Pilot Version

Instructions for interviewer, please state: '*We are conducting work for the Joint Research Centre on the use precision agriculture technologies and its impacts on wheat and potato sectors'.*

Q1 Did you grow wheat or potatoes in the last cropping seasons

☐ Yes

☐ No (If NO then Interviewer thanks them for their time)

Would you mind taking the next 15 minutes to help complete the following questions regarding your thoughts on precision agriculture. This would help inform us in understanding how precision agricultural technologies has impacted the farm. We will not ask your name and all data will be treated anonymously'.

For the Interviewer: This section should be completed by the interviewer prior to the interview

Q2 Interviewer name

☐ A

☐ B

☐ C

Q3 Questionnaire ID

☐☐☐☐

Q4 Region

☐ A

☐ B

☐ C

☐ D

☐ E

Q5 Date of interview

____

Q6 Event at which questionnaire was administered

____

Section 1: Area of crop grown

Instructions to Interviewer: This survey is focused on those growing either wheat and/or potatoes. Please state '*We'd first like to ask questions on the amount of wheat and/or potatoes you grew in the last cropping year?'.*

Q7 Did you grow any **wheat** in the last season?

- ☐ Yes
- ☐ No **(go to Q11)**

Q8 What area of winter wheat grown in the last crop year

____

Q9 In what unit?

- ☐ Acres
- ☐ Hectares

Q10 What is the area of spring wheat grown in the last crop year

____

Q11 Did you grow any area of **potatoes** in the last season?

- ☐ Yes
- ☐ No (**goto Q14)**

Q12 What is the area of ware potatoes grown in the last crop year

____

Q13 What is the area of seed potatoes grown in the last crop year

____

Section 2: Identifying MG+VRNT Adoption, MG Only Adoption and Non-Adoption

***We would like to ask you about* Variable rate nitrogen application *(VRNT)'* (Interviewer shows card 1 with description).**

Then the interviewer asks the filter question:

Q14 Are you aware of **Variable rate nitrogen application *(VRNT*?)**

- ☐ Yes, I am aware of VRNT
- ☐ No, I was not aware of VRNT **(goto Q17)**

Q15 Did you use VRTN in the last cropping season

	Tick if this applies	*{Go to:}*
Yes, I own a variable rate technology and have used it in the last cropping season	☐	Q16
Yes, I rented the variable rate technology and have used it in the last cropping seasons	☐	Q16
Yes, I have used/tried variable rate technology in the past but no longer use it	☐	Q17
No, I haven't used variable rate technology but am planning to adopt it in the future	☐	Q17
No, I haven't used variable rate technology and do not plan to adopt it in the future	☐	Q17

Q16 When did you start using the VRTN PAT on your farm (please state the cropping year) (for the farmers that have tried it, state the cropping years range)

____

GO TO Q24: SECTION 3 ON IMPACTS OF ADOPTION

We would like to ask you about Machine Guidance (Interviewer shows card 2 with description).

Then the interviewer asks the filter question (Q17)

Q17 Are you aware of Machinery Guidance?

- ☐ Yes, I am aware of Machinery Guidance
- ☐ No, I was not aware of Machinery Guidance (**goto Q29**)

Q18 Did you use machine guidance in the last cropping season

	Tick if this applies	{Go to:}
Yes, I own a machine guidance and have used it in the last cropping season	☐	Q19
Yes, I rented the machine guidance and have used it in the last cropping seasons	☐	Q19
Yes, I have used/tried machine guidance but no longer use it	☐	Q29
No, I haven't used machine guidance but am planning to adopt it in the future	☐	Q29
No, I haven't used machine guidance and do not plan to adopt it in the future	☐	Q29

Q19 When did you start using the machine guidance on your farm? (please state the cropping year) (for the farmers that have tried it, state the cropping years range)

____

THEN GO TO Q20 :SECTION 3 ON IMPACTS OF ADOPTION

Section 3: Impacts of Adoption

'This section seeks to examine the effects of each PAT on changes to the farm business and performance. Here we would like you to think about how the PAT has changed any of your key inputs and outputs within cropping enterprises. We would like to have estimates at the field level, but if not please try your best to estimate at the enterprise or farm level.'

Machine Guidance & Wheat

ONLY ASK IF RESPONDED YES TO HAVING USED MACHINE GUIDANCE (Q18 (1 & 2)) AND YES TO GROWING WHEAT

Q20 For Machine Guidance what in your opinion have been the impacts on your wheat enterprise?(please, provide the impacts for the wheat cropping area where you are using machine guidance

	Reduction						**Increase**							
	More than 40%	31-40%	21-30%	11-20%	@ 5-10%	No perceived effect	5-10	11%-20%	21-30%	31-40%	More than 40%	At Field Level? (Y)	At enterprise level? (Y)	At Farm Level (Y)
Yield (Kg per ha)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Fuel quantity (litres per ha)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Nitrogen fertiliser quantity applied (N Kg/ ha)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Cost of hired labour (£)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Labour Training Time (hrs)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Management Time (hrs)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Time spent in field (hrs)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Machinery costs (£)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Repairs and Spares (£)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Contractor costs (£)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Q21 How many years do you expect to recover the investment made on machine guidance?

State years ☐☐☐☐☐_________

IF RESPONDED NO TO Q11 THEN GOTO SECTION 4

Machine Guidance & Potatoes

ONLY ASK IF RESPONDED YES TO HAVING USED MACHINE GUIDANCE (Q18 (1&2)) AND YES TO GROWING POTATOES (Q11).

Q22 For Machine Guidance what in your opinion have been the impacts on your potato enterprise?

	Reduction						**Increase**							
	More than 40%	31-40%	21-30%	11-20%	@ 5-10%	No perceived effect	5-10	11%-20%	21-30%	31-40%	More than 40%	At Field Level? (Y)	At enterprise level? (Y)	At Farm Level (Y)
Yield (Kg per ha)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Fuel quantity (litres per ha)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Nitrogen fertiliser quantity applied (N Kg/ ha)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Cost of hired labour (£)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Labour Training Time (hrs)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Management Time (hrs)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Time spent in field (hrs)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Machinery costs (£)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Repairs and Spares (£)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Contractor costs (£)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Q23 How many years do you expect to recover the investment made on machine guidance?

State years ☐☐☐☐☐_________

GO TO SECTION 4

Variable rate nitrogen application and Wheat

ONLY ASK IF RESPONDED YES TO VRNT (Q15(1&2)) AND YES TO GROWING WHEAT (Q7).

Q24 For Variable Rate Nitrogen Application what in your opinion have been the impacts on your wheat enterprise?

	Reduction						Increase							
	More than 40%	31-40%	21-30%	11-20%	@ 5-10%	No perceived effect	5-10	11 %-20%	21-30%	31-40%	More than 40%	At Field Level? (Y)	At enterprise level? (Y)	At Farm Level (Y)
Yield (Kg per ha)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Fuel quantity (litres per ha)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Nitrogen fertiliser quantity applied (N Kg/ ha)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Cost of hired labour (£)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Labour Training Time (hrs)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Management Time (hrs)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Time spent in field (hrs)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Machinery costs (£)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Repairs and Spares (£)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Contractor costs (£)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Q25 How many years do you expect to recover the investment made on VRT?

State years ☐☐☐☐☐_________

INTERVIEWER: IF RESPONDED NO TO Q11 THEN GOTO SECTION 4

Variable rate nitrogen application and Potatoes

ONLY ASK IF RESPONDED YES TO VRNT (Q15 (1&2)) AND YES TO POTATO GROWING Q12.

Q26 For Variable Rate Nitrogen Application what in your opinion have been the impacts on your potato enterprise?

	Reduction						Increase							
	More than 40 %	31-40 %	21-30 %	11-20 %	@ 5-10 %	No perceived effect	5-10	11 %-20 %	21-30 %	31-40 %	More than 40 %	At Field Level? (Y)	At enterprise level? (Y)	At Farm Level (Y)
Yield (Kg per ha)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Fuel quantity (litres per ha)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Nitrogen fertiliser quantity applied (N Kg/ ha)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Cost of hired labour (£)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Labour Training Time (hrs)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Management Time (hrs)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Time spent in field (hrs)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Machinery costs (£)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Repairs and Spares (£)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Contractor costs (£)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Q27 How many years do you expect to recover the investment made on VRT?

State years ☐☐☐☐☐_________

GOTO SECTION 4

Section 4: Adoption Planning

Q28 Who influenced your adoption decision **(ONLY ASK IF THEY ARE MG ONLY OR MG+VRNT ADOPTERS)**

		Strong Influence	Some Effect	No Effect
A	Local farm advisor or extension agent	☐	☐	☐
B	Industry salesperson or machinery dealer	☐	☐	☐
C	Input-supplier	☐	☐	☐
D	Other farmers	☐	☐	☐
E	Co-operative	☐	☐	☐
F	Machinery collective/machinery ring	☐	☐	☐
G	Contractor	☐	☐	☐
H	Visit to a trade fair	☐	☐	☐
I	Researchers	☐	☐	☐
J	College/University open days	☐	☐	☐
K	Farmer's Union	☐	☐	☐
L	Other (*please state*)			

____

Q29 Are you planning to adopt any of these PATs in the future?

		Yes (already adopted)	Yes in 5-10 years	No intention to adopt
A	Machine Guidance (+/-2cm)	☐	☐	☐
B	Machine Guidance (+/-40cm)	☐	☐	☐
C	Variable Rate technology for nitrogen	☐	☐	☐
D	Controlled traffic farming	☐	☐	☐
E	Variable rate Irrigation	☐	☐	☐
F	Variable rate pesticide application	☐	☐	☐
G	Variable rate seeding/planting	☐	☐	☐
H	Precision physical weeding	☐	☐	☐

Q30 Could you indicate what incentives would encourage you to increase your use and adoption of precision agriculture technology?

		This would most definitely increase my use of PATS	This would most probably increase my use of PATS	This would have no effect on my decision
A	More support for training of my staff	☐	☐	☐
B	Confidence that yields would increase	☐	☐	☐
C	Confidence that my costs would reduce	☐	☐	☐
D	More support for training for myself and family	☐	☐	☐
E	More technical support from sales people	☐	☐	☐
F	Directed subsidy support for uptake of PATS	☐	☐	☐
G	Financial support from tax breaks	☐	☐	☐
H	A 10% reduction in the present cost of the technology	☐	☐	☐

Q31 Are there other incentives that would encourage you to increase your use and adoption of precision agriculture?

____

____

____

Reasons for Adoption : <u>Only if They adopted VRNT or Machine Guidance</u>

Q32 *Could you tell us the main reasons you decided to use or adopt PFT?*

____

____

____

Reasons for Non-Adoption : <u>Only if They DID NOT adopt VRNT or Machine Guidance</u>

Q33 *Why did you decide not to use or adopt PFT?*

____

____

____

Section 5: Farm and Farmer Characteristics

Interviewer states: The next section asks you about you and your farm.

Q34 Where the farm is based

- ☐ A
- ☐ B
- ☐ C
- ☐ D
- ☐ E
- ☐ F
- ☐ G
- ☐ H

Q35 What is the total utilised agricultural area of the farm ?

____

Q36 In what unit?

- ☐ Acres
- ☐ Hectares

Q37 How much of this is arable land?

____

Q38 How much is permanent pasture

____

Q39 How much is rough grazing

____

Q40 How much is other land?

____

Q41 How many full time employed staff do you employ on your holding?

____

Q42 How many part-time and seasonal staff did you employ on your holding in the last cropping season?

____

Q43 What is your role in the farm?

	Owner	Manag er	Tenant Farmer	Busine ss Partner	Other
Are you	☐	☐	☐	☐	☐

Please state if other

Q44 Education and Training

	School Only	Vocational training in a non-agricultural subject	Vocational training in an agricultural subject	HNC/Diploma in agriculture or related subject	Degree in agriculture or related subject	HNC/Degree in Non-Agricultural Subject	Higher than Degree (Masters/PhD)
Please state your highest award	☐	☐	☐	☐	☐	☐	☐

Other: ____

Q45 Please indicate your age ________________________________

Q46 Are you a member of a co-operative?

- ☐ Yes, marketing co-op
- ☐ Yes, machinery collective/machinery ring
- ☐ No

Q47 Could you indicate which of the following gross income categories would best apply to your farm? Please take into account the total income: salaries and/or other incomes of all family members.

- ☐ Under £12,000
- ☐ Between €12,000-24,000
- ☐ Between €25,000-39,000
- ☐ Between €40,000-60,000
- ☐ Between €61,000-72,000
- ☐ Over €72,000
- ☐ No answer

Q48 Could you indicate roughly how much of your farm income comes from wheat (in percentage terms)

	0%	1-20%	21-40%	41-60%	61-80%	81-90%	100%
Percentage of farm income	☐	☐	☐	☐	☐	☐	☐

Q49 Could you indicate roughly how much of your farm income comes from potatoes (in percentage terms)

	0%	1-20%	21-40%	41-60%	61-80%	81-90%	100%
Percentage of farm income	☐	☐	☐	☐	☐	☐	☐

Q50 We are very grateful for your time. All responses will be treated in the utmost confidence. We expect to have completed our analysis by Winter 2016. Would you be interested in receiving a short communication of the general results of the survey? If so please supply your email address

Appendix B: Supplementary materials presented during interviews

1 Machine guidance systems

Guidance technologies are systems that pilot machinery using GPS. They enable farm machinery to follow straight lines to reduce overlaps and avoid gaps of the tractor and equipment passes.

In order to use machine guidance systems, one needs a GPS receiver in the tractor or mounted on the machinery and a lightbar or a display on-board to provide driving direction. A more advanced option is to use machine auto-guidance systems (or auto-steering), which are integrated in the tractor's hydraulics and can directly take over steering operations.

Machine guidance systems come in different accuracies, entry level ones at ±40 cm to the highest accuracies up to ±2 cm. Besides guidance, most of these systems can also monitor the performance of the machinery (e.g. fuel usage, engine load) and provide tracking options that help integrate machine movements and operations in farm management information systems. As such, they are also essential parts of other precision farming technologies, like controlled traffic farming (permanent traffic lanes), variable rate seeding and fertiliser application.

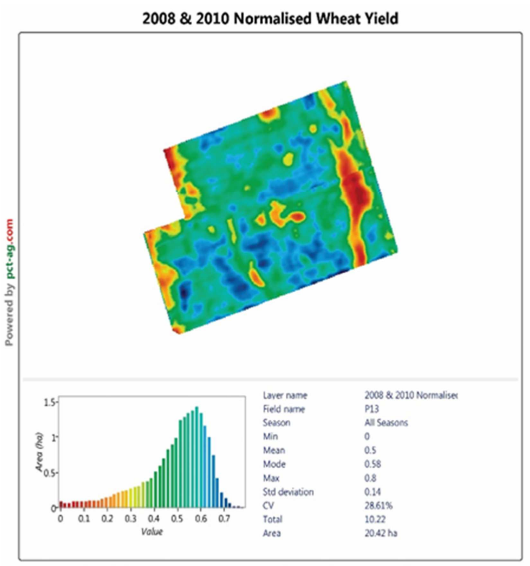
Santana-Fernández et al. (2010) Sensors 10, 10435-10447

2 Variable rate application – in particular variable rate nitrogen application

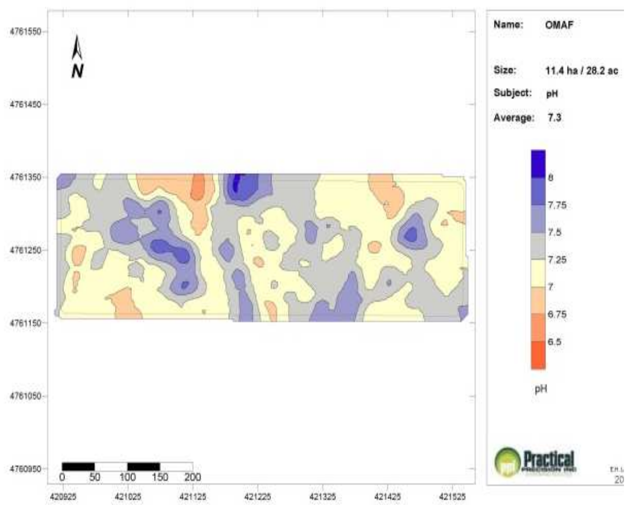
Variable rate application technologies (VRT) enable changes in the application rate to match actual need for fertiliser, lime, seeds, etc. in that precise location within the field. The basic idea is that, according to an electronic map or sensors, a control system calculates the input needs of the soil or plants and transfers the information to a controller, which delivers the input to the location.

VRT requires information on the soil properties and/or the crop properties to optimise application rate. The application rate is optimised based on measurements (e.g. soil conductivity, soil pH, former yield and grain protein performance, current crop nitrogen content).

Beyond the measurements and sensors machine guidance technologies are also used on the tractor and specific applicators with application control systems are required.



Source: www.agrioptics.co.nz



Source: www.ontariograinfarmer.ca

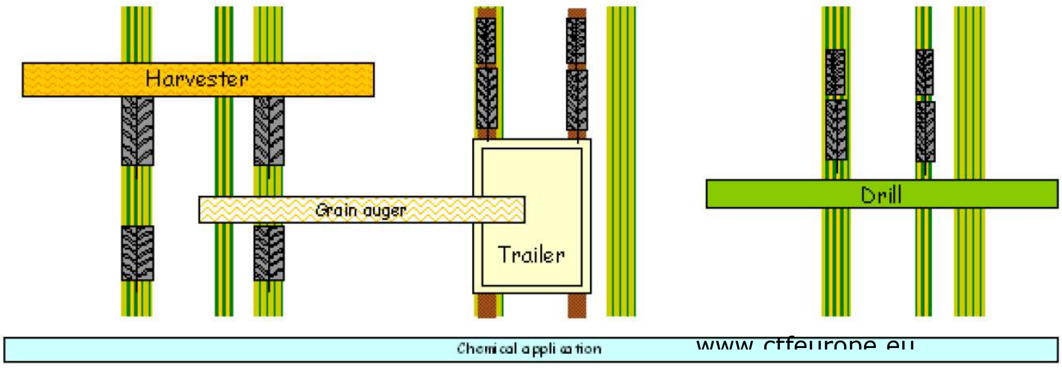
Source: blog.newtoncrouch.com

Source: http://www.purdue.ed

4 Controlled Traffic Farming

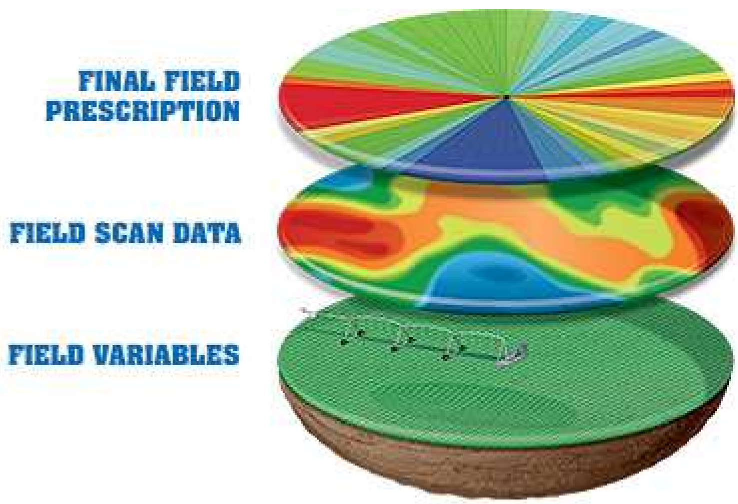
Controlled Traffic Farming (CTF) is a system which confines all machinery loads to the least possible area of permanent traffic lanes. Current farming systems allow machines to run at random over the land, potentially causing compaction on a large part of the field. CTF can reduce tracking surface, and thus compaction, to just 15% of the field area. The permanent traffic lanes are normally parallel to each other. CTF allows optimised driving patterns and more efficient operations (i.e. reduced overlaps). As all operations are aligned, input applications can be targeted very precisely relative to the crop rows.

For CTF permanent traffic lanes need to be planned based on the field and crop characteristics; in a combination suitable both for wider machinery (e.g. harvesters) and narrower ones. Machine guidance system is needed for CTF, and some of the machinery might have to be changed to be compatible with each other.



5 Variable Rate Irrigation

Variable rate irrigation (VRI) systems (also called precision irrigation systems) customise water application based on the crop's needs, derived from mapped topography information, soil data maps, prior yield data, and information about the crop's status. This can, for example, be achieved by pulsing sprinklers or boom sections on and off and/or controlling the system speed to modify the application depth along the length of the irrigator. VRI uses GPS technology and the control systems which can be easily retrofitted onto uniform sprinkler systems.



Source:http://www.reinke.com

Source: http://www.croplife.com

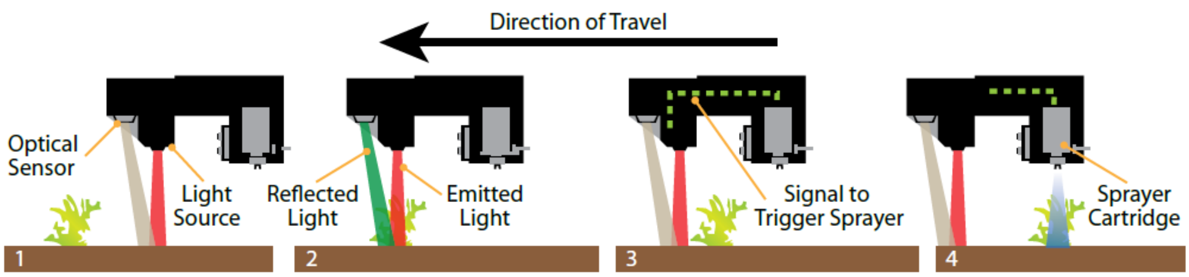
6 Variable Rate Pesticide Application

Variable rate pesticide application technologies enable changes in the application rate to match actual or potential pest stress in the field and avoid application to undesired areas of the field or plant canopies. They can also significantly reduce spray overlap. Current commercial applications focus on herbicide spraying.

One type of VR pesticide application adjusts the application rate based on a prescription map. Using the field position from a GPS receiver and a prescription map of desired rate, the input concentration is changed as the applicator moves through the field.

Source:www.deere.co.uk

The other type of VR pesticide application is based on a real-time sensor, which controls the application rate based on the current situation of pest stress or canopy characteristics, without the generation of a prescription map. These systems involve either contact (e.g. mechanical) or non-contact (e.g. camera) sensing to identify either pests that need to be controlled or the crop and foliage/canopy that needs to be protected.



Source: www.trimble.com

7 Variable Rate Seeding/Planting

Variable rate planters/seeders modify the rate of planting and seeding during application. This is often accomplished by disconnecting the planting/seeding system from the ground drive wheel, which normally keeps the planting/seeding rate constant when the speed of the tractor varies. By driving the planting/seeding system with an independent engine, gear box or hydraulic drive, the planting/seeding rate can be adjusted to the local soil potential. Besides being used for varying seed density, the technology of VRA seeding is also used to eliminate double planting in headlands and point rows.

The planting map is based on information like soil map, topography, irrigation, and long-term yield history. A GPS system and a seeder/planter equipped with a suitable control mechanism are also required for the system.

Source:www.southwestag.ca

Source:www.no-tillfarmer.com

8 Precision Physical Weeding

Precision physical weeding technologies enable changes in the configuration of mechanical weeders or weed burners (e.g. in the position of or the resistance exerted by the tines of a harrow or the flow rate of the fuel) during weeding, to match weed presence and/or density in the field. The challenge of physical weeding is to obtain a high degree of selective weed control without producing considerable crop damage as a result of weeding. The technology is still in an experimental phase.

Source:Peteinatos et al. (2015)

Source:www.rhea-project.eu

ANNEX 5: Survey results

Survey Results

Deliverable 5

PRECISION AGRICULTURE project

contract no. 199163-2015 A08-NL

Authors:

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Table of Contents

3 Introduction

This report presents the results of a survey of five European regions, focused on the uptake and perceived effects of precision agricultural technologies (PATs) on wheat and potato cropping enterprises.

Two PATs have been identified as the most promising mitigation technologies for investigation in this study: i) machine guidance technology and ii) variable rate nitrogen application technology (VRNT).

Machine guidance is defined as: "*Guidance technologies are systems that pilot machinery using GPS. They enable farm machinery to follow straight lines to reduce overlaps and avoid gaps of the tractor and equipment passes. In order to use machine guidance systems, one needs a GPS receiver in the tractor or mounted on the machinery and a lightbar or a display on-board to provide driving direction. A more advanced option is to use machine auto-guidance systems (or auto-steering), which are integrated in the tractor's hydraulics and can directly take over steering operations*".

Variable rate nitrogen application technology (VRNT) is defined as: "*enable changes in the application rate to match actual need for fertiliser in that precise location within the field. The basic idea is that, according to an electronic map or sensors, a control system calculates the input needs of the soil or plants and transfers the information to a controller, which delivers the input to the location".*

4 Data Collection

2.1 Target population

The population of study were farmers growing wheat and/or potatoes within the cropping season 2015/16. The sample was non-random in that it was targeted to meet quotas for adoption, namely:

- Non-adopters – those who have not adopted machine guidance or Variable rate nitrogen application (VRNT)
- MG Only – those who have adopted machine guidance alone
- MG+VRNT – adoption of VRNT requires machine guidance, so therefore are deemed to be full adopters

2.2 Recruitment

Principal recruitment was through specialist fairs, as well as related events specific to each region, namely demonstration days, farmer discussion and study groups, monitor farm networks and operation groups which exist within the candidate countries. These events were focused at the commodity or the technology level and were farmers most likely to have adopted the target technologies would attend. In addition, farm advisors were used in some regions to contact farmers in order to identify adopters. Private sector companies supplying equipment, e.g. Yaris, were also contacted to identify potential adopters.

This approach enabled targeting of those most likely to have adopted machine guidance and VRNT within the countries. Given the time constraint on potential interviewees, initial contacts were made at these events and follow up phone calls were used to complete the questionnaire to make up the quota within most countries.

The questionnaire was prepared as both an electronic and a paper version, which were to be administered at fairs and events. Data were collected through the core research team, with associated research assistants from within each region. Within Germany and the UK, a telephone survey was used to target farmers who were adopters of MG+VRNT. Before the interviews a training event was held with surveyors to explain the logic of the survey, demonstrate the survey operation and clarify any issues with interviewers. The interviewers of the pilot (described in D4) led the administration of the interviews for the main survey.

A web based platform was also established within the SNAP survey software framework for ease of data collection, which provided in the home language of each region for data collectors. This enabled centralisation of data within a harmonised format, which was held on the secure server of the SNAP webhost system and offer ease of download into .csv format. In the case of Germany, a telephone survey was operated, using the main questionnaire but recording to a computer assisted telephone interview system. Responses, which followed the main questionnaire, were harmonised to match the two data sources. For the UK, to increase the number of MG+VRNT adopters in the sample, a telephone survey was conducted and data entered directly into the SNAP web-host.

2.3 Data Preparation and Analysis

The data, collected electronically, was collated on a central server and downloadable for analysis as a .csv file. This was imported into STATA 14.2 (Stata Corp., 2016) for analysis.

Data analysis consisted of five principle areas, namely:

1) Descriptive statistics per region identifying characteristics of respondents,
2) Adoption and Non-Adoption levels per region, and the characteristics of respondents,
3) Perceived impacts of these adoptions,
4) Influences on adoption for those adopting PATs, and
5) Intentions and incentives related towards adoption.

Some farmers stated their area in terms of acres and these were converted in hectares to create a unified data set. Similarly, for the UK income figures were given in pounds which were converted into euros (at a rate of 1.23 Euros to the Pound).

To assess the levels of adoption and non-adoption farmers were given a range of choices of adoption over the last cropping season:

- Yes, I own a variable rate technology/machine guidance (option 1)
- Yes I rented the variable rate technology/machine guidance (option 2)
- Yes I have used/tried variable rate technology/machine guidance (option 3)
- No I haven't but I'm planning to adopt variable rate technology/machine guidance (option 4)
- No, I haven't and I do not plan to adopt variable rate technology/machine guidance (option 5)

Adopters were identified as those who own or rent (options 1 or 2) as oppose to those who did not adopt (options 3, 4 or 5). Accordingly, two further binary variables were created within STATA to indicate adoption of machine guidance ('adoptmg') and VRNT ('adoptvrnt').

In order to conduct the analysis, the data were encoded into numeric values. A spreadsheet is supplied with this deliverable giving both the textual and numeric data, along with a list of all categories used within the numeric analysis.

It is also important to note that the sample was not random but targeted with specific quotas for response within each adoption category. Therefore, the survey would not be expected to be representative of a particular region but more representative of the adoption profile of precision agricultural technologies within cropping farms within these regions.

5 Results

3.1. Belgium

Awareness and Adoption of PA technologies

Table 1 shows the responses to the questions *"Are you aware of Variable Rate Nitrogen Application" and "Are you aware of Machinery Guidance?"* This was a simple yes or no question and the table shows the distribution of awareness of the technologies.

Table 1. Awareness of precision agriculture technologies, percentage

	MG + VRNT	MG Only
Not aware	34%	10%
Aware	66%	90%

With machine guidance only, as would be expected, the majority of farmers were aware of this technology, whereas less of the farmers were aware of MG+VRNT.

The table below shows the overall adoption levels of farmers within Belgium.

Table 2. Level of adoption and non-adoption of precision agricultural technologies, percentage and number per technology

	No Adoption	MG Only	MG +VRNT
Number of respondents	150	42	4
Percentage	77%	21%	2%

What is clear is that only low levels of adoption were found for the Belgium farmers. Only 21% (42 farmers) had adopted machine guidance, whereas 2% (4 farmers) had only adopted MG+ VRNT. Given this low level of uptake a range of methods were used to recruit more VRNT and MG adopter farmers into the survey, however though farmer organisations and farming technology suppliers, e.g. Yaris, were contacted we found no further VRNT and MG adopters in Belgium.

General Descriptors

The distribution by cropping activity is shown in table 3 which indicates a fairly even spread between specialised wheat and potato growers and those farmers who had grown both in the last cropping season (in this case 2015/2016).

Table 3. Distribution of crops grown within the sample, numbers and percentages

	Wheat	Potatoes	Wheat & Potatoes
Number of respondents	61	68	67
Percentage	31%	35%	34%

Characteristics of Adopters versus Non-Adopters

Table 4 shows the characteristics of the adoption classes and the non-adopters. Where continuous variables were used, such as land area and staff numbers, the mean and standard deviation is given. For categorical responses, such as membership of a co-operatives, the median is presented.

There is bias in the sample towards non-adopters, with very few farmers indicating they had the MG + VRNT technology package. Between MG Only and non-adopters, there seems little difference in characteristics, indicating similar income brackets, management structures and educational levels. However, MG Only adopters managed a larger farm area and also were generally younger than non-adopters. Moreover, due to this larger area, MG Only adopters employed more part-time staff. As noted above, the MG+VRNT adopters sample was too small to draw any inferences.

Perceived Impacts

Farmers who had adopted PATs were asked to estimate the effects of adoption on a range of variables, such as yield, nitrogen use and other variable or fixed costs on the enterprises in which they had applied them. Tables 5 and 6 shows the frequency of response for each impact across the two adoption choice and two enterprise applications. These clearly show that for most impacts, the most frequent choice was no perceived impact.

Table 4. Characteristics of adoption and non-adoption, descriptive statistics

	Non-Adoption (n=150)		MG Only (n=42)		MG +VRNT (n=4)	
	Mean	*SD*	Mean	*SD*	Mean	*SD*
Winter Wheat, ha	5.2	*7.0*	10.6	*10.2*	7.3	*3.8*
Spring Wheat, ha	0.0	*0.2*	0.1	*0.8*	0.0	*0.0*
Ware Potatoes, ha	4.8	*8.5*	13.7	*15.0*	13.3	*15.9*
Seed Potatoes, ha	0.0	*0.0*	3.1	*15.3*	0.3	*0.5*
UAA, ha	35.7	*24.4*	70.6	*38.2*	49.3	*24.4*
Arable Area, ha	25.4	*18.5*	57.1	*37.5*	40.0	*32.3*
Full-Time Employees	0.0	*0.4*	0.1	*0.2*	0.0	*0.0*
Family Members	1.4	*0.9*	1.6	*0.9*	1.8	*1.0*
Part-Time & Seasonal Employees	0.8	*1.1*	1.2	*1.9*	2.3	*2.6*
	Median		Median		Median	
Management Structure	Owner		Owner		Owner	
Education Category	Vocational training in an agricultural subject		Vocational training in an agricultural subject		School Only	
Age Category	50-54		45-49		50-54	
Membership of Co-operative	Yes, machinery collective/machinery ring		Yes, machinery collective/machinery ring		No	
Income Category	Between €70,000-80,000		Between €70,000-80,002		Between €200,000-300,000	
%tage share income from wheat	1-20%		1-20%		1-20%	
%tage share income from potatoes	1-20%		1-20%		21-40%	

Table 5a. Perceived impacts on the wheat enterprise of MG only adoption, percentage distribution per impact

	Reduction						Increase				
	>40%	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)						72%	24%	3%			
Fuel quantity (litres per ha)				3%	48%	48%					
Nitrogen fertiliser quantity applied (N Kg/ ha)					48%	48%	3%				
Cost of hired labour (euro)					14%	86%					
Labour Training Time (hrs)							86%	7%	7%		
Management Time (hrs)					3%	69%	24%	3%			
Time spent in field (hrs)			3%	14%	48%	28%	7%				
Repairs and Spares (euro)						86%	10%	3%			
Contractor costs (euro)					10%	90%					

Table 5b. Perceived impacts on the potato enterprise of MG only adoption, percentage distribution per impact

	Reduction						Increase				
	>40%	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)						76%	17%	7%			
Fuel quantity (litres per ha)				10%	28%	62%					
Nitrogen fertiliser quantity applied (N Kg/ ha)				3%	55%	41%					
Cost of hired labour (euro)				3%	10%	86%					
Labour Training Time (hrs)						93%		3%	3%		
Management Time (hrs)						72%	28%				
Time spent in field (hrs)				14%	48%	28%	7%	3%			
Repairs and Spares (euro)					3%	79%	14%	3%			
Contractor costs (euro)			3%		14%	83%					

For machine guidance only adoption, there is some perceived effect on fuel quantity and nitrogen use, which is reduced between 5-10% at the field level, similarly the time spent in the field is also seen to reduced by around 5-10% as well.

Table 6a. Perceived impacts on the wheat enterprise of MG+VRNT adoption, percentage distribution per impact

	Reduction						Increase				
	>40%	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)						25%	75%				
Fuel quantity (litres per ha)					25%	50%		25%			
Nitrogen fertiliser quantity applied (N Kg/ ha)					50%	50%					
Cost of hired labour (euro)						75%		25%			
Labour Training Time (hrs)						50%	50%				
Management Time (hrs)						50%	50%				
Time spent in field (hrs)					25%	25%	50%				
Repairs and Spares (euro)						100%					
Contractor costs (euro)						100%					

Table 6b. Perceived impacts on the potato enterprise of MG+VRNT adoption, percentage distribution per impact

	Reduction						Increase				
	>40%	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)						33%	67%				
Fuel quantity (litres per ha)					33%	67%					
Nitrogen fertiliser quantity applied (N Kg/ ha)					33%	67%					
Cost of hired labour (euro)						100%					
Labour Training Time (hrs)						67%	33%				
Management Time (hrs)						67%	33%				
Time spent in field (hrs)					33%		67%				
Repairs and Spares (euro)						100%					
Contractor costs (euro)						100%					

For MG+VRNT, there is some perceived effect in terms of an increase in yield of 5-10% but a corresponding increase in the time spent on the enterprise, through management and labour training time.

Intentions for Adoption

Farmers were asked about their intentions towards adoption in terms of i) whether they had already adopted these PATs, ii) had no intention of adopting these PATs, or iii) intended to adopt them in 5-10 years time. Figure 1 shows the distribution of current adoption of associated PATs for those who had either adopted or not-adopted the target technologies, whereas table 7 presents the intentions of farmers assessed by those in different adoption categories[34].

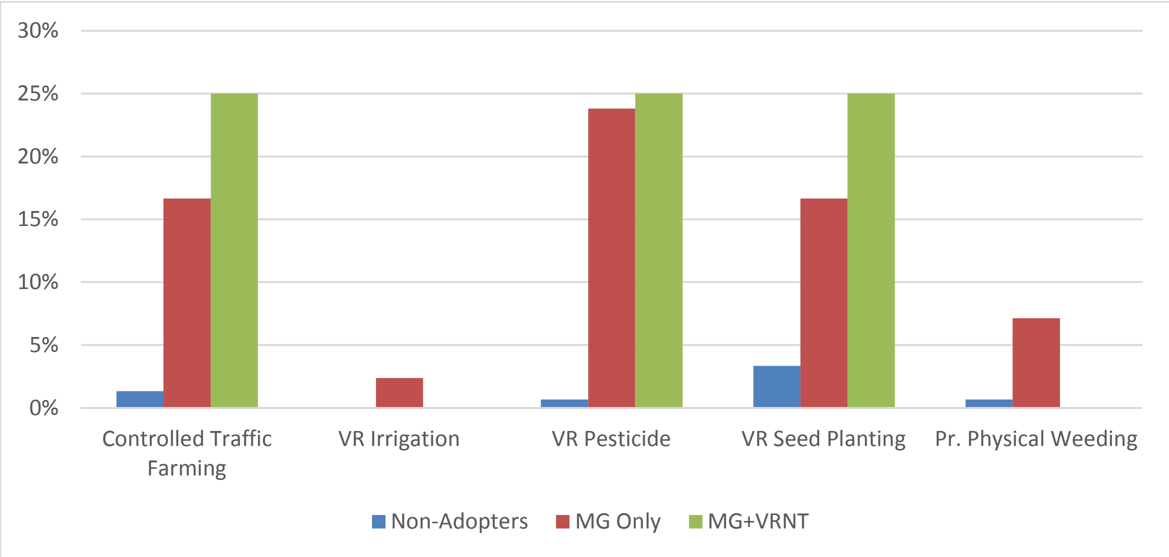

Figure 1. Current Adoption levels of related PATs by adoption class, percentage level of adoption

There is some communality between technology adoption and adoption of related technologies. This figure infers that around 15 to 25% of those who adopted MG or MG+VRNT technology have also adopted some combination of controlled traffic farmer, variable rate pesticide and variable rate seed planting.

Around 75% current non-adopters (table 7) had non-intention towards adopting the bulk of the technologies listed and this potentially presents a stark typology of non-adopters who generally do not wish to engage in PAT adoption for their farm.

MG Only adopters demonstrate a fairly even distribution of those with no intentions to adopt further and those who wish to adopt in five years' time, though higher percentages are indicated for no intention to adopt variable rate irrigation, seed planting and physical weeding technologies. Our definition of MG accommodated the range of variable widths available and consequently it seems that nearly 30% of MG adopters wish to adopt more accurate MG technology in the future.

This ambition for more accurate MG is revealed by the MG+VRNT adopters. These show extreme views towards adoption and non-adoption, driven by the low sample size of this group. As such no conclusions could be drawn on this adoption group.

[34] A list of these technologies along with their descriptions are provide in Deliverable 4.

*Table 7. Precision agricultural technologies intentions to adopt, percentage per adoption category**

	Non-Adopters (n=150)		MG Only (n=42)		MG+VRNT (n=4)	
	No intention to adopt	Yes in 5-10 years time	No intention to adopt	Yes in 5-10 years time	No intention to adopt	Yes in 5-10 years time
Machine Guidance (+/- 2cm)	75%	25%	33%	29%	25%	75%
Machine Guidance (+/- 40cm)	71%	29%	40%	0%	0%	0%
VRNT	71%	29%	45%	52%	0%	0%
Controlled Traffic Farming	73%	27%	57%	26%	75%	0%
VR Irrigation	91%	9%	90%	7%	100%	0%
VR Pesticide	65%	34%	36%	40%	25%	50%
VR Seed Planting	74%	23%	60%	24%	50%	25%
Pr. Physical Weeding	83%	16%	74%	19%	50%	50%

*The percentage level of adoption has current adoption levels of MG Only and MG+VRNT adopters removed and presented in Figure 1. Hence this table shows the intentions of the remaining level of adopters.

Reasons for adoption

Table 8 shows the responses of these farmers who had adopted the PATs in terms of what had influenced their decisions. Again, this is shown as a frequency distribution by adoption group. For all influences, the majority of farmers seem to indicate there was no effect. However, industry sales people, other farmers and visits to trade fairs had some impact on between 10-20% of respondents.

Table 8. Influences on adoption, percentage by adoption class

	MG Only (n=42)			MG+VRNT (n=4)		
	No Effect	Some Effect	Strong Influence	No Effect	Some Effect	Strong Influence
Local Farm Advisor	83%	10%	7%	75%	25%	0%
Industry Salesperson	62%	12%	26%	75%	25%	0%
Input Supplier	100%	0%	0%	100%	0%	0%
Other Farmers	71%	12%	17%	75%	25%	0%
Co-operative	95%	2%	2%	100%	0%	0%
Machinery Collective/ring	98%	2%	0%	100%	0%	0%
Contractor	88%	7%	5%	100%	0%	0%
Visit to trade fair	79%	12%	10%	75%	25%	0%
Researchers	90%	7%	2%	75%	25%	0%
College/Uni open days	90%	2%	7%	75%	25%	0%
Farmer Union	98%	2%	0%	75%	25%	0%

Incentives to adopt

All farmers were asked whether they could indicate what incentives would encourage an increase in use of precision agriculture technology. They were given a range of potential incentives and asked to indicate whether it would i) have no effect on adoption, ii) probably increase their adoption, or iii) definitely increase their adoption of PATs. Table 9 shows frequency distributions per adoption group and highlights very few incentives would encourage further adoption. However, the MG Only farmers indicated that more technical support for soil mapping, along with regulatory pressure would probably lead to an increase in their use of PATs.

Table 9. Proposed incentives and their effect on PAT adoption, frequencies by adoption class

	Non-Adopters (n=150)			MG Only (n=42)			MG+VRNT (n=4)		
	This would have no effect on my decision	This would most probably increase my use of PATS	This would definitely affect my decision	This would have no effect on my decision	This would most probably increase my use of PATS	This would definitely affect my decision	This would have no effect on my decision	This would most probably increase my use of PATS	This would definitely affect my decision
More support for training of my staff	88%	11%	1%	83%	7%	10%	100%	0%	0%
Confidence that yields would increase	62%	22%	16%	55%	14%	31%	75%	0%	25%
Confidence that my costs would reduce	59%	18%	23%	29%	17%	55%	75%	0%	25%
More support for training for myself and family	62%	25%	13%	36%	29%	36%	75%	25%	0%
More technical support from sales people	63%	27%	11%	45%	26%	29%	100%	0%	0%
Directed subsidy support for uptake of PATS	53%	22%	25%	29%	14%	57%	75%	0%	25%
Financial support from tax breaks	56%	21%	23%	29%	17%	55%	75%	0%	25%
A 10% reduction in the present cost of the technology	63%	18%	19%	36%	10%	55%	75%	0%	25%
Government support for soil mapping, by providing ground penetrating radar or intensive soil sampling	53%	31%	16%	19%	26%	55%	75%	25%	0%
Improving technology to provide working maps based on soil maps	57%	32%	11%	24%	24%	52%	75%	25%	0%
More stringent laws on pesticide and nitrogen application	55%	33%	13%	29%	29%	43%	75%	25%	0%

3.2. Greece

Awareness and Adoption of PA technologies

Table 10 shows the level of awareness to the two precision agricultural technologies.

Table 10. Awareness of precision agriculture technologies, percentage

	MG + VRNT	MG Only
Not aware	55%	12%
Aware	46%	88%

The level of awareness is high for machine guidance only, whereas it is much less for MG+VRNT. Only 46% of the sample (91 farmers) were aware of MG+VRNT, with the majority claiming they were not aware.

Table 11 shows the level of adoption across the chosen technologies and non-adopters. This shows that 71 farmers (36%) adopted machine guidance only, whereas, 27 farmers (14%) adopted VRNT.

Table 11. Level of adoption and non-adoption of precision agricultural technologies, percentage and number per technology

	Non-Adoption	MG Only	MG+VRNT
Number of respondents	102	71	27
Percentage of Sample	51%	35%	14%

General Descriptors

Half of the sample (100 respondents) grew only wheat, whereas only 8% (16 respondents) only grew cotton. The remaining 42% (84 respondents) grew both cotton and wheat.

Table 12. Distribution of crops grown within the sample, numbers and percentages

	Wheat	Cotton	Wheat & Cotton
Number of respondents	100	16	84
Percentage of Sample	50%	8%	42%

Characteristics of Adopters versus Non-Adopters

Table 13. Characteristics of adoption, descriptive statistics

	Non-Adoption (n=102)		MG Only (n=71)		MG + VRNT (n=27)	
Winter Wheat, ha	33.3	32.0	25.0	27.3	47.8	33.9
Spring Wheat, ha	14.3	22.0	36.1	36.2	43.3	42.1
Ware Potatoes, ha	12.5	15.4	14.6	23.6	55.7	52.1
Seed Potatoes, ha	0.0	0.0	0.0	0.0	0.0	0.0
UAA, ha	67.8	54.9	82.1	35.9	153.4	43.3
Arable Area, ha	67.4	54.9	82.0	36.1	153.4	43.3
Full-Time Employees	2.2	1.2	2.7	1.1	4.2	1.3
Family Members	1.8	0.7	1.9	0.7	2.2	0.9
Part-Time & Seasonal Employees	2.1	1.8	2.3	1.3	3.6	2.0

	Median	Median	Median
Management Structure	Tenant Farmer	Other*	Other*
Education Category	School Only	School Only	HNC/Diploma in agriculture or related subject
Age Category	45-49	40-44	40-44
Membership of Co-operative	No	No	No
Income Category	€70,000-80,000	€150,000-200,000	€200,000-300,000
% share income from wheat	41-60%	81-90%	41-60%
% share income from potatoes	21-40%	0%	41-60%

* Predominately these referred to various mixtures of management and tenancy arrangements.

There is some variance between those who adopted technologies and the non-adopters (Table 13). Income is significantly higher and adopters are younger. They are more likely to have a mixed management arrangement compared to non-adopters, who are mostly tenant farmers. Areas are generally larger for MG Only compared to non-adopters, and significantly higher for the MG+VRNT adopters. Accordingly, this seems to infer that the adopters and, especially, the more progressive adopters with MG+VRNT, follow the general adoption profile (outlined in D1).

Perceived Impacts

Farmers who had adopted VRNT or machine guidance were asked to estimate the effects of adoption on a range of farm level variables, such as yield, nitrogen use and other variable or fixed costs.

Table 14a. Perceived impacts on the wheat enterprise of MG only adoption, percentage distribution per impact

	Reduction						Increase				
	>40%	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)						86%	13%	1%			
Fuel quantity (l/ha)				21%	59%	20%					
Nitrogen fertiliser quantity applied (N Kg/ ha)			1%	23%	60%	16%					
Cost of hired labour (euro)				24%	30%	46%					
Labour Training Time (hrs)				1%		56%	21%	21%			
Management Time (hrs)			1%	11%	36%	33%	17%	1%			
Time spent in field (hrs)			1%	49%	47%	3%					
Repairs and Spares (euro)						94%	1%	4%			
Contractor costs (euro)						99%					1%

Table 14b. Perceived impacts on the cotton enterprise of MG only adoption, percentage distribution per impact

	Reduction						Increase				
	>40%	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)						96%	4%				
Fuel quantity (litres per ha)				18%	64%	18%					
N- fertiliser quantity applied (N Kg/ ha)				21%	61%	18%					
Cost of hired labour (euro)				7%	32%	61%					
Labour Training Time (hrs)						57%	21%	21%			
Management Time (hrs)			4%	4%	25%	46%	18%	4%			
Time spent in field (hrs)			7%	25%	61%	7%					
Repairs and Spares (euro)					4%	96%					
Contractor costs (euro)						96%					4%

Perceived impacts were small. On the wheat enterprise, there was a perceived 5-10% reduction for fuel, nitrogen and cost of hired labour for 60% of these adopters, and a significant reduction for time spent in the field of between 11-20%. For cotton, there were similar reductions in fuel and nitrogen used of between 5-10%, and time spent in the field was also found to have been reduced for a number of adopters.

Table 15a. Perceived impacts on the wheat enterprise of MG+VRNT adoption, percentage distribution per impact

	Reduction						Increase				
	>40%	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)						21%	42%	33%	4%		
Fuel quantity (litres per ha)			4%	0%	33%	58%	4%				
Nitrogen fertiliser quantity applied (N Kg/ ha)		13%	33%	50%		4%					
Cost of hired labour (euro)				4%	17%	54%	4%	17%	4%		
Labour Training Time (hrs)					4%	21%	17%	29%	21%	4%	4%
Management Time (hrs)					13%	46%	25%	13%			4%
Time spent in field (hrs)					29%	58%	13%				
Repairs and Spares (euro)					17%	75%	4%		4%		
Contractor costs (euro)						88%			4%		8%

Table 15b. Perceived impacts on the cotton enterprise of MG+VRNT adoption, percentage distribution per impact

	Reduction						Increase				
	>40%	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)						18%	47%	35%			
Fuel quantity (l/ha))					24%	71%	6%				
N- fertiliser quantity applied (N Kg/ ha)		12%	29%	53%		6%					
Cost of hired labour (euro)					18%	65%	0%	18%			
Labour Training Time (hrs)						29%	18%	35%	18%		
Management Time (hrs)					24%	41%	29%	6%			
Time spent in field (hrs)				6%	29%	47%	18%				
Repairs and Spares (euro)					24%	65%		6%	6%	0%	
Contractor costs (euro)					6%	88%					6%

The effects for MG+VRNT were more positive in terms of a noticeable effect on yield and a large effect on nitrogen use applied. However, labour training time was estimated to have increased between 11-20% for both crops. For other main factors, there was no perceived effect.

Intentions for Adoption

Figure 2 shows the distribution of current adoption of associated PATs for those who had either adopted or not-adopted the target technologies.

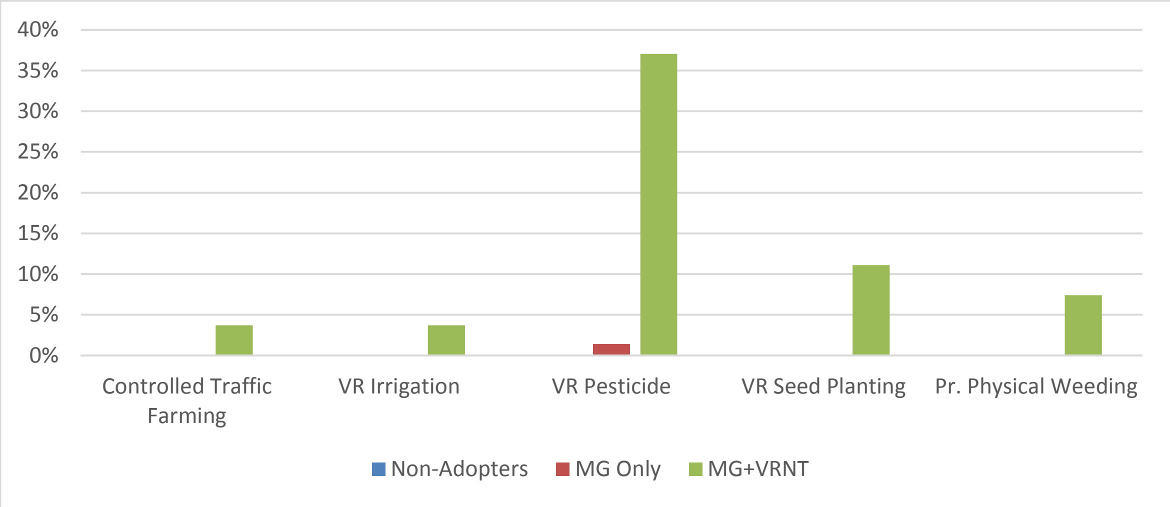

Figure 2. Current Adoption levels of related PATs by adoption class, percentage level of adoption

Clearly, it is only MG and VRNT adopters who have adopted associated PATs. The most popular being variable rate pesticides, where over 35% of MG+VRNT adopters had also adopted this technology.

Non-adopters, similar to those in Belgium, were not likely to adopt any of the listed PATs (Table 16). Similarly, the MG Only farmers were not likely to adopt any other PATs. More intentions to adopt were found with the MG+VRNT adopters. There were stated intentions to adopt more accurate machine guidance and variable rate seed planting. A range of other technologies had also been adopted, including variable rate pesticide applicators and precision physical weeding.

*Table 16. Precision agricultural technologies intentions to adopt, percentage per adoption category**

	Non-Adoption (n=102)		MG Only (n=71)		MG + VRNT (n=27)	
	No intention to adopt	Yes in 5-10 years time	No intention to adopt	Yes in 5-10 years time	No intention to adopt	Yes in 5-10 years time
Machine Guidance (+/-2cm)	78%	22%	46%	48%	11%	52%
Machine Guidance (+/-40cm)	54%	46%	6%	1%	30%	0%
VRNT	86%	14%	66%	34%	0%	0%
Controlled Traffic Farming	98%	2%	99%	1%	52%	0%
VR Irrigation	97%	3%	97%	3%	56%	0%
VR Pesticide	97%	3%	90%	8%	19%	44%
VR Seed Planting	98%	2%	96%	4%	22%	67%
Pr. Physical Weeding	98%	2%	97%	3%	48%	44%

*The percentage level of adoption has current adoption levels of MG Only and MG+VRNT adopters removed and presented in Figure 2. Hence this table shows the intentions of the remaining level of adopters.

Reasons for adoption

The farmers who had either adopted MG Only or MG+VRNT were asked who influenced their adoption decision. The distribution of responses, presented as a percentage of each adoption class is shown in Table 17.

Other farmers seemed to have an influence on adoption for MG Only and MG+VRNT farmers. However, other influences were more specific to the technology adopted, with industry salespeople and trade fairs having some influence on MG Only adoption. For MG+VRNT farmers, researchers had some effect on adoption.

Table 17. Influences on adoption, percentage by adoption class

	MG Only (n=71)			MG+VRNT (n=27)		
	No Effect	Some Effect	Strong Influence	No Effect	Some Effect	Strong Influence
Local Farm Advisor	99%	1%	0%	100%	0%	0%
Industry Salesperson	42%	24%	34%	93%	0%	7%
Input Supplier	100%	0%	0%	96%	4%	0%
Other Farmers	37%	10%	54%	37%	26%	37%
Co-operative	94%	0%	6%	96%	4%	0%
Machinery Collective/ring	100%	0%	0%	93%	0%	7%
Contractor	96%	1%	3%	100%	0%	0%
Visit to trade fair	45%	13%	42%	56%	15%	30%
Researchers	85%	6%	10%	37%	30%	33%
College/Uni open days	97%	1%	1%	85%	11%	4%
Farmer Union	99%	1%	0%	96%	4%	0%

Incentives to adopt

Table 18 shows that most incentives would have some effect on adoption of PAT for Greek farmers. There is little to discriminate between the different categories of adoption and non-adoption but for farmers with MG+VRNT confidence in either yield increases or cost reductions were not relevant to the decision to adopt. Nevertheless most other incentives would encourage uptake within the farmers surveyed.

Table 18. Proposed incentives and their effect on PAT adoption, frequencies by adoption class

	Non-Adopters (n=102)			MG Only (n=71)			MG+VRNT (n=27)		
	This would have no effect on my decision	This would most probably increase my use of PATS	This would definitely affect my decision	This would have no effect on my decision	This would most probably increase my use of PATS	This would definitely affect my decision	This would have no effect on my decision	This would most probably increase my use of PATS	This would definitely affect my decision
More support for training of my staff	11%	38%	51%	3%	24%	73%	4%	22%	74%
Confidence that yields would increase	8%	21%	72%	1%	7%	92%	0%	0%	100%
Confidence that my costs would reduce	8%	15%	77%	0%	4%	96%	0%	0%	100%
More support for training for myself and family	12%	35%	53%	6%	17%	77%	0%	26%	74%
More technical support from sales people	12%	22%	67%	0%	7%	93%	0%	11%	89%
Directed subsidy support for uptake of PATS	5%	12%	83%	0%	3%	97%	0%	4%	96%
Financial support from tax breaks	6%	13%	81%	0%	6%	94%	0%	15%	85%
A 10% reduction in the present cost of the technology	46%	39%	15%	27%	38%	35%	7%	41%	52%
Government support for soil mapping	23%	39%	38%	3%	23%	75%	4%	19%	78%
Improving technology to provide working maps based on soil maps	25%	41%	34%	3%	30%	68%	0%	22%	78%
More stringent laws on pesticide and nitrogen application	47%	39%	14%	32%	38%	30%	4%	33%	63%

3.3.UK

Awareness and Adoption of PA technologies

High levels of awareness were identified for both machine guidance and VRNT within the sample. Overall, only 3 farmers were not aware of VRNT, and all farmers were aware of machine guidance.

Table 19. Awareness of precision agriculture technologies by region, percentage

	MG + VRNT	MG Only
Not aware	1%	0%
Aware	99%	100%

This high level of awareness emerges in the adoption levels, where 35% (61) of farmers have used machine guidance in the last cropping season, and 48% (96) farmers have adopted VRNT. This means that 47 farmers had neither adopted machine guidance or VRNT.

Table 20. Level of adoption and non-adoption of precision agricultural technologies, percentage and number per technology

	Non-Adoption	MG Only	MG+VRNT
Number of respondents	47	61	96
Percentage	23	30	47

General Descriptors

Table 21 shows the general spread by enterprises. Wheat or mixed cropping was mostly found within the respondents, with only 9% of the sample growing only potatoes.

Table 21. Distribution of crops grown within the sample, numbers and percentages

	Wheat	Potatoes	Wheat & Potatoes
Number of respondents	98	21	85
Percentage	48%	10%	42%

Table 22. Characteristics of adoption, descriptive statistics

	Non-Adoption (n=47)		MG Only (n=61)		MG + VRNT (n=96)	
Winter Wheat, ha	33.7	36.8	54.3	50.1	70.5	69.0
Spring Wheat, ha	11.7	14.9	30.7	36.7	35.7	42.2
Ware Potatoes, ha	4.3	10.5	7.6	13.6	5.4	10.8
Seed Potatoes, ha	5.5	10.1	7.3	13.8	4.2	9.5
UAA, ha	228.3	210.6	251.8	130.9	352.4	426.3
Arable Area, ha	166.0	119.8	209.8	112.0	252.8	163.7
Full-Time Employees	1.4	1.4	1.8	2.0	2.0	2.2
Family Members	1.4	1.1	1.5	1.3	1.2	1.1
Part-Time & Seasonal Employees	5.1	18.3	3.8	10.2	2.9	6.6
	Median		Median		Median	
Management Structure	Owner		Owner		Owner	
Education Category	Higher award in agriculture		Higher award in agriculture		Higher award in agriculture	
Age Category	55-59		55-59		50-54	
Membership of Co-operative	Yes, machinery collective/machinery ring		Yes, machinery collective/machinery ring		Yes, machinery collective/machinery ring	
Income Category	Between €100,000-150,000		Between €100,000-150,000		Between €100,000-150,000	
%tage share income from wheat	1-20%		21-40%		21-40%	
%tage share income from potatoes	1-20%		1-20%		1-20%	

Whilst farmer characteristics do not differ between non-adopters and adopters, aside from MG+VRNT adopters being younger, there is a definite growth in mean areas managed between non-adopters and adopters. MG+VRNT adopters manage the largest utilised agricultural, arable and wheat areas compared to the other adopters.

Perceived Impacts

The perceived impacts for those who had adopted MG Only or MG+ VRNT are shown in table.23 below. Clearly, we find little in terms of effect for either wheat or potato enterprises aside from a slight reduction on time spent in the field for MG Only technologies. For MG+VRNT technologies, there seems to be some slight increase in management time recorded with wheat enterprises.

Table 23a. Perceived impacts on the wheat enterprise of MG only adoption, percentage distribution per impact

	Reduction						Increase				
	>40%	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)						84%	16%				
Fuel quantity (litres per ha)					49%	49%	2%				
Nitrogen fertiliser quantity applied (N Kg/ ha)					20%	78%	2%				
Cost of hired labour (euro)					7%	85%	7%				
Labour Training Time (hrs)					7%	65%	27%				
Management Time (hrs)				2%	9%	67%	20%	2%			
Time spent in field (hrs)					55%	38%	7%				
Repairs and Spares (euro)					9%	82%	7%	2%			
Contractor costs (euro)					5%	82%	13%				

Table 23b. Perceived impacts on the potato enterprise of MG only adoption, percentage distribution per impact

	Reduction						Increase				
	>40%	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)					5%	76%	19%				
Fuel quantity (litres per ha)					29%	71%					
Nitrogen fertiliser quantity applied (N Kg/ ha)					24%	76%					
Cost of hired labour (euro)					10%	81%	10%				
Labour Training Time (hrs)				5%	5%	81%	10%				
Management Time (hrs)					15%	85%					
Time spent in field (hrs)					43%	57%					
Repairs and Spares (euro)					14%	76%	10%				
Contractor costs (euro)					10%	86%	5%				

Table 24a. Perceived impacts on the wheat enterprise of MG+VRNT adoption, percentage distribution per impact

	Reduction						Increase				
	>40%	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)					2%	46%	46%	3%	1%		1%
Fuel quantity (litres per ha)					31%	62%	6%				
Nitrogen fertiliser quantity applied (N Kg/ ha)				2%	27%	66%	5%				
Cost of hired labour (euro)				2%	10%	74%	12%		1%		1%
Labour Training Time (hrs)					5%	56%	37%		1%		1%
Management Time (hrs)					8%	33%	55%	3%	1%		
Time spent in field (hrs)				3%	30%	47%	18%		1%		
Repairs and Spares (euro)				2%	5%	72%	20%				
Contractor costs (euro)		1%		2%	6%	61%	25%	3%		1%	

Table 24b. Perceived impacts on the potato enterprise of MG+VRNT adoption, percentage distribution per impact

	Reduction						Increase				
	>40%	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)						81%	19%				
Fuel quantity (litres per ha)				5%	10%	67%	19%				
Nitrogen fertiliser quantity applied (N Kg/ ha)					24%	76%					
Cost of hired labour (euro)					10%	71%	19%				
Labour Training Time (hrs)						62%	33%	5%			
Management Time (hrs)					5%	57%	33%	5%			
Time spent in field (hrs)					29%	52%	14%	5%			
Repairs and Spares (euro)						71%	19%	10%			
Contractor costs (euro)						67%	29%		5%		

Intentions for Adoption

Figure 3. shows the level of current adoption for those who had either adopted or not-adopted the target PATs.

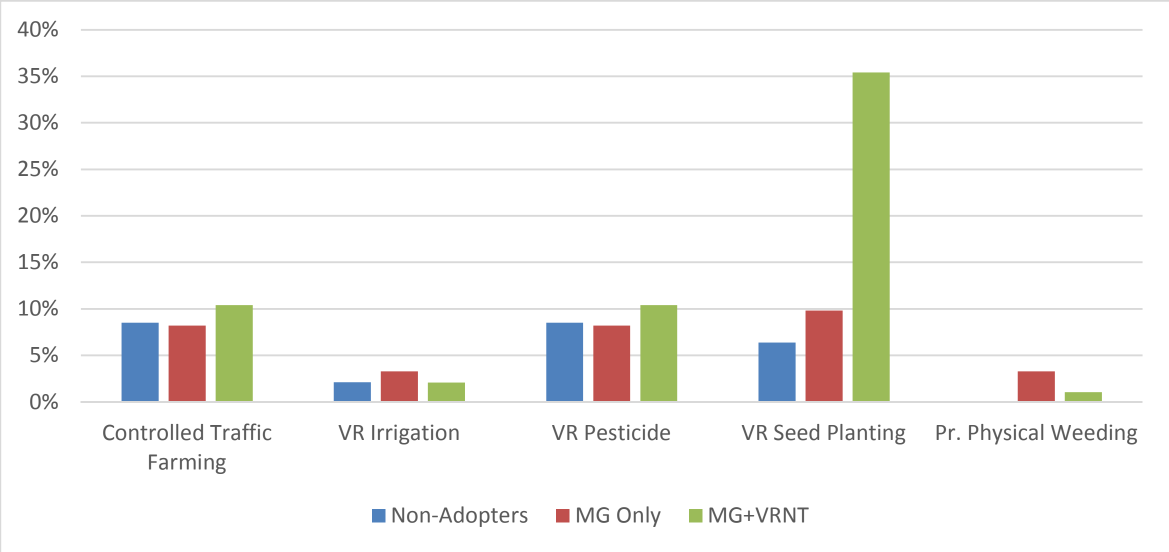

Figure 3. Current Adoption levels of related PATs by adoption class, percentage level of adoption

*Table 25. Precision agricultural technologies intentions to adopt, percentage per adoption category**

	Non-Adopters		MG Only		MG+VRNT	
	No intention to adopt	Yes in 5-10 years time	No intention to adopt	Yes in 5-10 years time	No intention to adopt	Yes in 5-10 years time
MG (+/- 2cm)	51%	49%	18%	18%	14%	28%
MG (+/- 40cm)	70%	30%	64%	0%	35%	0%
VRNT	43%	53%	38%	56%	0%	0%
Controlled Traffic Farming	81%	15%	70%	21%	61%	0%
VR Irrigation	94%	4%	89%	8%	95%	0%
VR Pesticide	55%	36%	43%	49%	27%	63%
VR Seed Planting	47%	47%	34%	56%	13%	52%
P Physical Weeding	83%	17%	85%	11%	77%	22%

*The percentage level of adoption has current adoption levels of MG Only and MG+VRNT adopters removed and presented in Figure 3. Hence this table shows the intentions of the remaining level of adopters.

There is no intention to adopt precision physical weeding, controlled traffic farming and variable rate irrigation amongst all types of adopters and non-adopters. A range of technologies have already been adopted by these farmers, with VR pesticide and VR seed planting being indicated as potential technologies which would be adopted in the future.

Reasons for adoption

The farmers who had either adopted MG Only or MG+VRNT were asked what had influenced their adoption decision. Responses are shown in Table 26.

Table 26. Influences on adoption, percentage by adoption class

	MG Only (n=61)			MG+VRNT (n=96)		
	No Effect	Some Effect	Strong Influence	No Effect	Some Effect	Strong Influence
Local Farm Advisor	64%	31%	5%	49%	35%	16%
Industry Salesperson	41%	43%	16%	46%	43%	11%
Input Supplier	70%	28%	2%	54%	32%	14%
Other Farmers	31%	51%	18%	24%	60%	16%
Co-operative	90%	7%	3%	92%	6%	2%
Machinery Collective/ring	87%	10%	3%	89%	8%	3%
Contractor	72%	18%	10%	61%	24%	15%
Visit to trade fair	52%	43%	5%	40%	46%	15%
Researchers	62%	33%	5%	42%	46%	12%
College/Uni open days	79%	18%	3%	71%	24%	5%
Farmer Union	92%	8%	0%	91%	8%	1%

Generally, other farmers and industry had some effect on the decision to adopt either MG or MG+VRNT. Other influences are more specific to the technology, i.e. visits to trade fairs, researchers and local farm advisors had some influence on the decision to adopt MG+VRNT packages.

Incentives to adopt

The table below shows response to a range of incentives by adoption within UK farmers. The effects are mixed but mostly positive. Only 'offering more support for staff' was not considered to be an incentive to adopt technologies. Secondly, the MG+VRNT adopters seem more open to incentives than MG Only adopters.

Table 27 Proposed incentives and their effect on PAT adoption, frequencies by adoption class

	Non-Adopters (n=47)			MG Only (n=61)			MG+VRNT (n=96)		
	This would have no effect on my decision	This would most probably increase my use of PATS	This would definitely affect my decision	This would have no effect on my decision	This would most probably increase my use of PATS	This would definitely affect my decision	This would have no effect on my decision	This would most probably increase my use of PATS	This would definitely affect my decision
More support for training of my staff	60%	36%	4%	62%	38%	0%	51%	36%	13%
Confidence that yields would increase	32%	47%	21%	25%	56%	20%	6%	42%	52%
Confidence that my costs would reduce	19%	47%	34%	11%	54%	34%	8%	38%	54%
More support for training for myself and family	47%	43%	11%	52%	46%	2%	39%	47%	15%
More technical support from sales people	60%	28%	13%	44%	43%	13%	31%	58%	10%
Directed subsidy support for uptake of PATS	21%	43%	36%	23%	34%	43%	8%	40%	52%
Financial support from tax breaks	30%	38%	32%	18%	54%	28%	16%	44%	41%
A 10% reduction in the present cost of the technology	53%	28%	19%	30%	48%	23%	29%	41%	30%
Government support for soil mapping,	30%	40%	30%	20%	51%	30%	21%	34%	45%
Improving technology to provide working maps based on soil maps	34%	49%	17%	28%	51%	21%	22%	48%	30%
More stringent laws on pesticide and nitrogen application	47%	38%	15%	41%	41%	18%	38%	38%	25%

3.4. Germany

Awareness and Adoption of PA technologies

Table 28 shows the level of awareness towards MG+VRNT and MG Only are high within German farmers and very few were not aware of MG+VRNT or machine guidance.

Table 28. Awareness of precision agriculture technologies by region, percentage

	MG + VRNT	MG Only
Not aware	7%	3%
Aware	93%	97%

The table below shows the levels of adoption for the two chosen technologies. Specifically, 66 farmers had adopted machine guidance, and 50 of the farmers in the sample had adopted MG+VRNT.

Table 29. Level of adoption and non-adoption of precision agricultural technologies, percentage and number per technology

	Non-Adoption	MG Only	MG+VRNT
Number of respondents	79.0	66.0	50.0
Percentage	40.5	33.9	25.6

General Descriptors

The bulk of respondents in Germany were specialised wheat enterprises. Very few specialist potato farms were identified, and 22% of the sample were growing wheat and potatoes.

Table 30. Distribution of crops grown within the sample, numbers and percentages

	Wheat	Potatoes	Wheat and potatoes
Number of respondents	144	8	43
Percentage	74%	4%	22%

Characteristics of Adopters versus Non-Adopters

Table 31 shows the characteristics of adopters against non-adopters.

Table 31. Characteristics of adoption, descriptive statistics

	Non-Adoption (n=79)		MG Only (n=66)		MG + VRNT (n=50)	
Winter Wheat, ha	25.3	28.7	147.5	244.0	284.6	352.9
Spring Wheat, ha	0.4	1.8	2.1	12.6	1.2	7.2
Ware Potatoes, ha	3.7	9.9	16.6	56.6	18.5	46.0
Seed Potatoes, ha	0.1	0.7	1.4	5.7	1.6	7.6
UAA, ha	141.7	187.3	639.9	984.1	1,046.1	1,122.0
Arable Area, ha	106.1	127.6	537.5	821.4	847.0	883.7
Full-Time Employees	1.0	2.5	6.0	12.1	10.3	13.1
Family Members	1.1	0.9	1.2	1.2	0.9	1.1
Part-Time & Seasonal Employees	0.9	1.5	3.4	7.4	2.3	3.9

	Median	Median	Median
Management Structure	Owner	Owner	Owner
Education Category	HNC/Diploma in agriculture or related subject	HNC/Diploma in agriculture or related subject	Degree in agriculture or related subject
Age Category	55-59	50-54	50-54
Membership of Co-operative	Yes, machinery collective/ ring	Yes, machinery collective/ ring	Yes, machinery collective/ ring
Income Category	Did not answer	Did not answer	Did not answer
% share income from wheat	21-40%	21-40%	21-40%
% share income from potatoes	Did not answer	Did not answer	Did not answer

Generally, adopters have a significantly higher mean area of land compared to non-adopters. Adopters are slightly younger than non-adopters. They are all members of marketing co-operatives, which suggests that this is not a significant predictor of adoption. Similarly, education is higher for MG+VRNT adopters compared to other categories. Income reflects a large amount of non-response and is therefore difficult to apply as a predictor of adoption.

Perceived Impacts

A number of impacts were perceived by the farmers when applying machine guidance. Fuel and nitrogen had a slight reduction, though time spent in the field was increased for the wheat enterprise. For potatoes the cost of hired labour was seen, by 40% of the adopters, as having reduced slightly

Table 32a. Perceived impacts on the wheat enterprise of MG only adoption, percentage distribution per impact

	Reduction						Increase				
	>40%	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)						71%	24%	6%			
Fuel quantity (litres per ha)				12%	53%	33%	2%				
Nitrogen fertiliser quantity applied (N Kg/ ha)				16%	45%	39%					
Cost of hired labour (euro)				14%	29%	53%	2%	2%			
Labour Training Time (hrs)					4%	45%	37%	10%	4%		
Management Time (hrs)				2%	12%	51%	31%	4%			
Time spent in field (hrs)			6%	8%	57%	27%	2%				
Repairs and Spares (euro)				6%	12%	65%	14%	4%			
Contractor costs (euro)				2%	8%	86%	2%	2%			

Table 32b. Perceived impacts on the potato enterprise of MG only adoption, percentage distribution per impact

	Reduction							Increase			
	>40%	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)						80%	20%				
Fuel quantity (litres per ha)					27%	73%					
Nitrogen fertiliser quantity applied (N Kg/ ha)					13%	87%					
Cost of hired labour (euro)					40%	60%					
Labour Training Time (hrs)				7%	7%	60%	27%				
Management Time (hrs)						80%	20%				
Time spent in field (hrs)				7%	33%	60%					
Repairs and Spares (euro)					7%	87%	7%				
Contractor costs (euro)						93%	7%				

Table 33a. Perceived impacts on the wheat enterprise of MG+VRNT adoption, percentage distribution per impact

	Reduction						Increase				
	>40%	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)						25%	75%	0%			
Fuel quantity (litres per ha)					25%	50%		25%			
Nitrogen fertiliser quantity applied (N Kg/ ha)					50%	50%					
Cost of hired labour (euro)						75%		25%			
Labour Training Time (hrs)						50%	50%				
Management Time (hrs)						50%	50%				
Time spent in field (hrs)					25%	25%	50%				
Repairs and Spares (euro)						100%					
Contractor costs (euro)						100%					

Table 33b. Perceived impacts on the potato enterprise of MG+VRNT adoption, percentage distribution per impact

	Reduction						Increase				
	>40 %	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)					8%	58%	25%	8%			
Fuel quantity (litres per ha)				8%	8%	83%					
Nitrogen fertiliser quantity applied (N Kg/ ha)				8%	50%	42%					
Cost of hired labour (euro)					17%	75%	8%				
Labour Training Time (hrs)						50%	50%				
Management Time (hrs)					8%	58%	33%				
Time spent in field (hrs)					8%	83%		8%			
Repairs and Spares (euro)						67%	25%	8%			
Contractor costs (euro)						100%					

No perceived effects were mostly found for MG+ VRNT for what enterprises, though for the small number of potato producers some reduction in nitrogen fertiliser was perceived, whereas labour training time was also seen to have increased slightly.

Intentions for Adoption

Figure 4. shows the current adoption levels of PATS for those who had adopted the target technologies. The MG+VRNT adopters had the most additional PATs , with 40% also adopting controlled traffic farming, nearly 50% also adopting variable rate pesticide application.

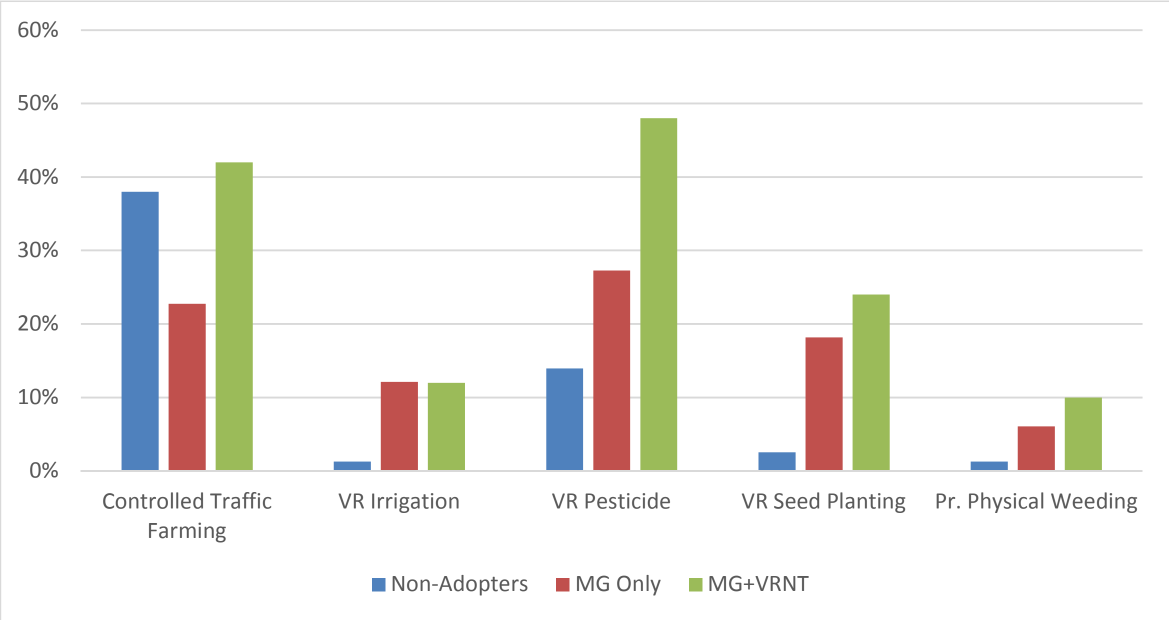

Figure 4. Current Adoption levels of related PATs by adoption class, percentage level of adoption

From table 34 it emerges that most farmers have little intention to adopt variable rate irrigation or precision physical weeding, though these frequencies are stronger for the current non-adopters. A tranche of MG and MG+VRNT users who have quite high current uptake (as shown in Figure 4) were likely to adopt most technologies in 5 to 10 years time. However, another tranche clearly stated they would not uptake these PATS.

*Table 34 Precision agricultural technologies intentions to adopt, percentage per adoption category**

	Non-Adoption (n=79)		MG Only (n=66)		MG + VRNT (n=50)	
	No intention to adopt	Yes in 5-10 years time	No intention to adopt	Yes in 5-10 years time	No intention to adopt	Yes in 5-10 years time
Machine Guidance (+/- 2cm)	54%	46%	20%	27%	18%	38%
Machine Guidance (+/- 40cm)	80%	20%	53%	0%	18%	0%
VRNT	61%	39%	39%	35%	0%	0%
Controlled Traffic Farming	62%	11%	48%	29%	36%	0%
VR Irrigation	90%	9%	82%	6%	78%	0%
VR Pesticide	46%	41%	29%	44%	18%	34%
VR Seed Planting	82%	15%	45%	36%	38%	38%
Pr. Physical Weeding	73%	25%	55%	39%	56%	34%

*The percentage level of adoption has current adoption levels of MG Only and MG+VRNT adopters removed and presented in Figure 4. Hence this table shows the intentions of the remaining level of adopters.

Reasons for adoption

The farmers who had either adopted MG only or MG+VRNT were asked who influenced their adoption decision.

Table 35. Influences on adoption, percentage by adoption class

	MG Only			MG+VRNT		
	No Effect	Some Effect	Strong Influence	No Effect	Some Effect	Strong Influence
Local Farm Advisor	61%	33%	6%	48%	44%	8%
Industry Salesperson	33%	55%	12%	36%	50%	14%
Input Supplier	82%	17%	2%	72%	26%	2%
Other Farmers	44%	45%	11%	41%	51%	8%
Co-operative	82%	15%	3%	84%	14%	2%
Machinery Collective/ring	76%	17%	8%	84%	10%	6%
Contractor	80%	15%	5%	84%	12%	4%
Visit to trade fair	23%	65%	12%	22%	68%	10%
Researchers	36%	52%	12%	26%	62%	12%
Collge/Uni open days	88%	11%	2%	76%	24%	0%
Farmer Union	76%	21%	3%	70%	30%	0%

The table shows fairly similar influences across both technologies, namely industry salespeople, other farmers, visits to trade fairs and researchers. Most other influences on the adoption decision, aside from local farm advisors who had some effect on MG+VRNT adoption, had no effect.

Incentives to adopt

The table below (Table 36) show the range of responses for each incentive, presented as frequencies by adoption class.

Table 36. Proposed incentives and their effect on PAT adoption, frequencies by adoption class

	Non-Adopters			MG Only			MG+VRNT		
	This would have no effect on my decision	This would most probably increase my use of PATS	This would definitely affect my decision	This would have no effect on my decision	This would most probably increase my use of PATS	This would definitely affect my decision	This would have no effect on my decision	This would most probably increase my use of PATS	This would definitely affect my decision
More support for training of my staff	72%	22%	6%	53%	35%	12%	54%	28%	18%
Confidence that yields would increase	35%	46%	19%	24%	48%	27%	30%	38%	32%
Confidence that my costs would reduce	44%	32%	24%	20%	41%	39%	16%	48%	36%
More support for training for myself and family	51%	29%	20%	39%	35%	26%	54%	36%	10%
More technical support from sales people	62%	28%	10%	39%	39%	21%	42%	36%	22%
Directed subsidy support for uptake of PATS	32%	43%	25%	26%	27%	47%	24%	32%	44%
Financial support from tax breaks	33%	38%	29%	20%	35%	45%	22%	34%	44%
A 10% reduction in the present cost of the technology	49%	30%	20%	32%	26%	42%	28%	34%	38%
Government support for soil mapping	38%	41%	22%	29%	30%	41%	36%	28%	36%
Improving technology to provide working maps based on soil maps	48%	33%	19%	26%	39%	35%	24%	44%	32%
More stringent laws on pesticide and nitrogen application	44%	37%	19%	35%	30%	35%	20%	30%	50%

A mixture of incentives emerge which would have a potential effect on increasing uptake of PATs. Fewer incentives were indicated by non-adopters as having an effect.

3.5. Holland

Awareness and Adoption of PA technologies

Table 37 shows the responses to the questions *"Are you aware of Variable Rate Nitrogen Application" and "Are you aware of Machinery Guidance?"* Awareness of MG+VRNT was high (90%) and very high for machine guidance only (97%).

Table 37. Awareness of precision agriculture technologies, percentage

	MG+VRNT	MG Only
Not aware	10%	3%
Aware	90%	97%

Whilst aware of the technology, the level of adoption of technology, shown in table 38, indicates that nearly half the sample (84 farmers) had adopted machine guidance only, and 43 farmers had adopted MG+VRNT.

Table 38. Level of adoption and non-adoption of precision agricultural technologies, percentage and number per region and technology

	Non-Adoption	MG Only	MG+VRNT
Number of respondents	50	84	42
Percentage	28	48	24

General Descriptors

Table 39 shows that the majority of Dutch farmers had more mixed enterprises, growing both wheat and potatoes in the last cropping season. The table also indicates that 12% of the sample were either specialised in wheat or potatoes only.

Table 39. Distribution of crops grown within the sample, numbers and percentages

	Wheat	Potatoes	Wheat and potatoes
Number of respondents	23	24	129
Percentage	13%	14%	73%

Characteristics of Adopters versus Non-Adopters

Table 40 shows the characteristics of adopters against non-adopters.

Table 40. Characteristics of adoption, descriptive statistics

	Non-Adoption (n=50)		MG Only (n=84)		MG + VRNT (n=42)	
Winter Wheat, ha				58.2	64.5	100.3
Spring Wheat, ha	0.8	2.8	1.1	4.9	5.6	13.6
Ware Potatoes, ha	11.1	13.5	61.5	278.7	70.4	110.2
Seed Potatoes, ha	4.7	15.4	6.6	15.2	7.3	11.7
UAA, ha	52.8	42.0	156.6	390.0	229.2	300.8
Arable Area, ha	48.9	42.0	152.2	391.1	211.1	236.8
Full-Time Employees	0.5	1.5	0.9	1.2	1.8	2.9
Family Members	1.1	1.1	1.4	1.2	1.4	0.9
Part-Time & Seasonal Employees	1.1	2.0	2.1	3.8	1.2	1.2
	Median		Median		Median	
Management Structure	Owner		Owner		Owner	
Education Category	degree or above agriculture		degree or above agriculture		degree or above agriculture	
Age Category	50-54		45-49		45-49	
Membership of Co-operative	Yes, marketing co-op		Yes, marketing co-op		Yes, marketing co-op	
Income Category	Between €30,000-40,000		Between €50,000-60,000		Between €60,000-70,000	
%tage share income from wheat	21-40%		1-20%		1-20%	
%tage share income from potatoes	41-60%		41-60%		41-60%	

This indicates that adopters manage larger areas than non-adopters. However, MG Only adopters manage larger potato areas than those adopting MG+VRNT. Adopters are younger than non-adopters and have a slightly higher income, though it is worth noting that income categories were distorted by the bulk of respondents refusing to answer. There is no difference in education levels or co-operative membership.

Perceived Impacts

The tables below show the perceived effects for the key field and farm level variables. For machine guidance, fuel quantity and time spent in the field have been reduced, whereas other variables had no perceived effect.

Table 41a. Perceived impacts on the wheat enterprise of MG only adoption, percentage distribution per impact

	Reduction						Increase				
	>40%	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)					1%	84%	14%				
Fuel quantity (litres per ha)			1%	10%	55%	31%	3%				
Nitrogen fertiliser quantity applied (N Kg/ ha)				8%	21%	70%		1%			
Cost of hired labour (euro)	1%			10%	30%	56%	4%	0%			
Labour Training Time (hrs)					13%	62%	21%	4%			
Management Time (hrs)				3%	17%	66%	13%	1%			
Time spent in field (hrs)		1%	1%	8%	51%	32%	4%	3%			
Repairs and Spares (euro)					8%	73%	16%	3%	1%		
Contractor costs (euro)					10%	82%	5%	3%			

Table 41b. Perceived impacts on the potato enterprise of MG only adoption, percentage distribution per impact

			Reduction						Increase		
	>40%	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)					1%	68%	30%	1%			
Fuel quantity (litres per ha)		0%	1%	9%	51%	36%	1%				
Nitrogen fertiliser quantity applied (N Kg/ ha)				5%	19%	73%		3%			
Cost of hired labour (euro)	1%				7%	31%	58%	4%			
Labour Training Time (hrs)				1%	14%	59%	22%	4%			
Management Time (hrs)				3%	23%	55%	16%	3%			
Time spent in field (hrs)				11%	47%	35%	4%	3%			
Repairs and Spares (euro)					7%	70%	20%	1%			1%
Contractor costs (euro)					8%	82%	5%	4%			

Table 42a. Perceived impacts on the wheat enterprise of MG+VRNT adoption, percentage distribution per impact

	Reduction						Increase				
	>40%	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)					3%	59%	32%	6%			
Fuel quantity (litres per ha)					47%	53%					
Nitrogen fertiliser quantity applied (N Kg/ ha)				3%	65%	29%	3%				
Cost of hired labour (euro)			6%	6%	29%	59%					
Labour Training Time (hrs)					6%	59%	32%	3%			
Management Time (hrs)				3%	12%	41%	38%	6%			
Time spent in field (hrs)				6%	41%	44%	6%	3%			
Repairs and Spares (euro)					6%	88%	6%				
Contractor costs (euro)					12%	88%					

Table 42b. Perceived impacts on the potato enterprise of MG+VRNT adoption, percentage distribution per impact

	Reduction						Increase				
	>40%	31-40%	21-30%	11-20%	5-10%	0	5-10%	11-20%	21-30%	31-40%	> 40%
Yield (Kg per ha)					2%	63%	32%	2%			
Fuel quantity (litres per ha)				5%	51%	44%	0%				
Nitrogen fertiliser quantity applied (N Kg/ ha)			2%	7%	54%	32%	5%				
Cost of hired labour (euro)				15%	37%	49%	0%				
Labour Training Time (hrs)				2%	7%	54%	37%				
Management Time (hrs)				2%	15%	54%	29%				
Time spent in field (hrs)				5%	46%	46%	2%				
Repairs and Spares (euro)				2%	2%	90%	5%				
Contractor costs (euro)				2%		98%					

For MG+VRNT there are differences between wheat and potato enterprises, with only a noticeable fall in nitrogen use identified for those applying the technology to wheat. For potato producers, a number of small positive effects were noted for users, namely a reduction in fuel quantity, nitrogen fertilisers, and the cost of hired labour, which infers labour savings from the technology. This also relates to a notified reduction in the time spent in the field.

Intentions for Adoption

Figure 5. shows that mostly MG+VRNT adopters had adopted other PATS. The most common being controlled traffic farming, though variable rate pesticide application and seed planting also proved popular amongst these adopters.

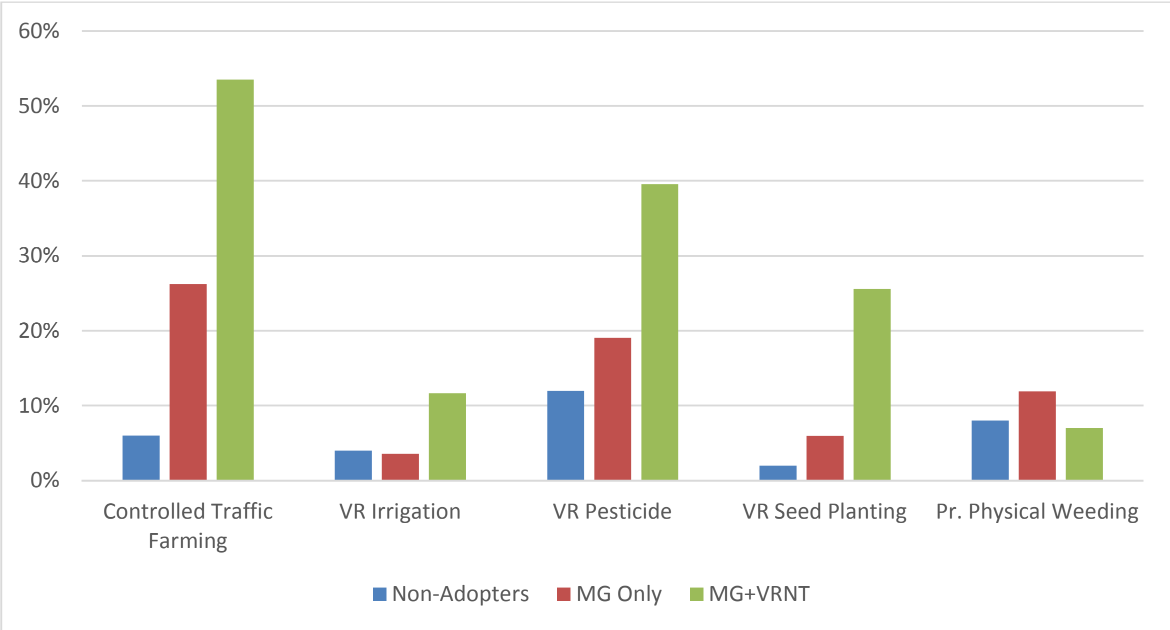

Figure 5. Current Adoption levels of related PATs by adoption class, percentage level of adoption

*Table 43 Precision agricultural technologies intentions to adopt, percentage per adoption category**

	Non-Adopters		MG Only		MG+VRNT	
	No intention to adopt	Yes in 5-10 years time	No intention to adopt	Yes in 5-10 years time	No intention to adopt	Yes in 5-10 years time
Machine Guidance (+/- 2cm)	42%	58%	5%	2%	2%	7%
Machine Guidance (+/- 40cm)	90%	10%	93%	0%	81%	0%
VRNT	56%	44%	25%	71%	0%	0%
Controlled Traffic Farming	82%	16%	46%	27%	14%	0%
VR Irrigation	92%	4%	76%	20%	40%	0%
VR Pesticide	46%	42%	19%	62%	7%	53%
VR Seed Planting	68%	30%	40%	54%	14%	60%
Pr. Physical Weeding	68%	24%	45%	43%	26%	67%

*The percentage level of adoption has current adoption levels of MG Only and MG+VRNT adopters removed and presented in Figure 5. Hence this table shows the intentions of the remaining level of adopters.

Generally, non-adopters had little intention to adopt PATs aside from machine guidance and had already adopted variable rate pesticide application. MG Only adopters had intentions to adopt variable rate nitrogen, pesticide and seed planting technologies in the next 5-10 years. Finally, MG+VRNT farmers had the highest levels of PATs already adopted or, in the case of variable rate pesticide, seed planting and also precision physical weeding, intend to adopt these in the next 5- 10 years.

Reasons for adoption

The farmers who had either adopted machine guidance only or MG+VRNT were asked who influenced their adoption decision. However, only other farmers were highlighted as having some effect on their adoption decision.

Table 44. Influences on adoption, percentage by adoption class

	MG Only			MG+VRNT		
	No Effect	Some Effect	Strong Influence	No Effect	Some Effect	Strong Influence
Local Farm Advisor	80%	17%	4%	72%	23%	5%
Industry Salesperson	57%	29%	14%	79%	16%	5%
Input Supplier	94%	6%	0%	81%	12%	7%
Other Farmers	32%	31%	37%	26%	58%	16%
Co-operative	87%	10%	4%	69%	29%	2%
Machinery Collective/ring	94%	5%	1%	93%	7%	0%
Contractor	79%	14%	7%	93%	7%	0%
Visit to trade fair	54%	39%	7%	51%	35%	14%
Researchers	76%	20%	4%	56%	33%	12%
College/Uni open days	92%	8%	0%	93%	2%	5%
Farmer Union	80%	14%	6%	60%	23%	16%

Incentives to adopt

A mixture of incentives was identified as having a possible effect on future adoption of PATs. Increased regulation, support for training of staff and farm managers and technical support from sales people, as well a 10% reduction in the cost of the technology, were deemed to have no effect across all non-adopters and adopters. For MG Only farmers, confidence in cost reductions, as well as financial support were also deemed important as having an effect. For MG+VRNT farmers confidence in both yields and costs were a factor, as were more technical support options focused on soil mapping.

Table 45. Proposed incentives and their effect on PAT adoption, frequencies by adoption class

	Non-Adopters			MG Only			MG+VRNT		
	This would have no effect on my decision	This would most probably increase my use of PATS	This would definitely affect my decision	This would have no effect on my decision	This would most probably increase my use of PATS	This would definitely affect my decision	This would have no effect on my decision	This would most probably increase my use of PATS	This would definitely affect my decision
More support for training of my staff	70%	16%	14%	62%	25%	13%	70%	23%	7%
Confidence that yields would increase	34%	38%	28%	32%	25%	43%	28%	35%	37%
Confidence that my costs would reduce	36%	34%	30%	30%	30%	40%	33%	35%	33%
More support for training for myself & family	56%	24%	20%	55%	26%	19%	53%	35%	12%
More technical support from sales people	54%	28%	18%	49%	30%	21%	56%	28%	16%
Directed subsidy support for uptake of PATS	28%	30%	42%	23%	25%	52%	56%	19%	26%
Financial support from tax breaks	36%	28%	36%	23%	29%	49%	56%	12%	33%
A 10% reduction in the present cost of the technology	48%	18%	34%	32%	24%	44%	40%	37%	23%
Government support for soil mapping	44%	28%	28%	31%	24%	45%	12%	33%	55%
Improving technology to provide working maps based on soil maps	46%	30%	24%	30%	19%	51%	17%	33%	50%
More stringent laws on pesticide and nitrogen application	60%	22%	18%	49%	29%	23%	53%	28%	19%

4. Conclusions

4.1 Awareness and Adoption of PATs

Awareness of both machine guidance and variable rate nitrogen technology was generally high. For most regions, awareness of machine guidance exceeds 90% of the sample. In addition, where MG+VRNT were most adopted, namely the UK, Germany and Holland, awareness of this technology was also around 90%. The lowest recorded levels of awareness were in Greece and Belgium. Responses in both these countries seem to be characterised by small scale agriculture or arable land area and, it would be expected, would tend to be less inclined to seek automation relative to those with more homogenous and larger field sizes.

Table 46. Adoption profile, summary by regions

	Belgium	Germany	Greece	Holland	UK	Total
MG+VRNT	4	50	27	42	96	220
MG Only	42	66	71	84	61	324
Non-Adoption	150	79	102	50	47	428
	196	195	200	176	204	971

The level of adoption are summarised in the table above. Overall it confirms the previous paragraph in terms of the high levels of non-adoption within Belgium and Greek system. Nevertheless, as this is a targeted sample it is difficult to identify how representative it is of the region or Europe generally.

4.2 Characteristics of Adopters

Some conclusions could be drawn on the characteristics of adopters compared to non-adopters. Traditional literature infers that the more innovative farmer would be younger, more educated, and generally operating a larger farm. Whilst some of these trends are prevalent it only occurs in specific regions. Certainly, this trend to follow the adoption literature is more explicit with MG + VRNT farmers. Accordingly, it may be that adoption is determined by a number of softer factors also.

This may be true when influences on adoption were considered, which seem to harmonise across the regions. For most regions, farming networks and commercial interests were the main motivators for adopting machine guidance or MG+VRNT. Thus, aspects of social networks and peer-to-peer learning emerge from these influences. Moreover, the opportunities for demonstrating the technology, through researchers and trade fairs, proved an important aspect of the determining uptake of these technologies.

4.3 Incentives for adoption

UK farmers seemed particularly favourable towards a variety of incentives, ranging from confidence, financial and training support. The Greek farmers seemed the least likely to adopt these technologies with these incentives. More textual analysis of open questions around incentives tended to focus on better prices, namely through rewards from the market as an incentive to drive adoption upward, and this may infer that public incentives alone may not be enough to increase adoption.

4.4. Impacts of adoption

As this was a face to face survey of farmers we could only measure perceived effects of the technology. Overall MG+VRNT and MG Only adoption tends to lead to slight reductions in fuel and fertiliser use and, in some cases, the time spent in the field. However, other key performance indicators, such as yield, did not seem to be significantly affected.

Consequently, the low level of impact on the farm business may indicate underlying factors for adoption of the technology beyond economic gains and analysing textual responses to open questions reveals aspects such as ease of use as a motivator. Again, whilst these are perceived impacts it may be that actual impacts are more pronounced, but their working in the field may be compromised by lack of operator training or farmer recording of performance through adequate use of the machinery. These aspects could not be elicited from the survey and perhaps merit further work to fully understand why the impacts of PATs are not so pronounced.

ANNEX 6. Agronomic, Socioeconomic and Environmental Analysis

Agronomic, Socioeconomic and Environmental Analysis

Deliverable 6

PRECISION AGRICULTURE project

contract no. 199163-2015 A08-NL

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1 Introduction

1.1 Research context

EU agriculture has to cope with global challenges such as food security and the sustainable use of natural resources, including climate change mitigation, as well as domestic issues like making farming more efficient and productive, increasing animal welfare and revitalising the countryside and its rural communities.

The active management of agricultural systems using appropriate technologies and practices could offer possibilities to reduce greenhouse gas (GHG) emissions while increasing agricultural productivity and incomes. One potential example is the adoption and dissemination of Precision Agriculture (PA) in the European Union.

Little evidence is available on **Precision Agriculture Technologies (PATs)** which could mitigate GHG emissions. The present study aims to narrow some of the abovementioned knowledge gaps with new empirical evidence by studying current and potential adoption of PATs by EU crop producers which could help increase farm productivity and, at the same time, mitigate GHG emissions.

1.2 Objectives

The global objective of the tender study is to empirically investigate the impact of those PATs that are holding the most promise for GHG emissions mitigation while simultaneously being economically attractive for EU farmers (e.g. by increasing or maintaining productivity and being cost-effective). The productivity and economic impacts, as well as the extent of GHG mitigation, will be estimated based on the collection of primary data (survey to farmers) and secondary information when needed.

This document, which is part of this greater study, provides the agronomic, socioeconomic and environmental analysis based on the survey results.

1.3 Structure of the study

This report is structured in 5 chapters. Chapter 2 provides background to the presented results, resuming the previous reports. Chapter 3 goes into the survey, how it is conducted and the characteristics of the adopters and non-adopters of technologies. Chapter 4 discusses the quantitative analysis of adoption. Chapter 5 presents the results of model runs under different adoption scenarios.

2 Background

2.1 Precision Agriculture Technologies (PATs) for greenhouse gas emissions mitigation

Precision Agriculture is a farming management concept based upon observing, measuring and responding to inter- and intra-field variability and needs in crops and to variability and needs of individual animals with the use of digital techniques. An earlier part of this study reports on a literature overview providing a typology of Precision Agriculture Technologies (PATs) in 3 main categories:

- **Guidance technologies** – including machine guidance and controlled traffic farming;
- **Recording technologies** – including sensor systems for water, nutrients, biomass, either from in situ or remote;
- **Reacting technologies** – including variable rate application technologies for nutrients, crop protection agents, irrigation, seeding etc. and precision weeding.

Agriculture productivity is reaching its limits and to continue improving its performance, there is a need to introduce these PATs in the mainstream agriculture to get a more optimised use of natural resources (soil and water) and agricultural inputs (fertilisers and agrochemicals) and to achieve higher yields in a sustainable manner.

Regarding their potential to reduce greenhouse gas (GHG) emissions, many PATs are contributing as the precise application of inputs (nutrients, water, seeds, crop protection agents) often implies a higher efficiency and/or a lower input rate, which both contribute to lower emissions. From the long list of PATs (Annex 2), Table 1 provides the top-7 best performing PATs regarding their GHG reduction potential.

Table 1: Selected PATs with direct GHG reduction potential

Ranking of PATs	PAT Type	GHG reduction potential
1	Variable Rate Nitrogen Application Technology (VRNT)	5
2	Variable rate irrigation (VRI)	3
3	Controlled Traffic Farming (CTF)	2
4	Machine Guidance (MG)	2
5	Variable rate pesticide application (VRPA)	2
6	Variable rate planting/seeding (VRP/VRS)	1
7	Precision physical weeding (PPW)	1

Scale of importance on GHG reduction potential (Likert-type scale identified by the authors): 5: very high potential; 4: high potential; 3: moderate potential; 2: slight potential; 1: low potential.

2.2 The potential and current adoption of PATs in the EU and globally

PA growth rate flattened during the first years of 2000s, because the results (productivity increase, inputs reduction, fuel use decrease, ease of use of PATs, low maintenance, compatibility between brands) were not as positive as expected by the agricultural community. However, PA technologies are currently taking up again, because technology problems have been gradually solved with more tangible results in farm level and new combinable technologies (software and hardware) that united can increase the positive impact in yield, input and profit. This uptake can be seen by the fact that PA is an important sector in growth with researchers estimating the PA market already amounted to €2.3 billion euros in 2014 on a global level (Euractiv, 2015; Roland Berger, 2015). They expect it to grow at an annual growth rate of 12% through 2020 (Euractiv, 2015; Roland Berger, 2015). The mature US and European markets are considered the most promising (Roland Berger, 2015). However, while most practitioners can see the benefits of PATs in agricultural production, the fast pace of development of the technology, its complexity, the small size and diversity of farm structures (in terms of crops, topography), cultural perception, lack of expertise and economic constraints are obstacles that have hindered adoption by end-users, resulting in a gap between the availability of PATs and their implementation in practice (Zarco-Tejada et al., 2014).

The main drawbacks of PA, which also form the main obstacles for farmers to adopt PA technologies, are:

- **Large knowledge gap in the knowledge transfer between developers and users**. Farmers and technologists do not communicate very often. A study among German stakeholders within the PA community explored the barriers in the innovation processes and it was found that there is a gap in the knowledge transfer between science and practice and limited communication and collaboration between farmers and technology providers. They also pointed out that farmers are not only adopters but that they can also propose innovation solutions to technology providers (Busse et al., 2014). The knowledge gap is however not limited to simply knowing how to build and operate precision farming equipment. It is also related to knowing about the return on investment of different technologies. Robertson et al. (2007) corroborate this aspect by also naming perceived risks of economic return next to barriers to using hi-tech elements as an adoption constraint. Fountas et al. (2005) argue that better understanding of the PA technologies and their benefits for the farmers would increase uptake;
- **High investment cost**. The various types of recording, reacting and guidance technology often do not come cheap and have to be added to the cost of the machinery. Lowering the investment costs would increase uptake (Fountas et al., 2005);
- **Time consumption**. It takes time to learn how a new system works. It also takes time to calibrate some systems;
- **The learning process combined with average educational level** (=farmer's expertise). Few farmers are specialists in the Information and Communication Technology (ICT). Robertson et al. (2007) corroborate this statement by claiming that lack of training and technical support are an adoption constraint;
- Low trust on internet-based data storage;
- **GPS operation problems** like signal loss and interoperability problems between brands;
- **Incompatibility of different PA technologies and software**. Some recording, reacting and guidance technology cannot be combined due to software issues (e.g. the data coming out of sensors is not in the right format to be used by the reacting technology) or hardware issues (e.g. connecting cables of the machinery do not fit in the sockets provided in the control unit in the tractor). A survey

among Canadian farmers showed that the compatibility of PA technology, and also the role of farmers' expertise (vide supra) were the main issues for PA technology acceptance and diffusion of innovation (Aubert et al., 2012). Robertson et al. (2007) confirm that equipment incompatibility is an uptake barrier;

- **Regulatory issues** (e.g. lacking legislation about Unmanned Aerial Vehicles). The European Climate KIC funded Climate Smart Agriculture (CSA) Booster is a collaboration of research institutes working on accelerated adoption of technologies and solutions for mitigation of climate change in agriculture. Their pathfinder report (2015) tackles this issue (among various other socio-economic barriers): both technology providers and potential users highlighted policy and regulatory issues acting as a barrier. This included a lack of knowledge of available support or subsidies, and inconsistent application of regulations across Europe. Table 2 shows an overview of the key socio-economic barriers identified in their report; many of them overlap with the barriers that are named in this list.

Table 2: Overview of socio-economic barriers. Source: modified from CSA Booster pathfinder report (CSA Booster, 2015).

Economic*	**Institutional/ regulatory****	**Organisational*****
High initial investments	Low institutional support for farmers	Lack required competencies/ skills
Poor access to capital	Use of overly scientific language (jargon)	Poor information
Competing financial priorities	Farmer's knowledge not considered in R&D	Inability to assess technologies
Long pay-back periods (ROI)	Lack of regulatory frameworks	
High implementation costs (actual and perceived)	Overly complex technologies	
Uncertain returns and results	Results/ effects of technology difficult to observe	
Temporal asymmetry between costs and benefits	Farmer's beliefs and opinions	
	Low trust	

* Cullen et al., 2013; Faber and Hoppe, 2013; Guerin and Guerin, 1994; Montalvo, 2008
** Bogdanski, 2012; Eidt et al., 2012; Montalvo, 2008
*** Montalvo, 2008

Besides these major drawbacks, several other obstacles that also hamper the wider applicability and adoption are the insufficient recognition of temporal, multi-annual variation by the technology (in many cases year-to-year variation overcomes spatial variation) is a drawback to use for instance yield maps as a means for next year's heterogeneity. Another drawback is focussing more on fields rather than a farm-level focus (i.e. application of PA techniques in all fields of the farm as a total) disregards the operational problem of managing a whole farm rather than an individual field as an adoption issue. Also, farmers' adoption would benefit from better incorporation of quality standards and traceability of the whole production process in the product price. Another barrier is that the impact of environmental protection data of farming systems in the price is not visible (McBratney et al., 2005).

2.3 GHG Policy context for PATs in EU

On 11 December 1997, The Kyoto Protocol (an international agreement, which commits its Parties by setting internationally binding emission reduction targets) was adopted which entered force on 16 February 2005. The participating countries were supposed to ensure, individually or jointly that their aggregate anthropogenic GHGs do not exceed their assigned amounts, calculated pursuant to their quantified emission limitation and reduction commitments, with a view to reducing their overall emissions of such gases below 1990 levels to an average of 5% in the commitment period 2008 to 2012. Energy production, industrial processes, solvent and other product use, agriculture and waste treatment sectors are the GHG sources under consideration to emissions cut-off (Kyoto Protocol, 1998). The detailed rules for the implementation of the Protocol were adopted at COP 7 in Marrakesh, Morocco, in 2001, and are referred to as the **"Marrakesh Accords"**. COP 7 also adopted a decision on Land Use, Land Use Change and Forest (LULUCF) with the obligation to undermine the environmental integrity of the Kyoto Protocol. In Doha, Qatar, on 8 December 2012, the **"Doha Amendment to the Kyoto Protocol"** was adopted, where a second commitment period was assembled from 1 January 2013 to 31 December 2020 in which a revised list of GHGs (included also Nitrogen trifluoride) was given for the participating states to report since then. During this period, Parties committed to reduce GHG emissions by at least 18% below 1990 levels in the eight-year period from 2013 to 2020 (Doha Amendment, 2012).

The last step of actions to reduce the greenhouse effect was the **Paris Agreement on December 2015**, where 195 countries adopted certain measures (to be into force in 2020). The most essential element of the agreement was to keep the increase in global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. In addition, all countries agreed to aim on reaching the GHGs peak as soon as possible in order to balance GHGs in the second half of our century. Sinks and reservoirs of GHGs should be conserved and enhanced and anthropogenic GHG production should be mitigated by both market and non-market approaches. The agreement recognises that adaptation is a global challenge and that national adaptation efforts can be enhanced by international cooperation. Policies on loss and damage are supported to help vulnerable countries to climate change effect; the obligation of developed countries to support less developed states in climate change confrontation was reaffirmed. All results from the participating countries should be transparently reviewed in an international basis that ensures reliability of each member effort. The so called "Global Stocktake" will be the instrument to be established in 2023 that will assess the progress globally and will reset the actions in 5-year intervals.

EU have identified the so called Intended Nationally Determined Contribution (INDC) for its members states on March 6th 2015 where they committed to a binding target of an at least 40% domestic reduction in GHGs by 2030 compared to 1990. The target represents a significant progression beyond its current undertaking of a 20% emission reduction commitment by 2020 compared to 1990 (which includes the use of offsets). This goal is in line with the EU objective (IPCC commitment of developed countries) to reduce its emissions by 80-95% by 2050 compared to 1990. Furthermore, it is consistent with the need for at least halving global emissions by 2050 compared to 1990. The EU and its Member States have already reduced their emissions by around 19% on 1990 levels while GDP has grown by more than 44% over the same period. As a result, average per capita emissions across the EU and its Member States have fallen from 12 tonnes CO_2-eq. in 1990 to 9 tonnes CO_2-eq. in 2012 and are projected to fall to around 6 tonnes CO_2-eq. in 2030. The emissions in the EU and its Member States peaked in 1979 (INDC of the EU, 2015).

This project's rationale is concerned with the contribution of PATs to farm productivity and the mitigation of greenhouse gas emissions in the EU. Consequently, it is reasonable to focus the case study selection on regions with high nitrous oxide (N_2O) emissions, as N_2O is the most important GHG arising from crop production activities. For example, 93% of crop-production related GHG emissions in Europe were in the form of N_2O in 2013 (Leip et al., 2014; personal communication dr. G.L. Velthof). In addition, as N_2O emissions mainly arise from fertiliser, the reduction of fertiliser through PAT adoption, especially the adoption of Variable Rate Nitrogen Application Technology (VRNT), is improving the economics of the farmer. Where PATs contribute to a more efficient use of the applied N, it may also increase yield. Hence, areas with large N_2O emissions provide a substantiated potential for PAT adoption.

Miterra (Oenema et al., 2007) modelling results are used for information on N_2O emission rates (kg N/ha/year) at the NUTS2 level (Figure 1).

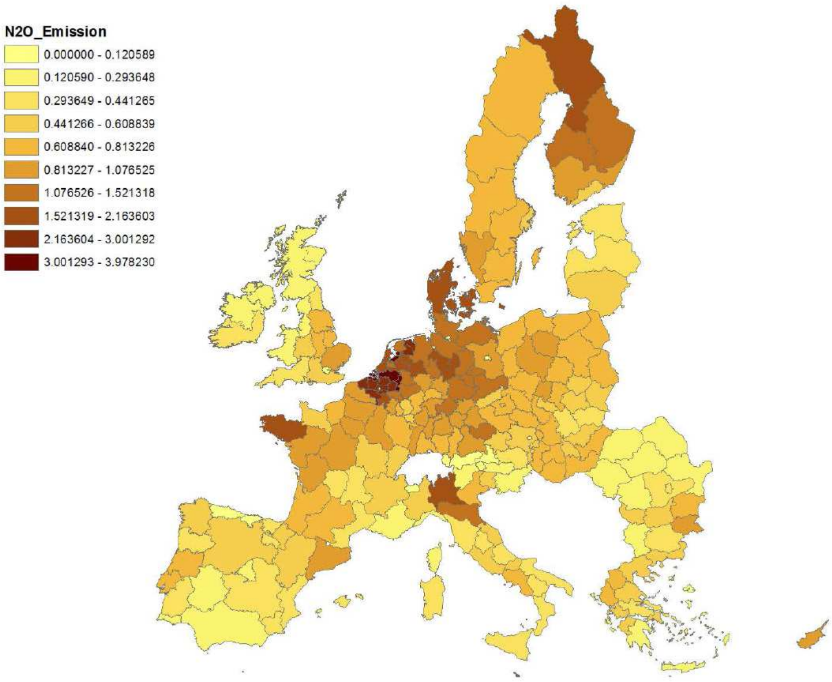


Figure1: N2O emissions (kg N / ha / year) resulting from mineral fertiliser application in Europe at NUTS2 level (Source MITERRA).

2.4 Selection of case studies

In Deliverable 1 and in Deliverable 2, PATs are described that are available at present in the EU, or have the potential to be available in the near future or by the year 2030. Because they reduce N_2O emissions and because they can be adopted in the EU context, Variable Rate Nitrogen Application, Variable Rate Irrigation and Machine Guidance were identified in Deliverable 1 and 2 as the most promising PATs.

In Deliverable 3, the project reported its motivation behind the selection of 5 case studies, being a combination of crops, technologies and countries. For each case study a survey is carried out to profile adopters and non-adopters of PATs. The case studies selected are shown in Table 3.

Table 3: Case studies in this study for which we have carried out surveys.

Country	Technique	Crop
Netherlands	Machine Guidance/ VRNT	Wheat / Potato
Belgium	Machine Guidance/ VRNT	Wheat / Potato
UK	Machine Guidance/ VRNT	Wheat / Potato
Greece	Machine Guidance/ VRNT	Wheat / Cotton
Germany	Machine Guidance/ VRNT	Wheat / Potato

As **techniques**, the survey looked at Machine Guidance and at Variable Rate Nitrogen Application. Deliverables 1 and 2 have shown that these two techniques are the most prominent techniques. Currently, Machine Guidance is the most applied PAT technique whilst Variable Rate Application has not yet mainstreamed, but offers major GHG mitigation potential within the next decade.

As **crops,** the survey looked at wheat as this crop is grown in all countries in the EU. In addition, the study considered a high value crop. Potatoes are a high value crop and therefore potato growers have a larger incentive to invest in precision technology and are among the early adopters that achieve an economic benefit from applying PATs. In terms of quantity produced and acreage, wheat is by far the most popular cereal crop grown in the EU, making up nearly half the total of all cereals grown. In practice potatoes, as a root crop, and wheat, as a cereal, are combined in a crop rotation system within the same farm. Accordingly, we will focus surveys on arable farmers, specializing in wheat (monoculture) production and potato-wheat crop rotation. In Greece, as representative of the Mediterranean region, potato is not much grown. Here cotton is selected as a high value crop where investments in PATs take place.

As **countries**, the survey is conducted in the UK, Netherlands, Belgium, Greece and Germany. These countries match criteria on diversity in farming systems and throughout Europe have relevant populations of adopters and non-adopters. Furthermore, these countries do represent the major agricultural regions in Europe and contain sufficient differences for the primary data collection and analysis.

3 Survey of farmers

3.1 Survey design and sample size

3.1.1 Survey Design

The survey was discussed in detail in Barnes et al. (2017) and results further described in Barnes et al. (2017b). The purpose was to gather information on the perceived impacts of adopted technologies, and the reasons and differences behind uptake of identified PAT options.

3.1.2 Target population

The population of study were farmers growing wheat and/or potatoes within the cropping season 2015/16. In the case of Greece, potato producers were substituted with cotton producers, as the most representative of that region’s agricultural production and the most likely to adopt these technologies. The sample was non-random in that it was targeted to meet quotas for adoption, namely:

- Non-adopters: Farmers who currently have not adopted machine guidance or VRNT technology or may have adopted these in the past but abandoned the technology;
- MG Only adopters: Farmers who currently have adopted machine guidance alone;
- MG+VRNT adopters: Farmers who currently have adopted both VRNT and machine guidance. In order to adopt VRNT this usually requires machine guidance.

The survey was administered through a questionnaire across the 5 regions, namely UK, Netherlands, Belgium, Greece and Germany. The surveys were conducted between August 2016 and February 2017.

3.1.3 Recruitment

Principal recruitment of farmers was through specialist fairs, as well as related events specific to each region, namely demonstration days, farmer discussion and study groups, monitor farm networks and operation groups within the chosen countries. These events were focused at the commodity or the technology level and it was expected that farmers would most likely to have adopted the target technologies would attend. In addition, farm advisors were used in some regions to contact farmers in order to identify the full adopters. A private marketing database, owned by the German marketing research company, was used to identify farmers within Germany. In the UK some farmers were identified through the SRUC consultancy client database. Furthermore, companies supplying equipment, e.g. Yaris, were contacted to identify potential adopters. Given the time constraint on potential interviewees, initial contacts were made at these events and telephone follow ups and visits were used to complete the questionnaire. Table 4shows the distribution of place and method of interviews by region.

Table 4: Distribution of contact methods by region, number.

	Interview method	n	Contacting method	n
Greece (n=200)	Face to face	200	Machinery dealers	183
	Telephone	0	Personal contacts	17
Belgium (n=196)	Face to face	196	Personal contacts	196
	Telephone	0		
Netherlands (n=176)	Face to face	175	Trade fair	142
	Telephone	1	Personal contacts	34
Germany (n=195)	Face to face	0		
	Telephone	195	Agricultural Database	195
UK (n=204)	Face to face	134	Trade fair	28
	Telephone	70	Agricultural Database	176

3.2 Data Collection

The questionnaire was prepared as both an electronic and a paper version. Data were collected through the core research team, with associated research assistants from within each region. Within Germany a telephone survey was used to collect data and, in other countries, telephones were used to follow up contacts and target MG+VRNT adopters. Before the interviews, a training event was held with surveyors to explain the logic of the survey, demonstrate the survey operation and clarify any issues with interviewers. The survey was piloted on 12 farmers per region (described in Barnes et al, 2017).

A web based platform was also established within the SNAP survey software framework for ease of data collection, which was provided in the home language of each region for data collectors. This enabled centralisation of data within a harmonised format, which was held on the secure server of the SNAP webhost system and offer ease of download into .csv format. Responses, which followed the main questionnaire, were harmonised to match the two data sources.

3.3 Data Preparation and Analysis

The data was imported into STATA 14 (Stata Corp., 2014) in a raw format for analysis. These were converted into numeric values. Further refining of codes was conducted to reduce the available categories for a number of variables within the regression analysis (these codes are provided in the additional excel file in Barnes et al, 2017b). Moreover, several open questions were asked around reasons for adoption or non-adoption and incentives. These were cleaned and itemised into categories for presenting frequency analysis of the textual responses.

3.3.1 Data Preparation

Some farmers stated their area in terms of acres and these were converted in hectares to create a unified data set. Similarly, for the UK, income figures were given in pounds which were converted into euros.

To assess the level of adoption and non-adoption farmers were given a range of choices related to adoption, namely:

- Yes, I own a variable rate technology/machine guidance;
- Yes, I rented the variable rate technology/machine guidance;
- Yes, I have used/tried variable rate technology/machine guidance;
- No, I haven't but I'm planning to adopt variable rate technology/machine guidance;
- No, I haven't and I do not plan to adopt variable rate technology/machine guidance.

Adopters were identified as those who own or rent as oppose to those who did not current adopt the technology (options 3, 4 or 5). For group 3 these were past adopters but were considered non-adopters, as our time frame was to have the technology in the last cropping season. On further inspection only 11 farmers were in this category. A categorical variable was developed from these responses indicating i) non-adoption, ii) MG Only adoption and iii) MG+VRNT adoption.

It is important to note that the sample was not random but targeted with specific quotas for response within each adoption category. Therefore, the survey would not be expected to be representative of a region and this inhibits any potential for scaling up of results. Hence, what follows is provided as indicative of these regions rather than representative of the EU regions generally. A set of tables are provided by Barnes et al., (2017b) with the main findings of the survey. Consequently, the purpose of this section is to present the key analysis of these data and implications.

3.4 Adoption of PATs in the five EU case studies

Table 5 shows the distribution by region and by adoption level. Clearly, this is indicative of the targeted approach used and indicates various levels of non-adoption and adoption of the technologies. In total 971 responses were gathered, with the UK targeting the highest level of MG+VRNT adopters and Belgium having the least number.

Table 5: Distribution by adoption for the five case studies, number of respondents by category.

	Belgium	**Germany**	**Greece**	**Netherlands**	**UK**	**Total**
MG+VRNT	4	50	27	42	96	220
MG Only	42	66	71	84	61	324
Non-Adoption	150	79	102	50	47	428
	196	195	200	176	204	971

3.4.1 The differences between adoption and non-adoption

In order to establish whether there are differences between adoption categories and non-adoption categories a series of statistical tests were conducted. Summary tables are provided in Barnes et al (2017b) on the key indicators at the farm and farmer level and tables 6-8 show the results of a comparison of structural and farmer variables by each region. Where continuous variables were used, a two sample t-test was applied and for categorical variables, a Pearson chi-square was conducted.

What emerges are quite distinct regional differences with very few common factors across the regions which could inform generalised conclusions. For Belgium, there was little difference between adoption categories, as they indicated similar income brackets, management structures and educational levels between MG Only and non-adopters, and none of these farmer variables are significantly different. However, MG Only adopters managed a larger farm area and these area indicators are all significantly different. Hence, MG Only adopters do manage a larger farm and arable area, but also more areas specialised in the target crops of wheat and potatoes. Similar land area differences were found by Daberkow and McBride (2003) in their study of US agricultural precision farming and, we would expect similar characteristics to emerge in EU agricultural systems.

For the remainder of adoption categories, which cover the MG+VRNT adopters, there is very little significant difference, aside from labour (compared to non-adopters), which is significantly higher for adopters. A similar difference was found by Paustian and Theuvsen (2016) in a study of German farmers. Specifically, they identified higher levels of regular labour as a predictor of adoption. Age was also significantly different to MG Only adopters who are younger compared the MG+VRNT adopters. Sheng-Tey and Brindal (2012), in a review of past studies of adoption also found operator age to be a significant driver of adoption. Though this is region specific and Paustian and Theuvsen (2016) did not find significant differences in their study of German farmers.

Greek farmers have more significant differences between MG+VRNT adoption, MG adoption and non-adoption classes. This indicates this group may be a distinct class of adopter compared to other farmers. Household income and specialised income from wheat are significantly higher for MG Only adopters, compared to non-adopters. This matches the idea of specialisation as a predictor of adoption, highlighted by Sheng-Tey and Brindal (2012). Structural variables, namely area and labour numbers are significantly higher for MG+VRNT adopters compared to both non-adopters and MG Only adopters. Again, size has been found to be a common predictor of uptake in a number of studies and Robertson et al. (2012) specifically examined variable fertiliser rate technology, finding size to be a significant driver of adoption. Accordingly, this seems to infer that the adopters and, especially, the more progressive adopters with MG+VRNT, follow the general adoption profile.

The farmers in the UK had fewer significant differences between adoption and non-adoption classes. For MG+VRNT farmers all classes of agricultural area are significantly larger than non-adopters, corresponding to previous findings outlined above. Potato area seems to be significantly higher for MG Only farmers, compared to non-adopters, and higher for MG+VRNT adopters compared to MG Only adopters. This again may infer that specialisation of activities does have an effect on uptake (Sheng-Tey and Brindal, 2012).

There are few significant differences between MG Only adopters and non-adopters in Germany, with only labour numbers being significantly higher for adopters, matching the findings of Paustian and Theuvsen (2016) also in Germany. More explicit differences emerge for MG+VRNT adopters, who have a higher significant area and labour numbers compared to non-adopters and, in the case of arable and wheat areas, higher than MG Only adopters. Farmer specific factors are less prevalent, though age (adopters are slightly younger) and more likely to be a member of co-operatives compared to non-adopters. Roberts et al. (2004) argue that older farmers have a shorter planning horizon and consequently this constrains the investment decision, leading to younger farmers more likely to adopt these technologies.

Similar to German farmers, Dutch farmers had very few significant differences between adoption classes. Nevertheless, MG Only adopters generate a significantly larger proportion of income from wheat compared to non-adopters, reflecting that specialisation may infer uptake (e.g Diederen et al. 2003). MG+VRNT adopters manage a significantly larger area than non-adopters and, against MG Only adopters, larger wheat areas.

Consequently, it seems that, physical area is a potential predictor of uptake and this is supported by a range of past studies (Daberkow and McBride 2003; Roberts et al. 2004; Lambert et al. 2014). Given the need for high capital costs and, therefore, a required rate of return, it would seem logical that larger areas under cultivation would be a common significant factor between adopters and non-adopters and this seems more explicit with MG + VRNT adopters. However, only for several regions are other common indicators of farmer technology adoption, such as age and income, significantly different to other adopters. This may be due to the particular nature of the technology applied and the ubiquity of MG only packages within the purchase of newer equipment. In order to explore these issues more the next section examines the drivers behind adoption and non-adoption of the precision agricultural technologies.

Table 6: Chi square and t-test results for main descriptors between MG only adopters and non-adopters.

	Belgium		**Greece**		**UK**		**Germany**		**The Netherlands**	
	χ2	**Sig.**	**χ2**	**Sig.**	**χ2**	**Sig.**	**χ2**	**Sig.**	**χ2**	**Sig.**
Level of Income	19.30	-	28.59	**	6.97	-	9.97	-	15.46	-
Percentage income from Wheat	7.06	-	19.69	**	4.60	-	1.34	-	13.47	*
Percentage income from Potatoes	11.61	-	11.00	-	5.54	-	3.26	-	12.17	-
Educational level	3.77	-	4.14	-	5.69	-	4.11	-	9.62	-
Membership of Co-operative	1.16	-	0.22	-	2.74	-	3.35	-	1.12	-
Ownership structure	13.61	-	12.19	-	6.17	-	5.57	-	12.66	-
Age	6.87	-	8.22	-	1.21	-	1.08	-	0.89	-
	t	Sig.	t	Sig.	t	Sig.	t	Sig.	t	Sig.
Total Utilised Area	-7.45	***	0.43	-	0.65	-	-1.32	-	-0.61	-
Total Arable Area	-7.12	***	0.45	-	1.22	-	-1.10	-	-0.45	-
Total Wheat Area	-4.06	***	0.71	-	0.09	-	-0.60	-	0.46	-
Total Potato Area	-5.53	***	1.58	-	-2.39	*	-1.20	-	-0.77	-
Total Labour	-1.68	-	-0.03	-	-0.21	-	-2.02	*	-1.55	-

*- not significant; * significant at 0.05; ** significant at 0.01; *** significant at 0.001*

Table 7: Chi square and t-test results for main descriptors between MG+VRNT adopters and non-adopters.

	Belgium		**Greece**		**UK**		**Germany**		**The Netherlands**	
	χ2	**Sig.**	**χ2**	**Sig.**	**χ2**	**Sig.**	**χ2**	**Sig.**	**χ2**	**Sig.**
Level of Income	7.67	-	79.85	***	10.68	-	10.22	-	23.90	*
Percentage income from Wheat	5.01	-	4.32	-	10.34	-	2.71	-	16.67	*
Percentage income from Potatoes	5.02	-	9.20	-	2.11	-	3.92	-	10.07	-
Educational level	4.14	-	12.56	*	1.72	-	7.46	-	21.76	-
Membership of Co-operative	1.58	-	12.77	**	1.16	-	7.47	*	0.66	-
Ownership structure	5.74	-	6.66	-	9.43	-	16.03	-	16.75	-
Age	6.83	-	10.34	*	3.53	-	14.80	**	3.52	-
	t	Sig.	t	Sig.	t	Sig.	t	Sig.	t	Sig.
Total Utilised Area	-0.55	-	-8.09	***	-3.14	**	-4.86	***	-1.92	*
Total Arable Area	-0.38	-	-8.06	***	-2.49	*	-4.92	***	-2.10	*
Total Wheat Area	-0.21	-	-4.55	***	-3.08	**	-5.23	***	-3.76	***
Total Potato Area	-0.92	-	-7.87	***	1.51	-	-1.39	-	-0.86	-
Total Labour	-2.00	*	-6.43	***	0.76	-	-3.75	***	-0.95	-

*[-] not significant; [*] significant at 0.05; [**] significant at 0.01; *** significant at 0.001*

Table 8: Chi square and t-test results for main descriptors between MG Only Adopters and MG+VRNT adopters.

	Belgium		**Greece**		**UK**		**Germany**		**The Netherlands**	
	χ2	**Sig.**	**χ2**	**Sig.**	**χ2**	**Sig.**	**χ2**	**Sig.**	**χ2**	**Sig.**
Level of Income	6.74	-	41.46	***	7.96	-	3.20	-	19.55	-
Percentage income from Wheat	3.37	-	12.43	-	7.48	-	6.16	*	14.59	*
Percentage income from Potatoes	1.14	-	10.37	-	2.66	-	8.47	-	9.09	-
Educational level	3.29	-	6.90	-	4.18	-	3.20	-	18.33	-
Membership of Co-operative	2.19	-	5.97	-	0.49	-	6.16	*	0.02	-
Ownership structure	4.32	-	6.74	-	7.30	-	8.47	-	15.81	-
Age	11.05	*	3.78	-	2.06	-	5.89	-	1.36	-
	t	Sig.	t	Sig.	t	Sig.	t	Sig.	t	Sig.
Total Utilised Area	0.88	-	-8.29	***	-1.80	-	-1.95	-	-0.95	-
Total Arable Area	1.09	-	-8.29	***	-1.79	-	-2.07	*	-1.11	-
Total Wheat Area	0.67	-	-3.24	**	-1.34	-	-2.42	*	-2.46	*
Total Potato Area	0.31	-	-5.37	***	2.18	*	-0.21	-	0.25	-
Total Labour	-1.08	-	-5.35	***	0.61	-	-1.08	-	-0.03	-

*- not significant; * significant at 0.05; ** significant at 0.01; *** significant at 0.001*

3.4.2 Factors behind adoption and non-adoption of precision agriculture

In order to understand the decision to either adopt or not adopt these technologies a small set of attitudinal questions were asked within the survey to elicit adoption barriers or enablers to adoption. Very few studies have examined the attitudinal or behavioural components of precision agricultural adoption (Sheng-Tay and Brindal, 2012). Paustian and Theuvsen (2016) identified job satisfaction as a determinant of adoption of precision agriculture but found no significant effect. Accordingly, what follows is a discussion of the response of farmers to attitudinal statements, developed from past literature and tested through the pilot stage of the survey. In addition, a further open question, dependant on whether the farmer had adopted or decided to not adopt the technology, aimed to elicit reasons for adoption behaviour. These open responses were reviewed and then categorised into common themes which occurred within the textual statement in order to reflect the diversity of responses received.

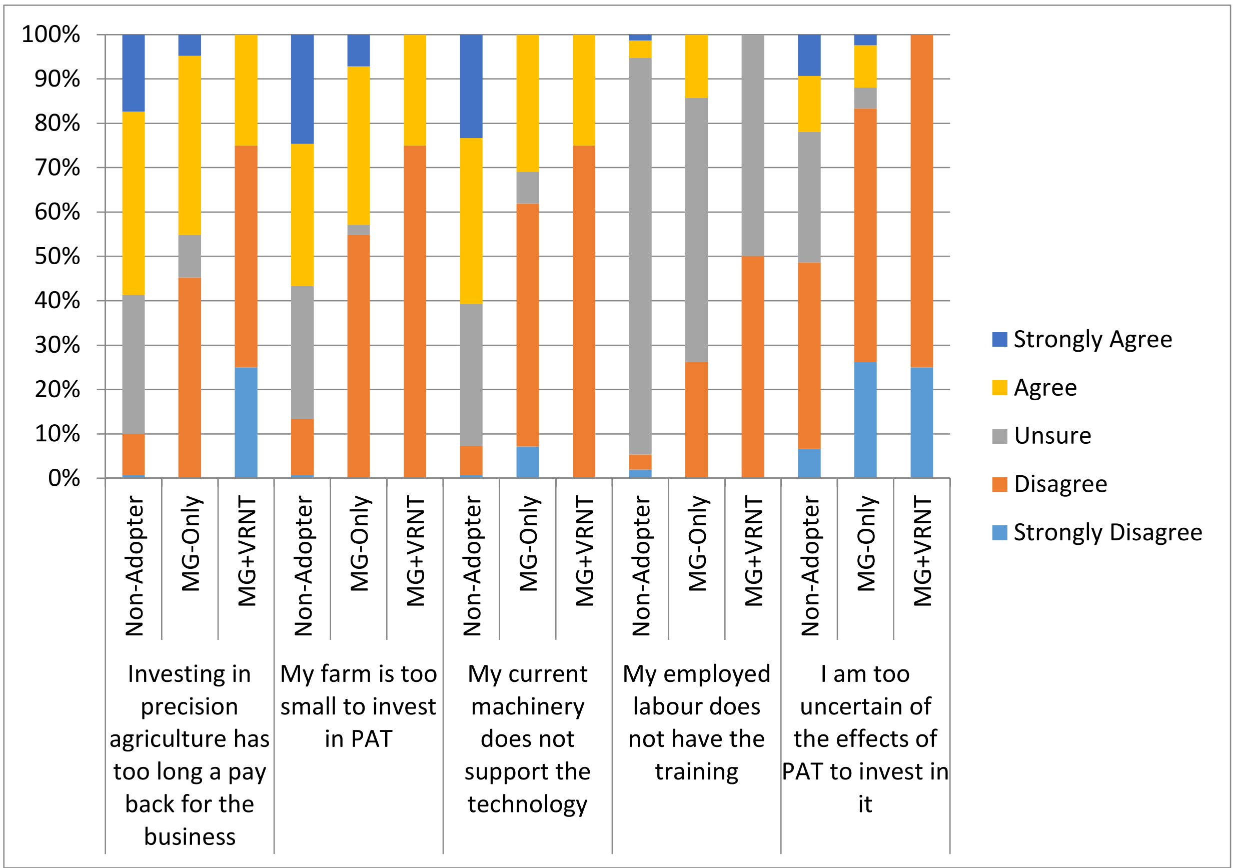


Figure 2: Belgium farmers by adoption profiles, response to attitude statements, distribution per adoption category.

The distribution of responses of Belgium adopters (Figure 2) tends to skew towards more disagreement with the negative attitudinal statements compared to non-adopters. Specifically, adopters disagree more with the statements that investing in PAT has too long a pay back, that their farm is too small to adopt PATS, that their machinery are not compatible and towards uncertainty of the outcome of adoption. Conversely, around 60% of non-adopters agree with statements that PAT has too long a payback and that their farm is too small to invest in PATs. This relates to the adoption characteristics of Belgium farmers in that non-adopters managed a smaller area. Similar levels of agreement by non-adopters related to the statement 'My machinery does not support the technology'. This may be linked to income and farm size characteristics of non-adopters who, whilst income was not significantly different, were still smaller than adopters. Hence this may restrict investment on newer machinery which would offer greater compatibility. The greatest level of uncertainty for both adopters and non-adopters was the statement 'My employed labour does not have the training'. Again, there were fewer differences in the numbers of regular labour employed between MG Only and non-adopters, but some differences in the numbers of family labour employed. Accordingly, this uncertainty may reflect the smaller employment profile of non-adopters farmers compared to MG+VRNT farms.

Nevertheless, whilst there are clear patterns in terms of the majority of responses there is some polarity voiced towards certain statements within the different technology adoption groups. Around 40% of MG Only adopters agree with the statement that investment has too long a pay back and that the farm is too small to invest in PATs. We take this latter point in terms of investment in further PATs and it may be a constraint that farmers perceive their land to be too small to generate an adequate rate of return or that land characteristics do not generate enough heterogeneity to merit investment in more sophisticated technologies, such as variable rate machinery technology.

To explore further, farmer reasons for adoption and non-adoption were queried. These were reviewed and then gathered under a series of themes to capture the tone of the qualitative responses. Table 9 shows the most frequent responses for Belgium by technology adoption group, namely reasons for non-adoption by non-adopters, and reasons for adoption by MG-Only adopters.

Table 9: Belgium farmer reasons for adoption or non-adoption, ranked by frequency.*

Non-Adopters		**MG-only Adopters**	
High cost of technology	29	Ease of use	22
Farm is too small	22	More accuracy	13
Too old	15	Reduced agrochemical input	7
Low ROI	6	Cost reduction	5
No machinery replacement needed	5	More efficiency	4
Technological constraints	3	Reduced workload	2
Farmer retiral	2		
Farmer sceptical of benefits	2		
Lack of self-knowledge	2		
Machinery compatibility	2		

* *Any reason mentioned only once is removed from the table. MG + VRNT adopters did not give more than 1 reasons for adoption and are therefore removed from this table.*

This reveals a set of key issues which can be related to their responses to attitudinal statements and towards the higher level issues of barriers to entry, outlined in Table 9. The key issues for non-adopters revolve around the high cost of the technology and, related to this, area of farmers is seen as a constraint to adoption. Aligned to the financial aspects, a low return on investment was identified by some non-adopting farmers and this has a parallel to their agreement with the attitudinal statement that investing in PATs has too long a payback.

Other reasons emerge related to farmer age, namely some farmers claimed to be too old or were reaching retirement age and therefore this limited the potential for investment on the farm. Presumably this could also relate to the lack of an identified successor on the farm to inspire investment in newer technologies. Paustian and Theuvisen (2016) tested the hypothesis that securing a farm successor would positively impact adoption, however they could not find a significant effect. Nevertheless it would seem that if older farmers are constrained by the shorter planning horizon (Roberts et al., 2004) then succession is an aspect of creating confidence in future farm planning and, therefore, should positively predict adoption of PATs.

Finally, qualitative reasons around the lack of a need for machinery replacement are voiced. This may infer future investment once these present machineries are fully depreciated, or it may be related to farmer's scepticism of the benefits to justify expenditures on the technologies. Moreover, a reason mentioned by a number of farmers was to reduce agro-chemical input, which is also reflected in several mentions around increasing efficiency, and increasing yields. Hence, whilst some of the response to adoption of PAT could be related to literature on environmental behaviours (e.g. Siebert et al., 2006), this seems to be mostly related to profitability concerns were environmental benefits are secondary to these farmers.

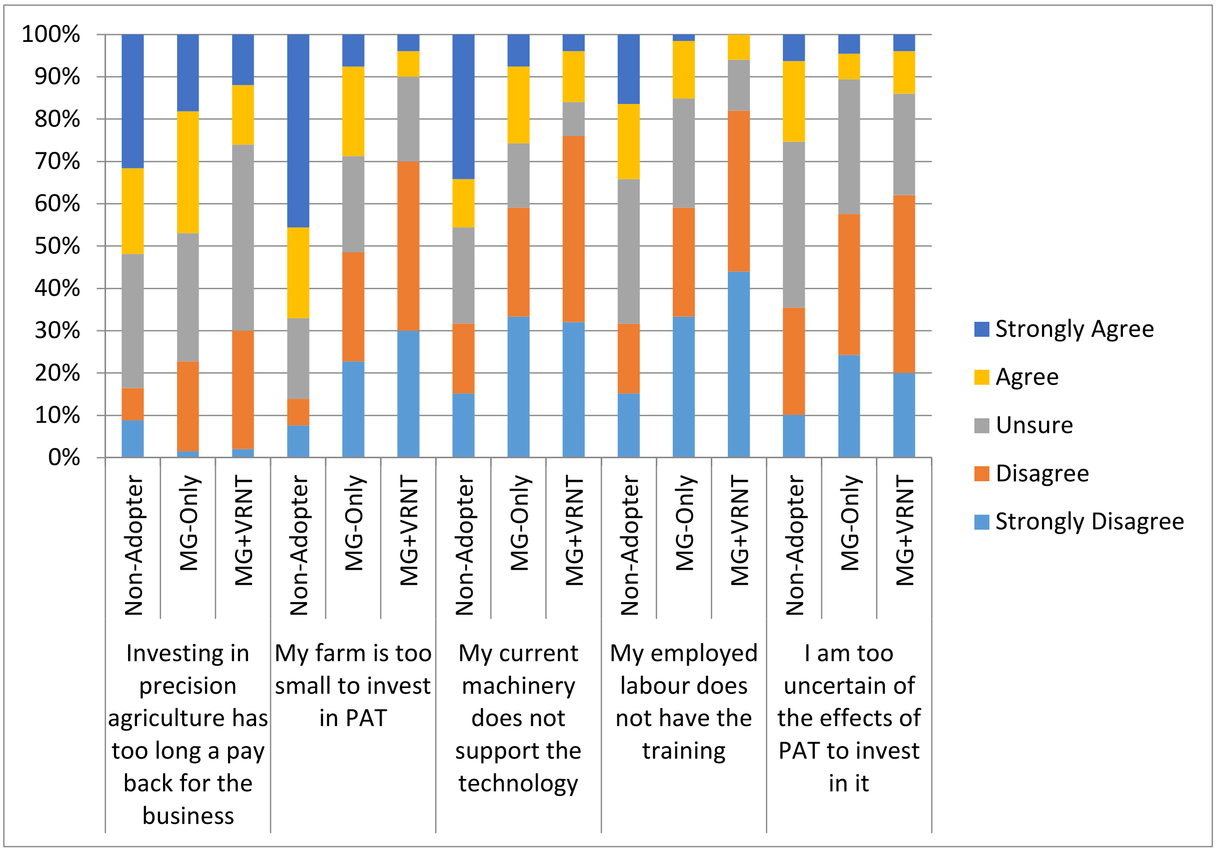


Figure 3: German farmers by adoption profiles, response to attitude statements.

For German farmers, there seems to be more uncertainty for adopters around the statements on the length of payback from investment and around the effects of PAT to inspire either initial investment (for non-adopters) or future investments for MG Only adopters (see Figure 3). This reveals a different picture to that of Belgium farmers where adopters tended to indicate more certainty towards the effects of the PATs. However, German non-adopters were also in agreement that their farm was too small to justify expenditure in PATs and this may revolve around issues of high cost and uncertainty of results to generate an acceptable rate of return. Diederen et al. (2003) referred to financial status as a driver of adoption of PATs and the requirement of high investment costs and this allows the potential to accommodate unfavourable results (Sheng-Tey and Brindal, 2012).

Non-adopters were mostly in agreement that their current machinery was not able to support the technology, which is mostly in opposition to MG-Only and MG+VRNT adopters who disagree with this statement. Finally, there seems to be a more distributed response for non-adopters in terms of the statement 'My employed labour does not have the training'. Specifically, around 35% of non-adopters were in agreement with this statement, and a similar proportion were in disagreement, the remaining third were unsure. These non-adopters did employ less labour and hence this may explain this level of uncertainty, but may reflect some diversity in the levels of regular labour employed on non-adopters farms. Moreover, most studies on training have tended to focus on the level of computer literacy to reflect management knowledge. However, testing these against PAT adoption has proven mixed (McBride and Daberkow, 2003; Roberts et al., 2004).

Table 10 shows the qualitative statements for non-adopters, MG-only and MG and VRNT adopters, ranked in terms of their frequency.

Table 10: German farmer reasons for adoption or non-adoption, ranked by frequency.*

Non-Adopters		**MG-only adopters**		**MG+VRNT Adopters**	
Farm is too small	27	Cost reduction	23	Cost reduction	18
High cost of technology	26	Reduced agrochemical input	11	Reduced agrochemical input	10
Farm land too scattered	9	Reduced workload	7	Reduced workload	5
Farmer sceptical of benefits	5	Ease of use	6	More efficiency	4
Against ecological principles	3	More accuracy	4	Progressive farmer	3
Farmer retiral	3	More labour efficiency	3	Ease of use	2
Low ROI	3	Progressive farmer	3	Higher ROI	2
Awaiting successor plans	2	Reduces labour requirements	3	Increase yields	2
No machinery replacement needed	2	Higher ROI	2	More accuracy	2
Too old	2	Improved product quality	2	Standardisation	2

** Any reason mentioned only once is removed from the table.*

Similar to Belgium non-adopters the key reasons revolved around limits to the farm size and the high cost of technology. This infers limits to generating an adequate rate of return to the technology and, for some farmers, a perceived low rate of return is mentioned. Similar to other regions discussed, issues around farmer age, retrial and successors were voiced to justify non-adoption in the future and the lack of need for current machinery replacement. Several reasons emerged around farmer scepticism towards the benefits of the technology:

'I do not see the benefits, I can drive yourself straight' *(Farmer DE128842)*

'I see no benefit….' *(Farmer DE431267)*

'…I am not convinced of the technology' *(Farmer DE139976)*

For a few farmers the adoption of technology was against their ecological approaches. This latter reason potentially highlights the issues of farming identity and those who adopt low input, organic or ecological methods viewing precision agriculture as a purely technological solution (e.g. Burton, 2004).

'because we are an eco-friendly operation and the acquisition costs are too high'

(Farmer DE38755)

'want to think myself, I make eco-agriculture and will have no influence on how the plants, I do not think highly of precision agriculture and have no electronics on my operation'

(Farmer DE461345)

'Because we are an eco-friendly operation and I refuse to employ electronics. It is scary with how few people are employed by us in the East and by the large farms.'

(Farmer DE39115)

Common main reasons for adoption for both technologies were focused on cost and input reductions. In addition, ease of use, more accuracy and reduced workload, including reduced labour requirements were mentioned. Several saw themselves as progressive farmers, namely accepting the fact that precision agriculture is part of the development of agriculture and consequently saw this as a reason to adopt.

'………we need to move with the times' *(Farmer DE279029)*

'Progress and effectiveness, we must move with the times'

(Farmer DE37804)

Finally standardisation and improved product quality were mentioned by some farmers, specifically the desire to create some uniformity in production, given the variance in soils. This knowledge of spatial variability has been found to be a factor in driving adoption from a number of studies (Isgin et al., 2008; Khanna, 2001).

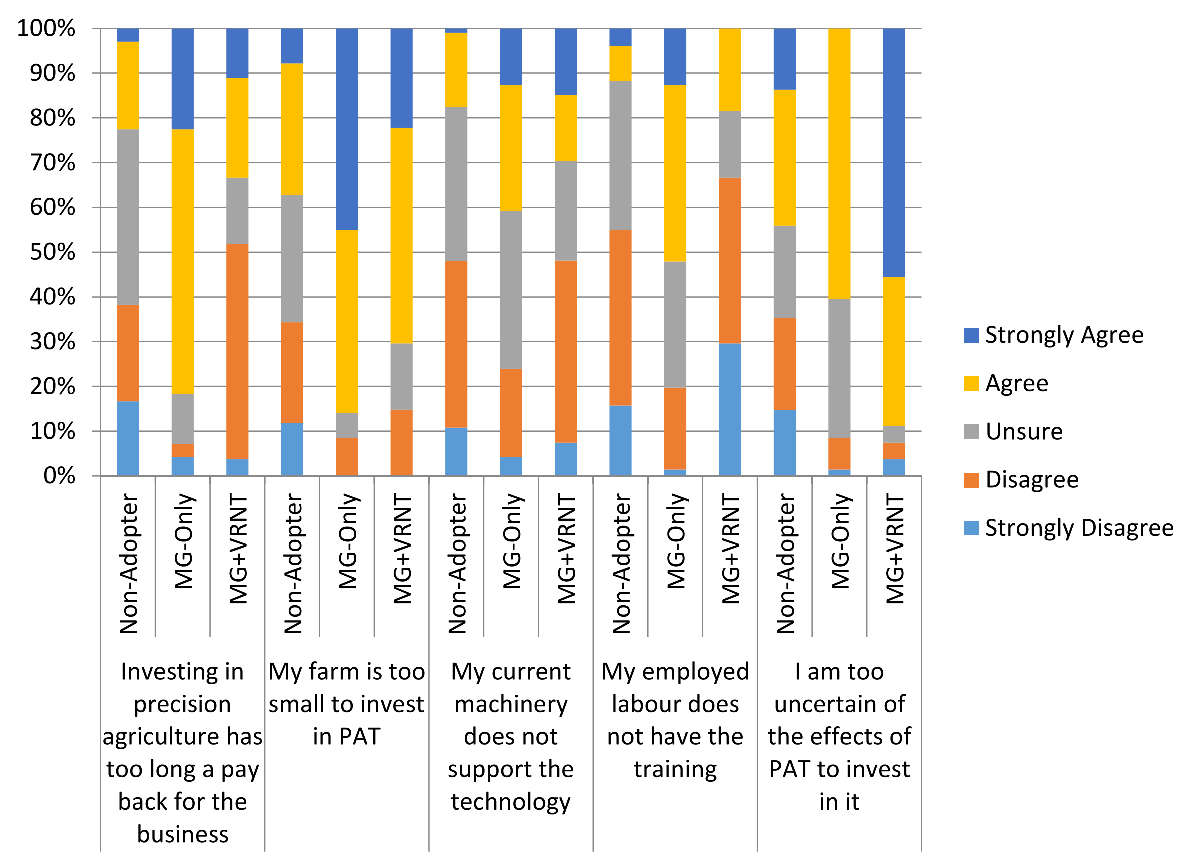


Figure 4: Greek farmers by adoption profiles, response to attitude statements.

In terms of the statement 'Investing in precision agriculture has too long a pay back for the business' Greek non-adopters are mostly unsure (39%), whereas MG-Only adopters, on the whole, agree or strongly agree (82%). This seems to highlight a sceptical perspective towards the technology's ability to generate a higher return. This also should be compared with the final statement 'I am too uncertain of the effects of PAT to invest in it', where 61% of MG Only adopters agree with the statement. Effectively this infers that those Greek farmers who adopted MG are generally not perceiving a benefit and are unsure of its effects to inspire them to invest further in PATs. This also seems to support the response to the second statement 'My farm is too small to invest in PAT', where 86% if MG Only adopters agree. Hence, though this cohort has adopted MG it would seem they may not intend to invest in further PATs due to these issues and uncertainties. No literature so far has explored this sequential phenomenon and tended to focus only on adoption against non-adoption. Studies have focused on the size of capital needed and response to unfavourable events (Larson et al., 2008; Roberts et al., 2002), but have not found these to be a significant factor in adoption.

MG+VRNT adopters are slightly more convinced of the technology, as the majority disagree with statements on length of payback, on compatibility of machinery, and the requirement for more labour training. However, a significant proportion do agree or agree strongly that they are too uncertain of effects of the PAT to invest in it. This seems to suggest that, for the majority of adopters, there is some disappointment with the performance of the technology and this may be to do with the technology itself, the data infrastructure needed or, indeed, whether the technology is operated correctly.

Further textural analysis is shown below, in terms of the top reasons for non-adoption or adoption. Clearly the prime reason for non-adopters seems to be lack of information and this also relates to lack of any self-knowledge around the technology. In addition, several farmers stated that the technology is too complicated. Given the role that dealers have in promoting the technologies it may be that messages are being promoted to these farmers and consequently this has an effect on limiting the decision to adopt. Financial and physical constraints are mentioned through 'lack of access to funds' and 'farm is too small'. In addition, some farmers identified that their land is too scattered, that is parcels of land which are not connected and hence movement of machinery may be costly. A second reason is that land is too homogenous. The purpose of precision agriculture is to reduce variance due to soil or other factors and, consequently, these farmers perceive no benefit from PAT adoption given their biophysical profile.

Table 11: Greek farmer reasons for adoption or non-adoption, ranked by frequency.*

Non-Adopters		**MG-only Adopters**		**MG+VRNT Adopters**	
Lack of information	36	More labour efficiency	25	Higher ROI	13
Low ROI	22	More accuracy	17	Ecological reasons	3
Farm is too small	17	Ease of use	10	More accuracy	3
Lack of self-knowledge	6	Higher ROI	9	Improved field management	2
Farm land too scattered	4	Reduced agrochemical input	4	Improved product quality	2
Land is too homogenous	4	Work longer periods	4	Reduced agrochemical input	2
Farm biophysical constraints	3	Reduced workload	2		
Lack of access to funds	3				
Machinery compatibility	2				
Technology too complicated	2				

** Any reason mentioned only once is removed from the table.*

There seems to be little commonality in the reasons for adoption between MG Only and MG+VRNT adopters. MG Only adopters highlight increased labour efficiency, which is also related to increased accuracy from the technology, as well as the ability to work longer periods, reduce the workload and ease of use. These reasons seem to indicate a value of MG Only adoption to freeing up time for farmers and, consequently, helping to improve field management. For several farmers there are other input efficiencies, particularly in terms of agrochemical inputs. Several comments also relate to farm biophysical characteristics, related to the ability of precision agriculture to homogenise farm harvesting:

'Tryout for further use in non-linear crops' *(Farmer GR81)*

For MG+VRNT, the higher return on investment is the most frequently mentioned reason to adopt. These reasons seem to relate to improved management of the farm and field, leading to better product quality and reduced input wastage.

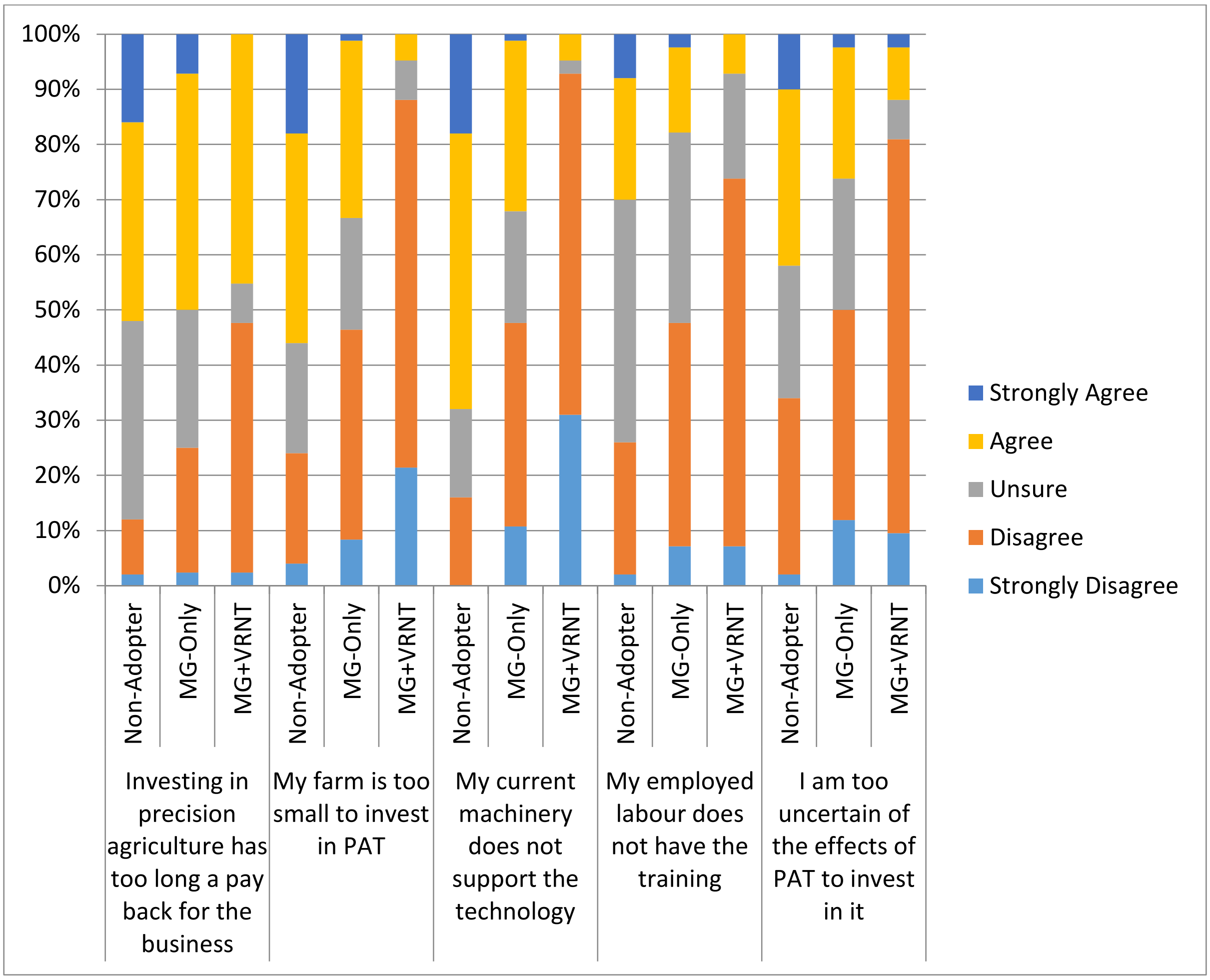


Figure 5: Dutch farmers by adoption profiles, response to attitude statements.

The statement 'Investing in precision agriculture has too long a payback for the business' tends to generate agreement with half of the adopters and non-adopters. For non-adopters, around 36% are also uncertain towards this statement, perhaps reflecting that they haven't considered this factor in their assessment of precision agricultural technologies. These non-adopters also seem to be in agreement (56% of agree and strongly agree) that their farm is too small to adopt PATs. However, there is strong disagreement with MG+VRNT adopters, which potentially reflects the adoption characteristics as larger farmers are more likely to adopt this technology.

More polarity is found with the statement 'My current machinery does not support the technology'. Non-adopters tend to agree with this statement (68% of agree and strongly agree) whereas 93% of MG+VRNT adopters tend to disagree or disagree strongly.

The statement 'My employed labour does not have the training' generates more uncertainty for non-adopters compared to adopters, who on the whole tend to disagree with statement. It seems that a standard characteristic of adoption of these PATs is more employed labour and consequently this response reflects these farm structural issues.

The majority of MG+VRNT disagree with the final statement 'I am too uncertain of the effects of PAT to invest in it'. However for both non-adopters and MG-Only adopters there is some polarity towards this statement. Whilst 42% of non-adopters agree or strongly agree, 32% disagree with the statement. For MG-Only adopters, whilst 38% disagree, 24% are unsure and 26% agree. Accordingly, this may reveal the variance of performance within farming systems which use machine guidance and this may be related to the type of technology adopted, i.e. integrated or add-on, and the competency of the user in responding to this information.

Table 12: Dutch farmer top 10 reasons for adoption or non-adoption, ranked by frequency.*

Non-Adopters		MG-only adopters		MG+VRNT adopters	
High cost of technology	8	More comfort	12	Cost reduction	11
Farm is too small	5	Cost reduction	9	Reduced agrochemical input	4
Farm land too scattered	3	Ease of use	6	Increase yields	3
Farmer sceptical of benefits	3	Better mapping	5	More accuracy	2
Lack of self-knowledge	3	More accuracy	5	More comfort	2
Low ROI	2	Reduced workload	4	More efficiency	2
Technology too complicated	2	Increase yields	3	Technical efficiency	2
		More efficiency	3		
		Reduced agrochemical input	3		
		Straight lines	3		

** Any reason mentioned only once is removed from the table.*

The main reasons stated for non-adoption seem to be the high cost of technology and restrictions on the farm, such as size and land is too scattered. In addition, there are limits to the farmer knowledge of the technologies, or scepticism towards the technology. One statement that seems unique to MG-only adopters in Holland is the belief that the technology offers more comfort, this relates to issues around accuracy and ability to drive and manage the field to support decision making. This also relates to ease of use and driving for straight lines. Moreover, other reasons mentioned include better mapping and more efficiency, which again may be associated with the comfort offered in terms of machine guidance.

Similar reasons emerge for MG+VRNT adoption but prioritise cost reductions and savings on inputs, as well as the improvement in yields. This is linked to further statements on technical efficiency gains. Moreover, ease of use and comfort are also cited which, again, relates to the improved support for decision making and field management that these technologies, farmers believed, offer.

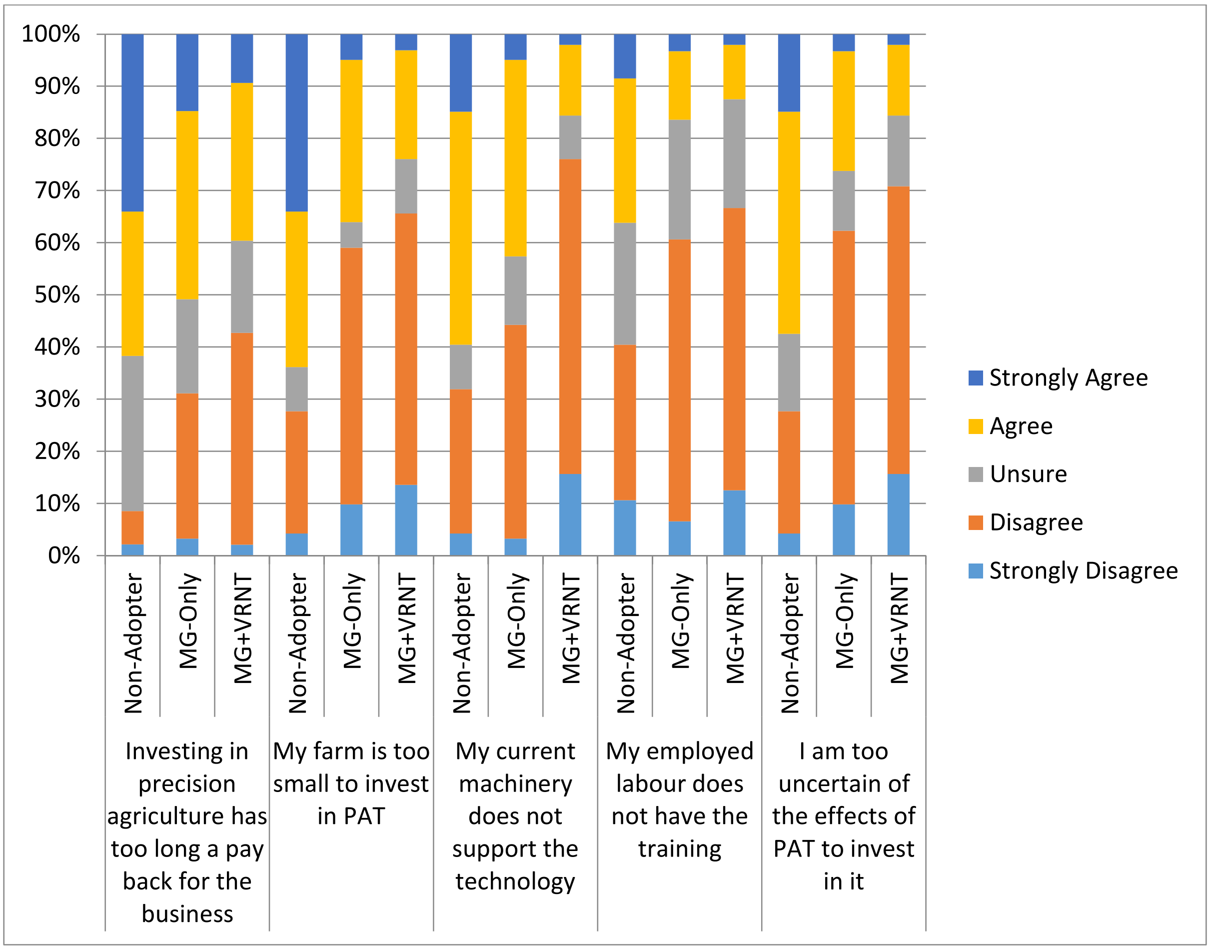


Figure 6: UK farmers by adoption profiles, response to attitude statements.

A similar pattern emerges for UK farmers in terms of skews towards disagreement with the negative statements as adoption increases (Figure 6Figure). Non-adopters tend to have high levels of agreement that payback is too long (cumulatively 62% agree or strongly agree), that their farm is too small (cumulatively 64%), and that their current machinery does not support the technology (cumulatively 60%). There is more of a polarity with non-adopters in terms of the need for training for employed labour, namely 37% of farmers agree or strongly agree that this is a constraint, whereas 41% disagree or disagree strongly with the statement. This may reflect the variance in the level of labour employed within non-adopters compared to adopters. Finally, with respect to the statement 'I am too uncertain of the effect of PAT to invest in it', 57% of non-adopters either agreed or strongly agreed with this statement, indicating that potentially some degree of demonstration or further information on the effects is needed to convince them to adopt PAT technologies.

There is also some ambivalence towards the length of pay back periods for adopters. For MG Only adopters 51% tend to agree or strongly agree with this statement, whereas 18% are unsure. Moreover, for MG+VRNT adopters around 40% are in agreement with this statement and 43% in disagreement, and 18% remain unsure. Consequently, whilst we would expect stronger opinions emerging, if only through reassurance that investment is providing a rate of return it may be that actual returns for some of these adopters are not providing the expected level of return to this investment. However, this is contradicted slightly by the stronger disagreement with the statement 'I am too uncertain of the effects of PAT to invest in it'. The majority of MG Only adopters (62%) and MG+VRNT adopters (71%) disagree or disagree strongly, indicating that they are potentially assured that the machinery is improving results on key factors such as yield and nitrogen efficiency. However, it may be that the high cost of the technology is still not providing the returns they were expecting.

Similarly, ambivalence emerges towards the statement 'My current machinery does not support the technology' for MG-Only adopters as just over 40% were in agreement and a similar percentage were in disagreement. This probably reflects the machinery inventory of these farmers and the age of their equipment as modern tractors tend to offer an integrated platform for PAT recording and visualisation equipment and, it would be expected, would allow additional equipment to be added, whereas older tractors have limited options for extension for PATs.

Further textual analysis is provided in the table below.

Table 13: UK farmer top 10 reasons for adoption or non-adoption, ranked by frequency.*

Non-Adopters		**MG-only Adopters**		**MG+VRNT Adopters**	
High cost of technology	20	More accuracy	17	Cost reduction	33
Perceived low ROI	8	Cost reduction	8	More accuracy	21
Farm is too small	7	More efficiency	7	More efficiency	10
Farmer sceptical of benefits	3	Ease of use	6	Increase yields	8
Machinery compatibility	3	Straight lines	6	Technical efficiency	6
Farmer knowledge superior	2	Reduced workload	4	Ease of use	3
Low commodity revenues	2	Work longer periods	3	Farm biophysical characteristics	3
Technology too complicated	2	Curiosity	2	More standardisation	3
Too old	2	Higher ROI	2	Progressive farmer	3
		Improved product quality	2	Machine compatibility	2

** Any reason mentioned only once is removed from the table.*

It is clear that a small number of reasons emerge quite frequently for both adoption and non-adoption. For non-adopters the clearest issue is the high cost of the technology as a barrier to uptake and this could be viewed in conjunction with the perceived low return on investment, low commodity revenues and that the farm is considered too small to merit this level of investment. These reasons have previously been raised and consequently infer a common set of barriers to adoption of PATs which also matches findings in previous studies.

A second theme emerges around the farmer, firstly simply through the age of the farmer but also the perceptions of the farmer in terms of their scepticism towards the benefits. Statements related to this were:

> *'no proof it works.'* (Farmer UK67)

> *'I'm not convinced that it's delivering reduced costs. I understand the case for maybe using it with the potatoes but not for grain. Our combine is all laser guided off the header, having a machinery guidance means the only difference is it's using a satellite instead of the laser to guide it so I don't see the point.'*
>
> (Farmer UK550)

Secondly, there was also a belief that their knowledge of farming the crop was superior to what the technology could offer:

'Skill levels of employees with machinery, knowledge of the ground are adequate'.

(Farmer UK245)

'We feel the soil sampling we do at the moment is adequate enough.'

(Farmer UK489)

There are some similarities in the reasons stated between MG Only and MG+VRNT adopters, for instance statements around 'more accuracy', 'more efficiency' and 'cost reduction' were mentioned by a number of farmers. A small number of farmers identified it was either their curiosity or they perceived themselves as progressive farmers, namely that they felt adoption of PAT was simply part of progress and therefore they were required to adopt this technology.

One element that only emerged for MG-Only adopters was the ability to work longer hours, the ease of use and to reduce workloads. Through automation processes this leads the farmer to be able to work safely and accurately after sunset. For MG-VRNT adopters a number of farmers identified increasing yields as a reason to adopt the technology, and some MG-Only farmers highlighted a higher return on investment and improved product quality.

A further interesting element related to the biophysical characteristics in terms of the ability to plough straighter lines, allow more standardisation and improved product quality. This links to previous research on identifying spatial variability as a factor in adopting PATs (Khanna, 2001). Selected statements related to these were:

'to try and even everything out, we have variable soil and with the applications we can even out harvest dates'

(Farmer UK34)

'It was to even out variation across ground to make more uniformed crops, better targeting of problem areas.'

(Farmer UK178)

'To try and even out yields across the fields.'

(Farmer UK52)

Logistic regression

One aim of the survey was to quantify the differences between non-adoption and adoption decisions. As the dependant variable is categorical then regression analysis must accommodate the discrete thresholds between different adoption states. Consequently, a logistic modelling approach is most appropriate. However, our adoption profile does not follow a hierarchy, as adoption of MG+VRNT does not require farmers to have first adopted MG Only, as MG+VRNT is sold as a package. Accordingly a binominal or multinominal structure is our preferred approach.

Under a binomial regression only two states are examined, e.g. adoption or non-adoption of MG-Only adoption and most previous studies on PAT adoption have used this approach (Shen-Tey and Brindal, 2012). Multinomial regression covers more than two relative states of adoption, which would cover the adoption profile examined here and offers a relative estimate of the factors which determine adoption of MG or MG+VRNT compared to other states. Accordingly our approach is to examine both a multinomial logistic regression, augmented by separate binomial regressions on adoption (that is both MG only and MG+VRNT adopters) compared to non-adoption and one focused within adoption classes, which compares MG only with MG+VRNT adoption.

In equation 1 let J be the number of nominal outcomes and m the class of y outcomes, that is, (0) non-adoption, (1) MG Only, and (2) MG+VRNT. Thus, considering the range of outcomes (y), the predicted probability of the i-th farmer choosing a nominal outcome (y = 0,1,2) with the base reference class of 0 is:

$$\Pr(y_i) = m|x_i' = \frac{\exp(x_i'\beta_m)}{\sum_{j=1}^{J}\exp(x_i'\beta_j)} \quad (1)$$

Where $\beta_0 = 0$

This provides indications of the probability of a change in the independent variable (x) affecting membership of one of the three classes of adoption. Moreover, a binominal regression simply reduces the nominal outcomes to a binominal structure (y=0,1).

A range of data were collected from the survey. These provide key indicators that would determine the main characteristics of adoption and non-adoption. Sheng-Tey and Brindal (2012) provided a review of why farmers have or have not adopted PATs and this revealed 10 papers, some of which covered more than one study. Hence they synthesised 25 studies conducted in various regions to identify the drivers of adoption. They categorised these into 7 categories, namely socio-economic, agro-ecological, institutional, informational, farmer perception, behavioural factors and technological factors.

Socio-economic factors such as formal education and age were found to be significant in determining adoption. This matches the bulk of literature on technology adoption which seems to support that younger and more educated farmers are more likely to adopt farm technologies (Ascough et al. 2002; Tiffin and Balcombe 2011).

Secondly, what they term 'agro-ecological' factors covers structural and financial aspects which they found to be significant, namely management structures, farm size, income specialisation, as well as debt asset ratios. These seemed to follow the standard characteristics of adoption of technology within agriculture, namely that adopters generally operate a larger agricultural area, as well as generate a higher income (Putler and Zilberman 1988; Batte et al.1990). More specialisation is less common in these studies but has also been found to be a factor in dictating uptake (Putler and Zilberman 1988). This can be inferred through the degree of income from specialised activities and also the amount of land dedicated to specialised activities (Woodburn et al. 1994), Moreover adopters seem to have a greater number of regular labour employed, which again is indicative of the larger size leading to greater financial leverage outlined above (Paustian and Theuvsen, 2016).

Whilst ownership and management structures have been explored, these tend to offer mixed results. Some studies identify owner-occupied farmers as more likely to adopt, again due to access to capital to enable investment in machinery (Putler and Zilberman 1988; Baker 1992), whereas some argue that tenanted farmers are more likely to adopt as these farmers tend to behave with a more innovative outlook and it is more imperative that they attain efficiencies within production.

This mixture of owner and tenanted farmers tends to be region specific, as do presence and engagement in farmer co-operatives, and, to accommodate these regional differences, regional indicators should be included. Notably no studies could be found which offer a cross national study and consequently do not provide useful in drawing out generalised conclusions for drivers of uptake. Accommodating for regional differences matches the third category of Sheng-Tey and Brindal (2012) namely institutional factors, which includes regional constraints.

A further factor identified by these authors was informational and these were positively linked to uptake of PATs. Hence, this can link to use of advisors or consultants or advisors, but also infers membership of marketing co-operatives and machinery collective groups where information is passed through informal mechanisms, usually from farmer to farmer.

Farmer perceptions and behaviours, though under-researched were also found to have an effect on uptake. Specifically, the level of perceived profitability of using precision agriculture could dictate uptake and this could be captured in the attitudinal statement 'Investing in precision agriculture has too long a payback for the business'. A behavioural factor which was also found to be positive was the willingness of farmers to adopt the technology and this could also be captured through the statement 'I am too uncertain of the effects of PAT to invest in it'.

A final factor which they found to be significant was the influence of technological factors. This related to on-farm technological aspects that would predict adoption of other technologies. Accordingly, whilst we could not capture the full technological profile of these farmers given the time constraint of the survey, we did ask about current adoption of PATs. Hence, an index of current PAT adoption at farm level could be calculated which simply added a 1 to the index for each PAT that the farmer had currently adopted, e.g. variable rate irrigation etc. This gave an index running from 0, where no current PATs were on the farm to 4 where the farmer had adopted all other PATs. This index did not include MG-Only and VRNT options to avoid multicollinearity issues. Table 14 shows the independent variables used, based on this review of factors that we would expect to have some influence on adoption of precision agricultural technologies. All explanatory variables were continuous, binary or categorical. Categorical responses were converted into dummy variables and are presented conditional on the reference value specified.

Table 14: Variables used within the empirical model and distributions.

Variable	**Type**	**Description**
Size	Continuous	Sum of total area in hectares
Age	Categorical	0:<45; 1:45-65; 2:>65
Management Structure	Binary	0:Owner; 1: Tenant; 2: Other
Member of a marketing co-op	Binary	0:Not a member; 1:Marketing Co-op
Member of machinery co-op	Binary	0:Not a member; 1: Machinery Collective;
Regular Labour	Continuous	Sum of regular labour in total staff numbers
Income Class	Categorical	0:<100k; 1:100-300k; 2:+300K
Income Specialisation	Binary	0: <60% of income from specific crop 1: > 60% of income from specific crop.
Farm Specialisation	Continuous	Ratio of arable land to total land area from 0 to 1, where 0 is no arable land to total land area and 1 is arable land covers total land area.
Level of current adoption	Continuous	A scale from 0 to 4 which indicates the amount of other PATs currently on farm where 0= no other PATS and 4=4 other PATs.
Agricultural Education	Binary	0: No ; 1: Yes
Positive towards payback	Binary	0: Not positive towards payback; 1: Positive towards payback statement of PATs
Uncertain towards outcomes	Binary	0: Less uncertain; 1: More uncertain towards outcomes
Advisor±	Binary	0: Not an influence; 1: Advisors as influences of adoption
Farmers±	Binary	0: Not an influence; 1: Other farmers as influences on adoption
Contractors±	Binary	0: Not an influence; 1: Contractors as influences on adoption
Region	Dummy	Representing the 5 case study regions

± Only adopters were asked this question and therefore could not be used to compare adoption with non-adoption.

Multinomial logistic regression (MLR)

The multinomial logistic regression is appropriate when we have more than 2 categories of dependant variables and these are not ordered. Accordingly, the dependant variable used for the multinomial logistic was:

- 0: Non Adoption (Base outcome);
- 1: MG Only Adoption;
- 2: MG+VRNT Adoption.

The regression estimates a set of binomial regressions between the base outcome class, in this case non-adoption, and the reference classes, in this case MG Only and MG+VRNT adoption (Table 15). The results are presented as odds ratios. This can be interpreted as the relative odds of a change in an independent variable affecting membership of a reference class relative to a base outcome class. Generally, if these odds are higher than 1 then an increase in that independent variable will increase the likelihood of membership of an adoption class, e.g. MG Only, compared to a non-adoption class with all other variables held equal.

The model fits well, indicated by the chi square value of 442 and probability of 0. This shows the null effect model with no independent regressors has a poorer fit than a model with the independent regressors. Nagelkerke's R2 (0.415) indicates a moderate to good relationship between the predictors and the prediction, though R2 are usually low logistic regression studies and similar studies (e.g. Paustian and Theuvsen, 2016).

Accordingly, for both adoption classes compared to non-adoption to adoption a number of significant variables was found. Less significance was found for MG+VRNT technologies, though there is commonality in the independent variables which are significant across both technologies, indicating that drivers for uptake of both are generally similar.

Size of farm is significant and marginally positive for both technologies. That is as utilised agricultural area expands there is a slightly higher propensity for farmers to adopt these PATs. This matches other studies within this area (Feder et al., 1985; Walton et al., 2008; Robertson et al., 2012). However, this is a small effect and does not compare with other significant variables. For age, the odds ratios are below 1 and significant for most categories, indicating that as farmers get older they are less likely to adopt these technologies. Again, this matches previous findings on age and the potential short planning horizon of older farming as a barrier to invest in PATs. It seems that management structure has no significant impact on determining adoption and both tenanted or owner occupiers are just as likely to adopt machine guidance of MG+VRNT. Paustian and Theuvsen (2016) did find some significant differences with farmers who leased larger areas of land but did not specifically examine ownership status as a predictor.

If a farmer were a member of marketing co-operative they are almost two times as likely to adopt MG than those who are not members of a co-operative. Membership of a marketing co-operative is significant for MG Only, with an odds ratio of 1.94. This serves as a proxy for information transfer between farmers which has found to have an effect (Rogers, 2003; Larson et al., 2008; Robertson et al., 2012). Moreover, this may also engender higher price premiums, which provides some returns for assuring farmer investment into the technology. Membership of a machinery group or collective does not seem to be significant, perhaps indicating that these technologies are purchased within the farm rather than as a group asset to be shared amongst farmers. Household income is also an important factor in determining uptake of machine guidance. The odds ratio is over 1 and increase as income increase. That is for farmers with over 300,000 euros annual income are more likely to adopt PATs than those with less than 100,000 euros per annum. This again agrees with literature on PATs, and also the findings within the qualitative part of this report, indicating that adoption has high entry costs and higher income farmers are more likely to adopt them (Diederen et al., 2003).

Notably the income specialisation from potatoes had to be dropped due to multicollinearity issues. In addition, specialisation of income from wheat does not seem to infer uptake. However, the ratio of arable land to total land strongly predicts adoption of both MG and MG+VRNT. That is, as the ratio increases by 1 unit towards more arable land in proportion to total area, farmers are over 7 times more likely to adopt machine guidance. This can also infer economies of scale, which again have been highlighted in qualitative reasons explored above, and this tends to support the requirement to reduce costs on a per unit basis. Attitudinal factors have an effect, specifically if farmer perception is that PATs will provide a suitable length of payback they are more likely to adopt PATs compared to those with who do not agree with this statement. Watson et al. (2008) used a fairly simple indicator of expected profitability but did not find a significant relationship. Hence, this variable may capture a longer term view of returns to investment and, consequently, offers some indication of potential for uptake of machine guidance. Moreover, if they have other PATs on the farms they are more likely to adopt both technologies. As would be expected MG + VRNT is more advanced which may explain the higher odds ratio over 1 for this variable. This can be taken as an indication that farmers have access to ancillary capacity for data collection, processing and decision making (e.g. Tiffin and Balcoumb, 2011).

The regional dummy was added as a way to condition the regression to accommodate the different systems and regions. What emerges is that there seems to be no significant difference between regions for machine guidance, aside from Dutch farmers, who are four times more likely to adopt this technology compared to Belgium. Moreover, all regions are strongly likely to adopt MG+VRNT compared to Belgium, which reflects the low level of uptake of this technology within this region.

Table 15: Maximum likelihood estimates for multinomial logistic regression, indicating MG Only or MG+VRNT adoption, relative to non-adoption.

	MG Only		**MG+VRNT**	
	OR[35]	**SE**	**OR**	**SE**
Size of Farm	1.00***	(0.00)	1.00***	(0.00)
Age (reference class: <45)				
45-65	0.56**	(0.11)	0.67	(0.16)
Over 65	0.21***	(0.08)	0.33**	(0.13)
Management. Reference class: owner-occupied				
Tenanted	0.68	(0.26)	0.96	(0.42)
Other	0.87	(0.22)	0.88	(0.27)
Membership of machinery collective	1.49	(0.36)	1.22	(0.39)
Membership of marketing co-operative	1.94*	(0.51)	1.48	(0.43)
Regular labour employed	1.02	(0.07)	1.03	(0.07)
Income class. Reference class: less than 100,000 euros				
100,000-300,000 Euros	1.53*	(0.32)	1.59	(0.41)
>300,000 Euros	1.77*	(0.48)	1.77	(0.57)
Above school agricultural education	1.02	(0.20)	1.52	(0.38)
Specialisation. Reference class: less than 60% income from wheat				
Wheat income	0.92	(0.11)	0.84	(0.13)
Ratio of arable land to total land	7.58***	(4.00)	7.14**	(4.83)
Positive towards payback	1.79***	(0.32)	0.93	(0.20)
More uncertain towards outcomes	0.89	(0.18)	0.63	(0.16)
Level of current adoption of PATs	1.22*	(0.10)	1.67***	(0.16)
Region. Reference class: Belgium				
Germany	1.23	(0.43)	7.04**	(4.35)
Greece	2.12	(0.84)	11.75***	(8.00)
The Netherlands	4.19***	(1.29)	18.93***	(11.22)
UK	1.76	(0.64)	25.84***	(15.69)
Reference class: Non-Adoption				
Number of Observations	971			
Nagelkerke's R^2	0.42			
LR Chi2	442			
Prob > Chi2	0.00			

*Standard errors in parentheses * p<.05 ** p<.01 *** p<.001*

[35] OR= Odds Ratio; SE = Standard Error

Table 16 shows the results for two binominal logistic regressions. Regression I shows the results of adopters compared against non-adopters, where the dependant variable is calculated, as:

- 0: Non-adopters;
- 1: MG only and MG+VRNT adopters.

Regression I finds a number of variables significant and positive predictors of PAT adoption. The model fits well, with a goodness-of-fit indicated by a Chi2 value of 335 and Nagelkerke's R^2 of 0.391, which is a moderate to good fit. The regression also shows that 75% of all cases were correctly classified to adoption, which was higher than the null model.

Significant variables are of a similar magnitude to those found in the multinomial regression and where discussed above. Area of farm again is nominal but significant and matches past literature on size being a predictor of uptake. Other indicators of size include income, which was also significant. Effectively farmers with more income are more likely to adopt PATs for reasons explained above. Positive attitudes towards payback are also predictors as is the amount of arable land to total land indicating both specialised activities and potential economies of scale are prerequisites to adoption.

Table 16: Maximum likelihood estimates for bi-nominal logistic regression, indicating membership of MG Only, MG+VRNT adoption, relative to non-adoption.

	I		II	
	OR[36]	**SE**	**OR**	**SE**
Size of farm	1.005***	(0.00)	1.00	(0.00)
Age (reference class: <45)				
45-65	0.59**	(0.11)	1.29	(0.29)
Over 65	0.24***	(0.08)	1.45	(0.64)
Management. Reference class: owner-occupied				
Tenanted	0.77	(0.26)	1.17	(0.57)
Other	0.88	(0.21)	1.06	(0.31)
Membership of machinery collective	1.42	(0.33)	0.83	(0.25)
Membership of marketing co-operative	1.77*	(0.42)	0.68	(0.20)
Regular labour employed	1.03	(0.07)	1.01	(0.03)
Income class. Reference class: less than 100,000 euros				
100,000-300,000 Euros	1.56*	(0.31)	1.01	(0.26)
>300,000 Euros	1.77*	(0.46)	1.16	(0.32)
Above school agricultural education	1.13	(0.21)	1.60	(0.38)
Specialisation. Reference class: less than 60% income from wheat				
Wheat income	0.90	(0.10)	0.89	(0.13)
Ratio of arable land to total land	7.44***	(3.61)	0.73	(0.48)
Positive towards payback	1.46*	(0.24)	0.51**	(0.11)
More uncertain towards outcomes	0.80	(0.15)	0.82	(0.23)
Level of current adoption of PATs	1.35***	(0.11)	1.36***	(0.12)
Influenced by farm advisors			1.62**	(0.29)
Influenced by other farmers			1.12	(0.25)
Influenced by contractors			0.88	(0.16)
Region. Reference class: Belgium				
Germany	1.71	(0.56)	5.12**	(3.23)
Greece	2.83**	(1.06)	7.58**	(5.46)
The Netherlands	5.35***	(1.57)	4.43*	(2.67)
UK	3.88***	(1.32)	13.95***	(8.67)
	Reference Class: Non-Adopters		Reference Class: MG Only Adopters	
Number of Observations	971		543	
Nagelkerke's R^2	0.391		0.253	
LR Chi2	335		113	
Prob > Chi^2	0.00		0.00	
% Correctly Classified	75%		69%	

*Standard errors in parentheses * p<.05 ** p<.01 *** p<.001*

[36] OR= Odds Ratio; SE = Standard Error

Regression II compares MG only adopters to MG+VRNT adopters, effectively with non-adopters removed, hence the dependent variable is:

- 0: MG Only adopters;
- 1: MG+VRNT adopters.

Regression II shows fewer significant variables determine uptake of MG+VRNT compared to MG Only. Whilst a good fit, as it provides greater prediction than a null model with no independent variables, the R^2 fit model is lower showing a good to poor level of fit. Around 69% of all cases were correctly classified which is higher than that for the null model, thus indicating a good fit.

In the multinomial logistic regression a common set of drivers proved significant in predicting adoption of both technologies. However, several aspects seem to be different around perceptions and current adoption levels of PATs. Given the higher level of investment it would be expected that MG+VRNT adopters have more current PATs on the farm and this is confirmed by an odds ratio above 1, indicating they are more likely to adopt MG+VRNT compared to MG Only. This may be reflective of the size issues behind the farm and the search for increasing economies of scale or seeking complementarities within the technology to address soil and field based heterogeneities. It may also infer a more innovative attitude towards the technology. Only adopters were asked about the influences on adoption, and a number of binary variables could be tested for a range of common influences found in relation to PAT adoption. We find a significant and positive effect from use of an advisor. This seems to match the findings of Robertson et al. (2012) and Larson et al. (2008), who found that if farmers respond to information provided on PATs provided by advisory services they are more likely to adopt these technologies. A further point is that the perceived profitability indicator with respect to positive responses to payback is significant but lower than 1. This probably infers the differences in cost of technologies when compared.

Regional differences are also more explicit in regression II where, compared to Belgium, there are significant and more positive odds ratios leading to potentially more likelihood that uptake of MG+VRNT, the more advanced technology, would be expected in these countries compared to Belgium.

Awareness and intentions of non-adopters

It is worth exploring in more depth the awareness of non-adopters within the sample to further understand the particular barriers and constraints which may inhibit future adoption levels. Table 17 outlines the key statistics available from FADN data compared to the non-adopters. It is clear that, following the above discussion, on the whole non-adopters are smaller than the average farms, aside from Greece where these are consistently higher. This is reflective of the sampling approach which targeted particular populations and consequently the sample is not representative of the wider population.

Table 17: Comparison of key area statistics between non-adopters and FADN by farm type.

	UAA (code 1510*)		Wheat Area		UAA (code 1610**)		Potato Area		Cotton Area	
	FADN	SV	FADN	SV	FADN	SV	FADN	SV	FADN	SV
Belgium	77	40	27	8	103	35	51	7		
Germany	270	144	103	26	121	97	40	97		
Greece	36	85	11	34	21	79			15	79
The Netherlands	81	52	54	13	117	58	56	58		
United Kingdom	218	197	54	41	268	285	70	285		

** Specialist cereals, oilseeds and protein crops*

*** Specialist root crops*

Table 18 shows the level of awareness of these technologies for non-adopters presented by region. It is notable that no studies have examined awareness of precision agricultural technologies within the population of non-adoption. Consequently, these are discussed below.

Table 18: Awareness of technology by region for non-adopters, number of observations and percentage per technology.

	VRNT				MG-Only			
	Not Aware		Aware		Not Aware		Aware	
Belgium	59	39%	91	61%	21	14%	129	86%
Germany	10	13%	69	87%	5	6%	74	94%
Greece	82	80%	20	20%	21	21%	81	79%
The Netherlands	9	18%	41	82%	4	8%	46	92%
UK	2	4%	45	96%	0	0%	47	100%

Results are presented the spread of awareness of each technology within each region. These show quite diverse distributions of awareness of the technology. As would be expected awareness of machine guidance is high with only Greek farmers with the lowest level of awareness. For VRNT this is more diverse, as again Greek farmers have the lowest level of awareness. This is followed by Belgium farmers, where 39% of farmers claim to be not aware of VRNT. Conversely, UK farmers have the highest level of awareness of both technologies.

The intentions of adoption are presented in Table 19 and Table 20. These show the non-adopters grouped by their awareness and non-awareness and their intentions to adopt MG and MG+VRNT technologies.

Table 19: Intentions to adopt Machine Guidance for non-adopters by level of awareness, number of observations and percentage.*

	Not Aware of MG				Aware of MG			
	No intention		Intend to adopt in 5-10 years' time		No intention		Intend to adopt in 5-10 years' time	
Belgium	44	75%	15	25%	66	72%	26	28%
Germany	8	80%	2	20%	45	65%	24	35%
Greece	59	72%	23	28%	9	43%	12	58%
The Netherlands	6	61%	4	39%	28	67%	14	33%
UK	2	100%	0	0%	27	59%	19	41%

** This sums the responses for both 2cm and 40cm machine guidance.*

Of those not aware of the technology, the majority do not intend to adopt the machine guidance. However, around 20 to 40%, dependant on region, of those not aware of the technology do intend to adopt machine guidance in 5-10 years' time. For those who were aware of the technology around half had no intention of adopting the technology, whereas a smaller proportion do intend to adopt in 5-10 years' time.

Table 20: Intentions to adopt VRNT for non-adopters, number of observations and percentage by awareness and technology, percentage.

	Not Aware of VRNT				Aware of VRNT			
	No intention		Intend to adopt in 5-10 years' time		No intention		Intend to adopt in 5-10 years' time	
Belgium	15	71%	6	29%	92	71%	37	29%
Germany	2	40%	3	60%	46	62%	28	38%
Greece	21	100%	0	0%	67	83%	14	17%
The Netherlands	3	75%	1	25%	25	54%	21	46%
UK	0	0%	0	0%	20	43%	27	57%

Those not aware of VRNT have, on the whole, no intention to adopt the technology. This ranges from 0% for the UK to 100% in Greece, which tended to indicate more resistance towards technological adoption more than other regions. A wider diversity of response is found for those who are aware of the technology. UK farmers who are aware of VRNT tend to be the most likely to adopt the technology in the future, with Greek farmers proving the most resistant, potentially offering some insight into the low level of adoption found for VRNT in this study.

3.4.3 Incentives for future adoption

Barnes at el (2017b) presented results on the incentives by region and by adoption type, finding that some incentives were common across regions (i.e. those that would either definitely or probably increase their use of the technology), but different across adoption classes. Accordingly, this section examines these incentives by the awareness of technologies for levels of adopters. We follow a hierarchy of adoption, where we firstly explore non-adopters and their response to incentives dependent on their awareness of the technologies to assess whether there are any differences and, consequently, informational needs to raise awareness of these technologies. Secondly, MG-Only adopters are examined with respect to their perceptions of VRNT. This also identifies potential opportunities for encouragement of uptake of more PATs in the future.

Table 21: Incentives which would have an effect on increasing uptake for current non-adopters by region and by awareness of Machine Guidance technology, number and percentage by region and incentive.

	Belgium				Germany				Greece				The Netherlands				UK			
	Not Aware		Aware		Not Aware		Aware		Not Aware		Aware		Not Aware		Aware		Not Aware		Aware	
More support for training of my staff	0	0%	39	19%	0	0%	62	15%	0	0%	3	5%	0	0%	81	15%	0	0%	87	18%
Confidence that yields would increase	0	0%	26	13%	0	0%	31	8%	0	0%	1	2%	0	0%	38	7%	0	0%	21	4%
Confidence that my costs would reduce	0	0%	15	7%	0	0%	21	5%	0	0%	0	0%	0	0%	38	7%	0	0%	15	3%
More support for training for myself and family	0	0%	18	9%	0	0%	53	13%	0	0%	4	7%	0	0%	68	13%	0	0%	69	15%
More technical support from sales people	0	0%	23	11%	0	0%	47	12%	0	0%	0	0%	0	0%	64	12%	0	0%	57	12%
Directed subsidy support for uptake of PATS	0	0%	15	7%	0	0%	29	7%	0	0%	0	0%	0	0%	42	8%	0	0%	22	5%
Financial support from tax breaks	0	0%	15	7%	0	0%	24	6%	0	0%	0	0%	0	0%	42	8%	0	0%	26	5%
A 10% reduction in the present cost of the technology	0	0%	18	9%	0	0%	35	9%	0	0%	21	36%	0	0%	43	8%	0	0%	46	10%
Government support for soil mapping, by providing ground penetrating radar or intensive soil sampling	0	0%	11	5%	0	0%	37	9%	0	0%	3	5%	0	0%	30	6%	0	0%	32	7%
Improving technology to provide working maps based on soil maps	0	0%	13	6%	0	0%	29	7%	0	0%	2	3%	0	0%	31	6%	0	0%	38	8%
More stringent laws on pesticide and nitrogen application	0	0%	15	7%	0	0%	33	8%	0	0%	24	41%	0	0%	63	12%	0	0%	61	13%

For those non-adopters who were not aware of machine guidance technology there were no intentions to adopt the technology in the future. For those non-adopters who were aware of machine guidance, there was a fairly even distribution of agreement with the main incentives which would encourage adoption. Clearly, for most regions, aside from Greece, support for training seems one of the most common incentives both for staff and for the farm family household. In addition for these regions around 11-12% of farmers thought that more technical support from sales people would also encourage uptake of PATs. Greece seems somewhat anomalous to the other regions, with a high proportion of non-adopters supporting a reduction in the price of the technology and more stringent laws on agrochemical use. This may infer that Greece, which has smaller farms and, also more family farms, is less exposed to options for training of precision agriculture. In terms of further textual statements towards incentives, there was some consensus between Greek and UK farmers who mentioned a greater reduction in the cost of the technology as a driver for uptake, and, for Belgium farmers, support for higher commodity prices as an incentive for uptake of PATS. This infers a closer link within the supply chain of these farmers, and may highlight the need to generate a higher return on investment as a reason for adoption.

Table22: Incentives which would have an effect on increasing uptake for current non-adopters by region and awareness of Variable Rate Nitrogen Technology, percentage by region and incentive.

	Belgium				Germany				Greece				The Netherlands				UK			
	Not Aware		Aware		Not Aware		Aware		Not Aware		Aware		Not Aware		Aware		Not Aware		Aware	
More support for training of my staff	6	38%	33	17%	2	25%	60	15%	1	4%	2	6%	5	12%	76	15%	1	100%	86	18%
Confidence that yields would increase	3	19%	23	12%	1	13%	30	8%	0	0%	1	3%	1	2%	37	7%	0	0%	21	4%
Confidence that my costs would reduce	1	6%	14	7%	1	13%	20	5%	0	0%	0	0%	1	2%	37	7%	0	0%	15	3%
More support for training for myself and family	0	0%	18	9%	0	0%	53	13%	3	12%	1	3%	6	14%	62	12%	0	0%	69	15%
More technical support from sales people	2	13%	21	11%	2	25%	45	11%	0	0%	0	0%	3	7%	61	12%	0	0%	57	12%
Directed subsidy support for uptake of PATS	1	6%	14	7%	0	0%	29	7%	0	0%	0	0%	4	10%	38	8%	0	0%	22	5%
Financial support from tax breaks	1	6%	14	7%	0	0%	24	6%	0	0%	0	0%	3	7%	39	8%	0	0%	26	5%
A 10% reduction in the present cost of the technology	2	13%	16	8%	0	0%	35	9%	7	28%	14	42%	5	12%	38	8%	0	0%	46	10%
Government support for soil mapping, by providing ground penetrating radar or intensive soil sampling	0	0%	11	6%	1	13%	36	9%	2	8%	1	3%	3	7%	27	5%	0	0%	32	7%
Improving technology to provide working maps based on soil maps	0	0%	13	7%	0	0%	29	7%	2	8%	0	0%	3	7%	28	6%	0	0%	38	8%
More stringent laws on pesticide and nitrogen application	0	0%	15	8%	1	13%	32	8%	10	40%	14	42%	8	19%	55	11%	0	0%	61	13%

For those non-adopters who were either aware or not-aware of VRNT there are stronger trends towards incentives for uptake of PATs. For farmers who were not aware of VRNT, more support for training of staff was highlighted by most regions, aside from Greece. More technical support from sales people was also mentioned and seemed popular, especially with German farmers, who were not aware of the technology. For those aware of the technology the incentives seem more evenly distribute across the regions. The anomaly again is Greece, who highlights reductions in the cost of the technology and more stringent laws on agrochemicals as incentives. Further textual analysis found that for non-aware Greek farmers, 'more information provided' would be an incentive to uptake PATs. This, perhaps echoes the previous finding, related to lack of exposure to training and identifies more effort needed to publicise precision agricultural technologies with these farmers. For those who were aware of the technology a greater reduction in the cost of the technology again was raised as a potential incentive for a number of farmers across the regions.

Finally, farmers who had adopted MG-Only technologies were asked to indicate the effect of incentives on their adoption of PATs. These are presented below in terms of their awareness of VRNT, as it reflects a progression of technology adoption.

Table23: Incentives which would have an effect on increasing uptake for current MG Only-adopters by region and awareness of Variable Rate Nitrogen Technology, percentage by region and incentive.

	Belgium				Germany				Greece				The Netherlands				UK			
	Not Aware		Aware		Not Aware		Aware		Not Aware		Aware		Not Aware		Aware		Not Aware		Aware	
More support for training of my staff	1	3%	6	3%	1	8%	30	6%	8	14%	43	9%	2	10%	28	5%	0	0%	23	5%
Confidence that yields would increase	2	6%	15	7%	2	17%	48	10%	3	5%	43	9%	3	14%	49	9%	0	0%	45	10%
Confidence that my costs would reduce	5	14%	24	11%	0	0%	51	11%	1	2%	44	10%	5	24%	51	10%	0	0%	53	12%
More support for training for myself and family	7	19%	20	9%	1	8%	37	8%	4	7%	43	9%	1	5%	35	7%	0	0%	28	6%
More technical support from sales people	3	8%	18	8%	1	8%	39	8%	1	2%	44	10%	1	5%	37	7%	1	50%	33	7%
Directed subsidy support for uptake of PATS	4	11%	24	11%	2	17%	46	10%	1	2%	44	10%	3	14%	60	12%	0	0%	46	10%
Financial support from tax breaks	1	3%	24	11%	2	17%	50	11%	2	3%	44	10%	5	24%	59	11%	0	0%	49	11%
A 10% reduction in the present cost of the technology	2	6%	22	10%	1	8%	42	9%	13	22%	32	7%	1	5%	53	10%	0	0%	42	9%
Government support for soil mapping, by providing ground penetrating radar or intensive soil sampling	4	11%	27	12%	1	8%	45	9%	6	10%	44	10%	0	0%	52	10%	0	0%	48	11%
Improving technology to provide working maps based on soil maps	4	11%	25	11%	1	8%	46	10%	8	14%	44	10%	0	0%	53	10%	0	0%	43	10%
More stringent laws on pesticide and nitrogen application	3	8%	23	10%	0	0%	41	9%	11	19%	31	7%	0	0%	42	8%	1	50%	35	8%

For farmers who had adopted MG-Only, it seems that there is a more even distribution of the incentives which would have an effect on uptake of PATS and it is difficult to draw any clear trends. Only Greece seems to indicate higher levels of agreement with a reduction in the present cost of the technology and more stringent laws on agro-chemical use. Similarly, for Dutch farmers, financial support from tax breaks was highlighted as potentially relevant in terms of encouraging uptake, for those not aware of the technology. Very few further textual statements were made by MG-Only adopters with respect to incentives that created a consensus. For 8 of the farmers in the UK, who were aware of the technology, they stated that a greater reduction in the cost of the technology would lead to more uptake and, for 6 of the Dutch farmers who were also aware of the technology, standardisation of technology was mentioned. This relates to compatibility issues within the technology and the software, which is especially relevant to the scenario where a farmer may adopt MG and then seek to augment this technology with VRNT. Consequently, compatibility between systems becomes an important issue for further adoption.

Whilst examining awareness and non-awareness provides a useful indication of differences towards incentives, those aware of the technology are more likely to uptake the technologies. Incentives are grouped into three categories and presented by type of incentive to uptake technologies, namely

Financial Incentives:

- Confidence that yields would increase;
- Confidence that my costs would reduce;
- Directed subsidy support for uptake of PATs;
- Financial support from tax breaks;
- A 10% reduction in the present cost of the technology;

Training Support Incentives

- More technical support from sales people;
- More support for training of my staff;

Non-Financial Incentives

- Government support for soil mapping, by providing ground penetrating radar or intensive soil sampling;
- Improving technology to provide working maps based on soil maps;
- More stringent laws on pesticide and nitrogen application.

These are collated by country and presented as percentage distributions per region.

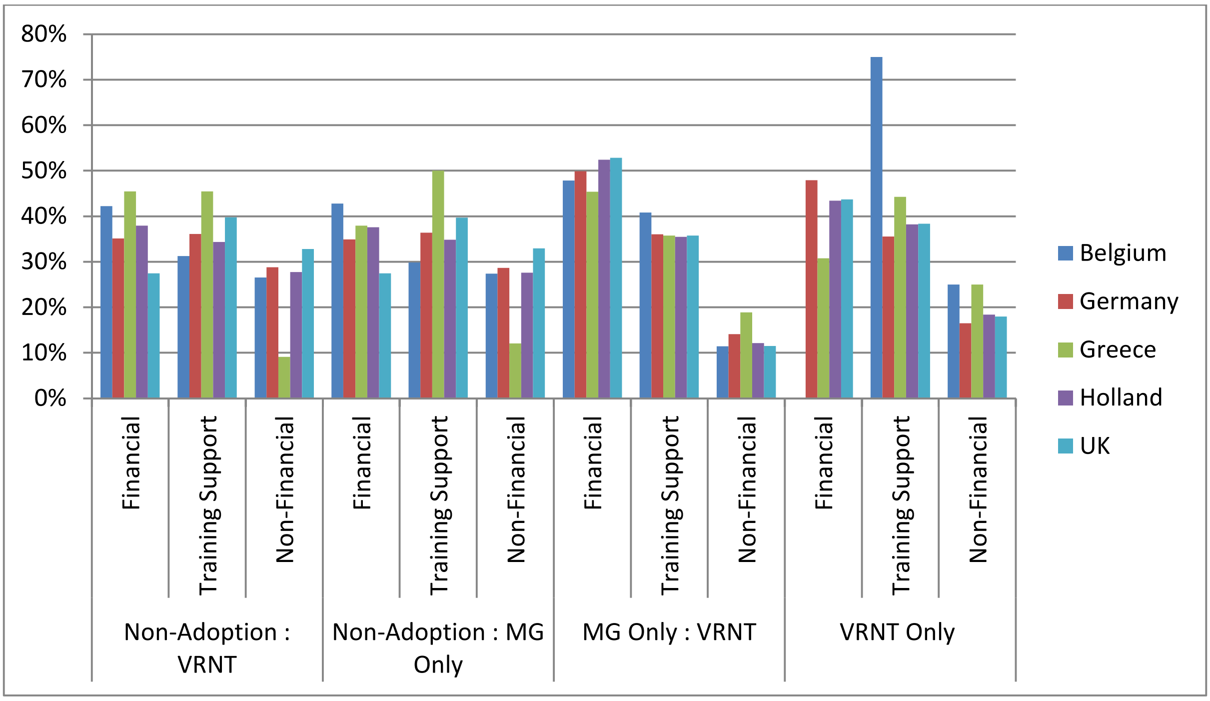


Figure 7: Grouped incentives which would have an effect on increasing uptake for those that are aware of the technology; non-adopters to uptake VRNT and MG, MG adopters to uptake VRNT and VRNT only, percentage summed positive responses by region.

Figure 7 tends to indicate some divergence across the countries in terms of their support for incentives. For Belgium, around 40 to 50% of farmers within each category would positively respond to financial incentives, whereas for Germany this ranged from 35% (for non-adopters) to 50% for those who either already have adopted MG or MG+VRNT. For Greece, a similar percentage of between 38 to 45% farmers would respond positively to financial incentives. For both The Netherlands and the UK the number of non-adopters who would respond positively is lower than those who had already adopted the technology. In the Netherlands, around 38% and in the UK, 27%, of non-adopters would respond to financial incentives, whereas 53% of MG Only and 48% of MG+VRNT adopters stated they would respond to these incentives.

Training support has a similar level of response across the regions, though Belgium MG+VRNT only adopters should be discounted as only 4 farmers had adopted this technology and therefore no conclusions can be drawn on this group. Hence, between 31% of Belgium non-adopters to 45% of Greek non-adopters would favourably respond to training support incentives. Certainly, this latter result may explain the observation the Greek farmers are less aware of the technologies and seem to be lacking post-sales support in using this technology. These distributions remain for adopters, which range from 35% of Dutch farmers to 41% of Belgium MG Only adopters, and 36% of German farmers to 44% of Greek MG+VRNT adopters who would respond to more training and technical support.

Finally, other incentives which include support in provision of maps to more stringent laws of pesticide and nitrogen application tend to have a less positive response across the regions. For non-adopters, these range from 9% for Greece up to 33% of UK farmers. For MG only adopters these support mechanisms would also be less of an incentive, with between 10 to 20% of farmers stating it may encourage their uptake. For MG+VRNT adopters, only around 20% of farmers are likely to respond to these mechanisms.

3.5 Discussion and conclusions

There is a relatively limited yet growing literature examining the uptake of precision agriculture. As PATs are becoming more ubiquitous within developed country policy dialogue as a mechanism that could meet sustainability and food production aspirations, it would seem that understanding how further adoption is engendered would be a key task for researchers. We add to this literature by offering the first cross regional empirical study of uptake of precision agriculture in Europe and find some commonality between barriers within the five regions.

The main barriers tend to focus on the high cost element of the initial investment, leading to longer payback periods. Moreover. uncertainty towards the potential for improved profitability to recoup this investment creates a significant barrier towards further adoption. This is in contrast to the adopters who, on the whole, provide a more positive perspective on the technology’s ability to ease the workload and free up time for other tasks on the farm or extend work during critical times. Consequently, there seems to be a different perspective in that non-adopters focus on the financial barriers, whereas adopters highlight the ancillary benefits of the technology.

A common finding in previous studies has been that larger farmers tend to have the capacity to adopt these technologies but also the diversity of operations to accommodate the risk from investment and the longer term for payback on these technologies. This is evidenced here. Important within this also is what Sheng-Tey and Brindal (2012) found in relation to the farmer perception of the technology, specifically those farmers who perceived that PATs would bring about profitability were more likely to adopt it and here we find a positive response to payback periods leads to more uptake. Consequently, this highlights that given the high level of investment, farmers are seeking self-assurance or legitimacy to validate their decisions. This self-confirmation aspect may temper the responses within the survey. Some of this may be evidenced in the polarity of opinion expressed towards certain statements by adopters, in particular adopters of Machine Guidance where in some regions equal proportions of agreement and disagreement were found. This may infer that there are further groups operating within these adoption classes based on outlook and experience of the PAT and perhaps further work can explore ways to cluster farmers beyond purely technology adoption classes presented here.

What is less clear is the role of socio-economic factors in determining uptake. Whereas a review of past literature did find operator age and education to be important (Sheng-Tey and Brindal, 2012) a recent study in Germany could find no significant effect of education or age status in predicting uptake (Paustian and Theuvsen, 2016). We find that, on the whole, younger farmers are more likely to adopt the technology but we could find no effect of educational status. This is even when the education variable explored is focused on agricultural education compared to other forms of education. Within the literature on technology adoption education does generate mixed results. This is perhaps also reflective of Huffman’s (2001) argument that education variables tend to lead to biased interpretations of intellectual achievement which, in terms of precision agriculture, should extend to skills accommodating data management and interpretation, and knowledge of more complex operating systems. Potentially this calls for a more sophisticated latent variable approach to understanding uptake, where knowledge is proxied by a number of candidate variables of which only aspect is educational attainment (e.g. Toma et al., 2016).

Awareness of both machine guidance and variable rate nitrogen technology was generally high. For most regions, awareness of machine guidance exceeds 90% of the sample. In addition, where VRNT was most adopted, the UK, Germany and the Netherlands, awareness of this technology was also around 90%. The lowest recorded levels of awareness were in Greece and Belgium. Both these samples seem to be characterised by small scale agriculture or arable land area and, it would be expected, would tend to be less inclined to seek automation relative to larger field sizes.

Few studies have focused on non-adopters and the planning transition between non-adoption and adoption is complicated by the role of industry and, in particular, their influence on determining the purchase decision and creation of scepticism towards the results. There is no regulatory push to adopt PATs, nor any government subsidy to promote the technology. Consequently, as this is purely a commercial decision it may be the role of the Government to provide a balance to industry promotion of these technologies in offering demonstration of actual benefits, support for training and, if these benefits are economically justified, potential subsidisation for smaller farmers to engage in precision agricultural technologies on farm.

Whilst we have quantified the main drivers of uptake it is probably the case that softer factors determine adoption. For most regions, farming networks and commercial interests were the main motivators for adopting machine guidance or VRNT. Thus, aspects of social networks and peer-to-peer learning emerge from these influences. Moreover, the opportunities for demonstrating the technology, through researchers and trade fairs proved an important aspect of the determining uptake of these technologies. Some of this qualitative dialogue is captured within the survey but mostly confirm the literature. On the margins more intriguing reasons emerge for adoption, e.g. precision agriculture is part of progress, and for non-adoption, e.g. technologies do not fit within the ecological ethos of the farm. The literature is lacking in any detailed qualitative studies of uptake of precision agriculture and further work such probably examine the role of these cultural factors of farming and how sophisticated technologies, such as PAT, may create barriers to future adoption.

4 Quantification of adoption of selected PATs

One of the study's objectives was to quantify the farm level economic impact adoption of PA technologies. There are a range of approaches available to empirically investigate farm level economic impacts of technological changes. A common requirement in all approaches is to estimate farm economic metrics without the technology and with the technology – either on the same farm or on different farms. Given the budget and time constraints of the study approaches based on time series data of adopter and non-adopter farms could not be used, neither methodologies which require a large sample size of adopter and non-adopter farms with matching characteristics. Instead, the partial budget methodology was used utilising existing information on typical farm budgets of the case study regions and farm types and the information on perceived impacts on farms collected in the survey. The perceived impacts were projected upon the relevant farm budget items to estimate the effect of adoption of a particular PAT on gross and net margins for different sizes of typical farms within each case study region.

4.1 Farm budget data

FADN data was used to derive the average farm budget in the case study regions, for two farm types in each region (Table 24). FADN data from years 2009 to 2013 were used, averaging the five years' data. Wheat growers where represented by the farm type "Specialist cereals, oilseed and protein crops" (FADN code 1510), potato growers by the farm type "Specialist root crops" (FADN code 1610) and cotton producers by the farm type "Specialist cotton" (FADN code 1650); farms where respectively wheat, potato and cotton total production was zero were excluded from the dataset. For each region and farm type the farms were grouped by farm size corresponding to the survey analysis farm size categories (<50ha, 50-100ha, >100ha). The relevant FADN data were averaged across the years for each region, farm type and farm size (30 categories). Table 25 and Table 26 show the averaged data derived from the FADN dataset.

Table 24: FADN data used in the partial budget analysis.

	NUTS2 regions included	**Farm types selected (col. A25 in the FADN dataset)**
Belgium	All	1510 and 1610
Germany	All	1510 and 1610
Greece	All	1510 and 1650
The Netherlands	All	1510 and 1610
United Kingdom	Scottish NUTS2 regions (UKM2, UKM3, UKM5, UKM6)	1510 and 1610

Table 25: Averaged FADN data for the 30 farm categories (years 2009-2013)37. NaN: No data available

Country	Farm type	Farm Size	Number of farms	UAA	Economic Size	Economic Size	Total Output	Total Input	Total Specific Costs	Total Farming Overhead	Depreciation	Total External Factors	Unpaid Labour Input	Paid Labour Input	Total Output Crops
				ha	ESU	€	€	€	€	€	€	€	hours	hours	€
				SE025	SE005	A27	SE131	SE132D	SE281	SE336	SE360	SE365	SE016	SE021	SE135
BEL	wheat	large	13	165	208	208,033	258,291	215,245	65,403	51,298	49,764	48,779	3,260	2,000	237,631
BEL	wheat	medium	19	62	80	80,046	106,929	97,460	29,699	27,295	27,503	12,963	1,839	240	98,930
BEL	wheat	small	20	35	43	43,384	66,247	50,916	15,263	16,410	8,907	10,336	2,151	100	59,034
BEL	potato	large	20	157	496	496,041	653,009	505,840	213,077	83,823	72,948	135,992	4,315	1,781	592,858
BEL	potato	medium	12	74	196	196,300	285,842	251,856	83,512	70,695	61,052	36,597	3,423	222	259,856
BEL	potato	small	10	31	99	98,674	173,022	113,273	34,829	41,959	20,768	15,717	3,116	984	169,225
DEU	wheat	large	2,816	411	389	389,433	544,039	565,133	185,605	159,103	68,549	152,120	3,020	7,539	477,885
DEU	wheat	medium	1,022	72	70	69,656	97,067	96,465	31,794	34,968	16,505	13,278	2,546	763	82,477
DEU	wheat	small	850	37	37	36,569	52,522	56,217	16,556	23,811	9,888	6,089	2,030	511	43,123
DEU	potato	large	237	193	489	489,128	583,091	510,434	184,695	145,924	78,863	100,952	3,280	3,242	521,075
DEU	potato	medium	127	74	202	202,341	214,961	190,904	70,147	59,559	30,706	30,492	2,728	1,213	188,431
DEU	potato	small	129	33	100	100,046	119,706	101,259	30,820	40,073	14,946	15,657	2,297	1,736	103,857
ELL	wheat	large	36	131	81	81,307	82,863	94,521	32,803	29,690	12,537	19,492	2,481	945	81,896
ELL	wheat	medium	111	69	45	44,587	52,462	59,780	21,400	17,693	8,844	11,844	2,069	619	51,105

[37] *A full definition of the variables used within this analysis can be found here: http://ec.europa.eu/agriculture/rica/definitions_en.cfm*

Country	Farm type	Farm Size	Number of farms	UAA	Econo-mic Size	Econo-mic Size	Total Output	Total Input	Total Specific Costs	Total Farming Overhead	Depre-ciation	Total External Factors	Unpaid Labour Input	Paid Labour Input	Total Output Crops
				ha	**ESU**	**€**	**€**	**€**	**€**	**€**	**€**	**€**	**hours**	**hours**	**€**
				SE025	**SE005**	**A27**	**SE131**	**SE132D**	**SE281**	**SE336**	**SE360**	**SE365**	**SE016**	**SE021**	**SE135**
ELL	wheat	small	515	22	19	18,596	24,947	27,030	8,739	8,519	5,687	4,207	1,561	572	24,540
ELL	cotton	large	5	108	136	135,653	67,462	102,315	34,772	31,180	7,597	28,766	2,235	4,414	67,462
ELL	cotton	medium	72	63	71	71,479	65,051	92,526	25,789	32,877	14,754	19,106	3,530	1,718	63,578
ELL	cotton	small	1,404	19	23	22,984	25,076	33,487	9,415	12,377	5,646	6,325	2,060	653	24,758
NED	wheat	large	10	151	178	177,790	392,971	297,958	65,627	94,942	91,032	46,357	2,490	877	304,435
NED	wheat	medium	12	62	78	77,963	172,387	109,682	24,256	45,338	18,678	21,410	2,304	454	135,539
NED	wheat	small	11	40	50	50,474	113,455	128,031	20,950	55,724	25,372	25,985	1,941	254	73,470
NED	potato	large	208	183	648	648,184	940,943	798,810	258,244	198,076	138,531	203,959	4,253	2,679	838,777
NED	potato	medium	162	72	246	245,973	400,799	331,119	111,522	86,345	55,607	77,645	3,071	1,551	356,629
NED	potato	small	79	33	106	106,283	200,183	151,488	56,091	43,188	24,505	27,704	2,219	567	128,270
UKI	wheat	large	210	228	222	222,236	280,895	312,359	113,131	94,755	58,999	45,912	3,233	2,589	225,305
UKI	wheat	medium	16	90	90	89,588	120,289	130,733	42,890	54,454	25,428	7,960	2,233	119	97,885
UKI	wheat	small	1	34	40	40,077	32,996	56,345	16,794	29,000	10,323	228	3,150	NaN	29,207
UKI	potato	large	13	283	796	795,969	801,809	805,533	280,596	222,359	139,883	162,696	5,157	6,403	766,241
UKI	potato	medium	1	82	167	166,576	96,973	94,282	42,996	28,444	16,619	6,223	3,170	80	79,313
UKI	potato	small	0	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Table 26: Averaged FADN data for the 30 farm categories (years 2009-2013).TP referes to Total Production, NaN: data not available

Country	Farm type	Farm Size	Number of farms	Common Wheat TP	Potatoes TP	Cotton TP	Common Wheat Area	Potatoes Area	Cotton Area	Motor Fuel and Lubricants	Fertilisers	Wages Paid	Contract Work	Mach./ Build. Current Costs
				€	€	€	ha	ha	ha	€	€	€	€	€
				K120TP	**K130TP**	**K347TP**	**K120AA**	**K130AA**	**K347AA**	**F62**	**SE295**	**SE370**	**SE350**	**SE340**
BEL	wheat	large	13	90,911	2,903	NaN	61	2	NaN	12,999	30,093	30,334	16,921	14,075
BEL	wheat	medium	19	31,216	39,957	NaN	21	4	NaN	5,290	10,699	2,934	7,934	9,304
BEL	wheat	small	20	16,442	13,200	NaN	10	1	NaN	2,689	4,005	500	6,613	4,837
BEL	potato	large	20	57,991	441,896	NaN	31	80	NaN	15,691	37,923	17,477	33,258	22,794
BEL	potato	medium	12	43,822	180,471	NaN	29	29	NaN	19,296	16,494	1,685	20,198	20,250
BEL	potato	small	10	10,555	140,164	NaN	6	18	NaN	12,528	8,572	7,962	14,321	10,309
DEU	wheat	large	2,816	200,136	23,267	NaN	157	8	NaN	42,427	80,239	97,418	31,056	37,041
DEU	wheat	medium	1,022	32,995	3,689	NaN	26	1	NaN	8,614	14,023	6,427	6,650	9,289
DEU	wheat	small	850	18,158	3,619	NaN	14	1	NaN	4,785	7,314	3,856	4,413	6,707
DEU	potato	large	237	62,732	325,923	NaN	43	63	NaN	34,304	55,424	35,994	28,092	40,331
DEU	potato	medium	127	37,570	104,539	NaN	24	25	NaN	14,854	19,247	11,764	11,960	15,520
DEU	potato	small	129	18,866	68,472	NaN	13	13	NaN	7,921	8,270	11,686	6,975	10,554
ELL	wheat	large	36	21,176	NaN	19,750	34	NaN	18	13,542	20,081	3,804	9,842	4,584
ELL	wheat	medium	111	14,362	8,587	7,250	25	1	8	8,286	11,341	2,246	6,265	2,075

Country	Farm type	Farm Size	Number of farms	Common Wheat TP	Potatoes TP	Cotton TP	Common Wheat Area	Potatoes Area	Cotton Area	Motor Fuel and Lubricants	Fertilisers	Wages Paid	Contract Work	Mach./ Build. Current Costs
				€	€	€	ha	ha	ha	€	€	€	€	€
				K120TP	K130TP	K347TP	K120AA	K130AA	K347AA	F62	SE295	SE370	SE350	SE340
ELL	wheat	small	515	3,790	1,200	3,486	7	0	3	3,668	4,525	1,732	2,665	1,080
ELL	cotton	large	5	4,839	NaN	54,592	8	NaN	83	15,600	11,785	14,447	13,008	3,060
ELL	cotton	medium	72	2,297	NaN	46,105	5	NaN	40	14,672	10,634	4,581	9,253	3,809
ELL	cotton	small	1,404	1,574	1,500	19,721	3	0	13	4,868	3,615	2,034	3,492	1,459
NED	wheat	large	10	204,322	NaN	NaN	108	NaN	NaN	16,828	16,591	12,453	10,649	36,205
NED	wheat	medium	12	62,206	270,053	NaN	37	NaN	NaN	7,774	7,449	8,259	13,411	7,806
NED	wheat	small	11	35,705	NaN	NaN	23	NaN	NaN	4,288	4,995	2,670	14,326	15,233
NED	potato	large	208	63,867	570,647	NaN	38	91	NaN	31,203	39,312	55,351	29,271	57,298
NED	potato	medium	162	33,297	238,137	NaN	20	33	NaN	10,813	17,090	25,839	18,311	24,250
NED	potato	small	79	16,906	80,727	NaN	11	14	NaN	4,803	6,336	10,889	9,710	13,017
UKI	wheat	large	210	78,345	66,811	NaN	56	15	NaN	22,221	48,508	31,994	13,611	31,811
UKI	wheat	medium	16	35,333	699	NaN	24	0	NaN	7,549	18,415	1,094	19,099	12,325
UKI	wheat	small	1	18,926	NaN	NaN	22	NaN	NaN	4,267	6,586	NaN	3,867	12,365
UKI	potato	large	13	90,661	498,701	NaN	52	74	NaN	43,353	87,578	77,928	33,129	74,757
UKI	potato	medium	1	12,004	47,019	NaN	14	14	NaN	6,883	24,755	721	1,832	13,865
UKI	potato	Small	0	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

The net margin (*NM*) and gross margin (*GM*) were calculated as the difference between the total output and total input and total output and total specific costs, respectively:

$$NM = SE131 - SE132D \quad \text{(Eq.1)}$$

$$GM = SE131 - SE281 \quad \text{(Eq.2)}$$

Where SE131 is Total output [EUR], SE132D is Total input [€] and SE281 is Total specific costs [€]

Table 27 presents the net and gross margin and the share of wheat and potato and cotton area to the whole farm area.

Table 27: Average net and gross margin and proportion of wheat and potato+cotton area for the 30 farm categories derived from the FADN data (2009-2013).

Country	Farm type	Farm Size	Net margin	Gross margin	Wheat area / UAA	Potato and cotton area / UAA
			€/farm/y	€/farm/y	%	%
BEL	wheat	large	43,046	192,888	37%	1%
BEL	wheat	medium	9,469	77,231	34%	6%
BEL	wheat	small	15,331	50,984	29%	4%
BEL	potato	large	147,169	439,932	20%	51%
BEL	potato	medium	33,987	202,330	39%	40%
BEL	potato	small	59,748	138,192	20%	57%
DEU	wheat	large	-21,094	358,435	38%	2%
DEU	wheat	medium	603	65,273	36%	1%
DEU	wheat	small	-3,695	35,966	38%	2%
DEU	potato	large	72,658	398,396	22%	33%
DEU	potato	medium	24,057	144,813	33%	34%
DEU	potato	small	18,446	88,885	39%	38%
ELL	wheat	large	-11,658	50,060	26%	13%
ELL	wheat	medium	-7,318	31,062	37%	14%
ELL	wheat	small	-2,083	16,208	30%	13%
ELL	cotton	large	-34,853	32,690	8%	77%
ELL	cotton	medium	-27,476	39,262	7%	64%
ELL	cotton	small	-8,411	15,661	14%	73%
NED	wheat	large	95,013	327,344	72%	0%
NED	wheat	medium	62,705	148,131	60%	0%
NED	wheat	small	-14,576	92,505	57%	0%
NED	potato	large	142,133	682,699	21%	50%
NED	potato	medium	69,680	289,277	27%	46%
NED	potato	small	48,695	144,092	33%	44%
UKI	wheat	large	-31,464	167,764	25%	7%
UKI	wheat	medium	-10,444	77,399	27%	0%

Country	Farm type	Farm Size	Net margin	Gross margin	Wheat area / UAA	Potato and cotton area / UAA
			€/farm/y	€/farm/y	%	%
UKI	wheat	small	-23,349	16,203	64%	0%
UKI	potato	large	-3,724	521,213	18%	26%
UKI	potato	medium	2,690	53,976	17%	17%
UKI	potato	small	NaN	NaN	NaN	NaN

NaN: data not available

4.2 Perceived farm economic effects

The farm economic effects of adoption were approximated using the information on perceived impacts as revealed by the survey (average for farm type and size in the five case study regions).

Table 28: Average perceived impacts of adoptions of MG only and MG+VRNT [38].

PAT	Country	Farm type	Farm size	Number of observations	Yield (kg/ha)	Fuel quantity (l/ha)	N applied (kg N/ha)	Repairs and Spares (€)	Contractor costs (€)	Hired labour cost (€)	Training time (hrs)	Management time (hrs)	Field time (hrs)
MG	BEL	Wheat	Large	4	NoEffect	-5-10%	NoEffect	NoEffect	NoEffect	-5-10%	+5-10%	NoEffect	-5-10%
MG	BEL	Wheat	Medium	16	NoEffect	-5-10%	-5-10%	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	-5-10%
MG	BEL	Wheat	Small	9	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	-5-10%
MG	BEL	Potato	Large	5	NoEffect	-5-10%	NoEffect	NoEffect	NoEffect	-5-10%	NoEffect	+5-10%	-5-10%
MG	BEL	Potato	Medium	17	NoEffect	NoEffect	-5-10%	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	-5-10%
MG	BEL	Potato	Small	7	NoEffect	NoEffect	-5-10%	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	-5-10%
MG	DEU	Wheat	Large	42	NoEffect	-5-10%	-5-10%	NoEffect	NoEffect	NoEffect	+5-10%	NoEffect	-5-10%
MG	DEU	Wheat	Medium	8	NoEffect	-5-10%	-5-10%	NoEffect	NoEffect	-5-10%	NoEffect	+5-10%	-5-10%
MG	DEU	Wheat	Small	1	NoEffect	-5-10%	NoEffect	+ 11-20%	+5-10%	-5-10%	+ 11-20%	+5-10%	+5-10%
MG	DEU	Potato	Large	10	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect
MG	DEU	Potato	Medium	3	NoEffect	-5-10%	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	+5-10%	NoEffect
MG	DEU	Potato	Small	2	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	-5-10%	NoEffect	NoEffect	-5-10%
MG	ELL	Wheat	Large	17	NoEffect	-5-10%	-5-10%	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	- 11-20%
MG	ELL	Wheat	Medium	44	NoEffect	-5-10%	-5-10%	NoEffect	NoEffect	-5-10%	NoEffect	NoEffect	-5-10%
MG	ELL	Wheat	Small	9	NoEffect	-5-10%	-5-10%	NoEffect	NoEffect	NoEffect	NoEffect	-5-10%	- 11-20%
MG	ELL	Cotton	Large	9	NoEffect	-5-10%	-5-10%	NoEffect	NoEffect	NoEffect	+5-10%	NoEffect	-5-10%
MG	ELL	Cotton	Medium	15	NoEffect	-5-10%	-5-10%	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	-5-10%
MG	ELL	Cotton	Small	4	NoEffect	-5-10%	-5-10%	NoEffect	NoEffect	NoEffect	NoEffect	-5-10%	-5-10%
MG	NED	Wheat	Large	25	NoEffect	-5-10%	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	-5-10%
MG	NED	Wheat	Medium	37	NoEffect	-5-10%	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	-5-10%

[38] *Where NA is stated this relates to no survey data available at this level of disaggregation.*

PAT	Country	Farm type	Farm size	Number of observations	Yield (kg/ha)	Fuel quantity (l/ha)	N applied (kg N/ha)	Repairs and Spares (€)	Contractor costs (€)	Hired labour cost (€)	Training time (hrs)	Management time (hrs)	Field time (hrs)
MG	NED	Wheat	Small	9	NoEffect	-5-10%	NoEffect	NoEffect	NoEffect	-5-10%	NoEffect	NoEffect	-5-10%
MG	NED	Potato	Large	27	NoEffect	-5-10%	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect
MG	NED	Potato	Medium	35-37	NoEffect	-5-10%	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	-5-10%
MG	NED	Potato	Small	7	NoEffect	-5-10%	NoEffect	NoEffect	NoEffect	-5-10%	NoEffect	NoEffect	-5-10%
MG	UKI	Wheat	Large	51	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	-5-10%
MG	UKI	Wheat	Medium	4	NoEffect	-5-10%	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	-5-10%	-5-10%
MG	UKI	Wheat	Small	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
MG	UKI	Potato	Large	19	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect
MG	UKI	Potato	Medium	18	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect
MG	UKI	Potato	Small	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
MG+VRNT	BEL	Wheat	Large	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
MG+VRNT	BEL	Wheat	Medium	1	+5-10%	-5-10%	-5-10%	NoEffect	NoEffect	NoEffect	+5-10%	NoEffect	+5-10%
MG+VRNT	BEL	Wheat	Small	3	+5-10%	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	+5-10%	NoEffect
MG+VRNT	BEL	Potato	Large	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
MG+VRNT	BEL	Potato	Medium	1	+5-10%	-5-10%	-5-10%	NoEffect	NoEffect	NoEffect	+5-10%	NoEffect	+5-10%
MG+VRNT	BEL	Potato	Small	2	+5-10%	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	+5-10%	NoEffect
MG+VRNT	DEU	Wheat	Large	42	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect
MG+VRNT	DEU	Wheat	Medium	5	NoEffect	NoEffect	-5-10%	+5-10%	NoEffect	NoEffect	NoEffect	+5-10%	NoEffect
MG+VRNT	DEU	Wheat	Small	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
MG+VRNT	DEU	Potato	Large	11	NoEffect	NoEffect	-5-10%	NoEffect	NoEffect	NoEffect	+5-10%	NoEffect	NoEffect
MG+VRNT	DEU	Potato	Medium	1	NoEffect	NoEffect	-5-10%	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect
MG+VRNT	DEU	Potato	Small	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
MG+VRNT	ELL	Wheat	Large	20	+5-10%	NoEffect	- 11-20%	NoEffect	NoEffect	NoEffect	+ 11-20%	NoEffect	NoEffect
MG+VRNT	ELL	Wheat	Medium	3	+ 11-20%	-5-10%	- 40%	NoEffect	NoEffect	NoEffect	+5-10%	+ 11-20%	-5-10%

PAT	Country	Farm type	Farm size	Number of observations	Yield (kg/ha)	Fuel quantity (l/ha)	N applied (kg N/ha)	Repairs and Spares (€)	Contractor costs (€)	Hired labour cost (€)	Training time (hrs)	Management time (hrs)	Field time (hrs)
MG+VRNT	ELL	Wheat	Small	1	NoEffect	-5-10%	- 21-30%	-5-10%	+ 40%	-5-10%	-5-10%	-5-10%	-5-10%
MG+VRNT	ELL	Cotton	Large	15	+5-10%	NoEffect	- 11-20%	NoEffect	NoEffect	NoEffect	+ 11-20%	NoEffect	NoEffect
MG+VRNT	ELL	Cotton	Medium	1	+5-10%	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	+5-10%	+5-10%	NoEffect
MG+VRNT	ELL	Cotton	Small	1	NoEffect	-5-10%	- 21-30%	NoEffect	+ 40%	NoEffect	NoEffect	NoEffect	NoEffect
MG+VRNT	NED	Wheat	Large	10	NoEffect	-5-10%	-5-10%	NoEffect	NoEffect	NoEffect	NoEffect	+5-10%	-5-10%
MG+VRNT	NED	Wheat	Medium	10	+5-10%	NoEffect	-5-10%	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect
MG+VRNT	NED	Wheat	Small	1	NoEffect	-5-10%	NoEffect	NoEffect	NoEffect	-5-10%	-5-10%	NoEffect	-5-10%
MG+VRNT	NED	Potato	Large	11	NoEffect	-5-10%	-5-10%	NoEffect	NoEffect	-5-10%	NoEffect	+5-10%	-5-10%
MG+VRNT	NED	Potato	Medium	11	+5-10%	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect
MG+VRNT	NED	Potato	Small	1	NoEffect	-5-10%	NoEffect	NoEffect	NoEffect	-5-10%	-5-10%	-5-10%	-5-10%
MG+VRNT	UKI	Wheat	Large	86	+5-10%	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	+5-10%	NoEffect
MG+VRNT	UKI	Wheat	Medium	7	NoEffect	NoEffect	-5-10%	NoEffect	+5-10%	NoEffect	NoEffect	NoEffect	NoEffect
MG+VRNT	UKI	Wheat	Small	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
MG+VRNT	UKI	Potato	Large	17	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect	NoEffect
MG+VRNT	UKI	Potato	Medium	4	+5-10%	NoEffect	NoEffect	+5-10%	+5-10%	NoEffect	+5-10%	NoEffect	-5-10%
MG+VRNT	UKI	Potato	Small	0	NA	NA	NA	NA	NA	NA	NA	NA	NA

Given that the survey reported the effects as a range (e.g. no effect: between -5% and +5%), pessimistic, central and optimistic scenarios were considered for the impacts, using the assumptions in Table 29.

Table 29: Pessimistic, central and optimistic assumptions on the perceived effects (both for MG only and MG+VRNT).

	Yield and labour			**Costs**		
	Pessimistic	**Central**	**Optimistic**	**Pessimistic**	**Central**	**Optimistic**
No perceived effect	-0.04	0	0.04	0.04	0	-0.04
5-10% reduction	-0.1	-0.075	-0.05	-0.05	-0.075	-0.1
11-20% reduction	-0.2	-0.15	-0.11	-0.11	-0.15	-0.2
21-30% reduction	-0.3	-0.25	-0.21	-0.21	-0.25	-0.3
31-40% reduction	-0.4	-0.35	-0.31	-0.31	-0.35	-0.4
More than 40% reduction	-0.5	-0.45	-0.41	-0.41	-0.45	-0.5
5-10% increase	0.05	0.075	0.1	0.1	0.075	0.05
11-20% increase	0.11	0.15	0.2	0.2	0.15	0.11
21-30% increase	0.21	0.25	0.3	0.3	0.25	0.21
31-40% increase	0.31	0.35	0.4	0.4	0.35	0.31
More than 40% increase	0.41	0.45	0.5	0.5	0.45	0.41

4.3 Calculation of the impacts

The impact categories in the survey were matched with relevant FADN financial data categories as described in Table 30. It is important to highlight that the categories were not matching exactly, the FADN data usually covering a larger group of inputs/outputs (for example the survey asked about impact on nitrogen fertiliser costs while the FADN input category is all fertiliser costs), meaning that the calculated impact on the budget somewhat overestimates the real impact.

Table 30: FADN data and survey data categories assigned.

FADN farm budget categories	**Survey farm economics categories**
Common wheat total production (*K120TP*) [€] Potato total production (*K130TP*) [€] Cotton total production (*K347TP*) [€]	Yield (E_{Yield}) [% of kg per ha]
Motor and fuel lubricants (*F62*) [€]	Fuel quantity (E_{Fuel}) [% of litres per ha]
Fertilisers (*SE295*) [€]	Nitrogen fertiliser quantity applied (E_{Fert}) [% of kg nitrogen / ha]
Wages paid (*SE370*) [€]	Cost of hired labour (E_{Hired}) [% of €]
Contract work (*SE350*) [€]	Contractor costs (E_{Contr}) [% of €]
Machinery and building current costs (*SE340*) [€]	Repairs and Spares (E_{Maint}) [% of EUR]
Unpaid labour input (*SE016*) [hours]	Labour Training Time ($E_{LTraining}$) [% of hours]
Paid labour input (*SE021*) [hours]	Management Time (E_{LMgmt}) [% of hours] Time spent in field (E_{LField}) [% of hours]

The net farm financial impact (I_{Fin}) was calculated as the difference between the impact on wheat and potato and cotton yield and the impact on costs:

$$I_{Fin} = (K120TP + K130TP + K347TP) * E_{Yield} - F62 * E_{Fuel} - SE295 * E_{Fert} - SE370 * E_{Hired} - SE350 * E_{Cont} - SE340 * E_{Maint} \quad \text{(Eq.3)}$$

The relative impact on the net margin (I_{NM}) and gross margin (I_{GM}) were calculated using the following formulae:

$$I_{NM} = \frac{I}{|NM|} \quad \text{(Eq.4)}$$

$$I_{GM} = \frac{I}{|GM|} \quad \text{(Eq.5)}$$

The impact on labour input (I_{Lab}) was calculated assuming that the impacts on training, management and field time affect paid and unpaid labour proportionally and that the paid and unpaid labour consists of training, management and field time in a share of 5%, 25% and 70%, respectively:

$$I_{Lab} = (SE016 + SE021) * \left(E_{LTraining} * 0.05 + E_{LMgmt} * 0.25 + E_{LField} * 0.7\right) \quad \text{(Eq.6)}$$

I_{Fin} , I_{NM} , I_{GM} and I_{Lab} were calculated for all three scenarios (I_{Fin-P}, I_{Fin-C}, I_{Fin-O}, I_{NM-P}, I_{NM-C}, I_{NM-O}, I_{GM-P}, I_{GM-C}, I_{GM-O}, I_{Lab-P}, I_{Lab-C}, I_{Lab-O}, respectively).

4.4 Results and discussion

The main annual financial impacts (excluding capital cost) of machine guidance and variable rate nitrogen technology uptake on farms are presented in Table 35 and 37. The table shows the relative impact on net and gross margin and also the impact on hours worked (note that there were no available FADN data for small UK potato farms and there were no available impact data for large Belgian wheat and potato, small Dutch wheat and potato and small UK wheat farms). All impacts are calculated with pessimistic, central and optimistic impact assumptions.

The net annual impacts of both MG and MG+VRNT uptake are highly variable across countries, farm sizes and farm types. Over two thirds of the mean perceived impact data fall in the category "No effect" and a further 29% into either the 5-10% reduction or 5-10% increase category, indicating small effects. This suggests that the variability in the net impacts were mostly due to variability in the farm accounts data. Similarly, there were no observable trends in either financial or labour impacts between countries, farm sizes and farm types.

With central impact assumptions the highest increase in farm margins as caused by MG adoption (Table 36) is estimated for large German wheat farms (€9,200/farm/y); on a per ha basis small Dutch potato and small Greek cotton farms are the most positively impacted (€36/ ha /y and €34/ha/y, respectively). The largest negative impact could be experienced by small wheat farms in Germany both at the farm level (€-689/farm/y) and at an area basis (€-18/ha/y). By far the largest positive net margin impact (362%) is estimated for medium sized German potato farms due to the very low net margin of those farms €603/farm/y). The largest negative net margin impact is -19% for small potato farms in Germany. The proportional gross margin impacts are smaller as the average gross margin of the farms are 1.4-140 times larger in absolute value than the net margin in all but two cases. The gross margin effects are most positive for the six Greek farms (4-6%) and most negative for small German potato farms (-2%).

MG+VRNT adoption (Table 38), with central assumption, has the most positive impact on medium Dutch wheat farms (€25,478/farm/y and €411/ha/y). The effect is worst on Greek small cotton farms (€-303/farm/y and €-16/ha/y). The impact on net and also gross margin is most positive on medium sized wheat farms in Greece (140% and 33%, respectively), and most negative on small cotton farms in Greece (-4% and -2%, respectively).

The variability of these findings is corroborated by the variability of financial impacts of precision agriculture technologies as reported in the literature (see table 35), with studies finding the net benefits (including investment costs) ranging between €-0.14/ha/y – €4.8/ha/y to up to €41/ha/y. The investment costs are estimated to be between €1,700 and €135,000, guidance systems being around €5,000 and a medium level variable technology system commonly costing €10,000 – €20,000. Assuming a €5,000 MG investment the payback period for the average farms is between ½ year (large German wheat farms) and 10 years (small Dutch wheat farms), not considering the farm types which would experience no impact or annual loss from adoption (see Table 32). For MG+VRT investment an assumed €15,000 capital cost would result in a payback period between 0.6 year (medium Dutch wheat farms) and 42 years (medium German wheat farms). The payback period is below 5 years in 14 and 13 cases for MG and MG+VRNT, respectively. In an additional 8 cases the payback period is between 5-10 years for MG, while for MG+VRNT the payback period is 5-10 years in two cases and beyond 10 years in 5 cases (Table 31).

Table 31: Payback period (years) for MG and MG+VRNT technologies based on assumed investment rates (€5,000 for MG and €15,000 for MG+VRNT).

Country	Farm type	Farm Size	MG payback period	MG+VRNT payback period
BEL	wheat	large	1.5	NA
BEL	wheat	medium	4.2	2.3
BEL	wheat	small	NA	6.7
BEL	potato	large	2.0	NA
BEL	potato	medium	4.0	0.8
BEL	potato	small	7.8	1.3
DEU	wheat	large	0.5	NA
DEU	wheat	medium	2.3	42.3
DEU	wheat	small	NA	NA
DEU	potato	large	NA	3.6
DEU	potato	medium	4.5	10.4
DEU	potato	small	5.7	NA
ELL	wheat	large	2.0	2.5
ELL	wheat	medium	3.0	1.5
ELL	wheat	small	8.1	35.9
ELL	cotton	large	2.4	2.4
ELL	cotton	medium	2.6	4.1
ELL	cotton	small	7.9	NA
NED	wheat	large	4.0	6.0
NED	wheat	medium	8.6	0.6
NED	wheat	small	9.6	28.7
NED	potato	large	2.1	1.6
NED	potato	medium	6.2	0.7
NED	potato	small	4.2	12.7
UKI	wheat	large	NA	1.4
UKI	wheat	medium	8.8	NA
UKI	wheat	small	NA	NA
UKI	potato	large	NA	NA
UKI	potato	medium	NA	4.6
UKI	potato	small	NA	NA

NA: cannot be calculated since the net farm impact is non-positive or there is no survey data available at this level of disaggregation

The survey results show high variability in the payback period (Table 32 and Table 33), in total across countries and farm types 47% and 40% of farmers expect a payback 5 years or less for MG and MG+VRNT, respectively. Another 28% and 36% of farmers estimated the payback period being more than 5 but less than 11 years for MG and

MG+VRNT, respectively. These ratios correspond well with the payback period calculations above, where an assumed investment rate was compared to the net farm impact of the adoption.

Table 32: Frequency of expected payback period for MG.

Payback period	Wheat farms					Potato/cotton farms				
(years)	**BELL**	**DEU**	**ELL**	**NED**	**UKI**	**BELL**	**DEU**	**ELL**	**NED**	**UKI**
0	0	0	0	2	0	0	0	0	0	0
1	1	1	3	0	1	0	0	1	1	1
2	2	3	18	1	2	1	0	2	0	0
3	1	2	20	1	3	4	2	7	5	1
4	0	9	15	2	3	0	1	8	4	2
5	8	7	9	8	14	12	2	5	8	4
6	0	1	1	3	2	0	3	1	2	2
7	2	2	1	1	0	2	1	0	2	0
8	0	5	0	2	1	1	1	0	2	1
9	1	0	0	0	1	0	0	0	0	0
10	7	9	2	16	8	5	3	0	28	4
11	0	0	0	0	0	0	0	0	0	0
15	1	1	0	2	1	1	1	0	1	1
18	0	0	0	0	1	0	0	0	0	1
20	0	1	0	2	0	0	0	0	0	0
>20	0	0	0	4	1	0	1	0	1	0
Already paid back	1	0	0	2	9	1	0	0	1	3

Table 33: Frequency of expected payback period for MG+VRNT.

Payback period	Wheat farms					Potato/cotton farms				
(years)	**BELL**	**DEU**	**ELL**	**NED**	**UKI**	**BELL**	**DEU**	**ELL**	**NED**	**UKI**
0	0	0	0	0	0	0	0	0	0	0
1	0	1	0	2	1	0	1	0	2	0
2	0	0	0	0	0	0	0	0	0	0
3	0	3	0	3	11	0	1	0	4	1
4	0	3	0	0	0	0	2	0	0	0
5	2	14	0	10	14	2	3	0	10	0
6	0	5	0	0	0	0	2	0	0	0
7	0	8	1	2	3	0	1	2	5	3
8	0	2	0	0	0	0	0	0	0	0
9	0	1	0	0	0	0	0	0	0	0
10	0	2	10	8	5	0	2	6	11	2
11	0	1	0	0	0	0	0	0	0	0
15	0	0	3	1	1	0	0	3	1	0
18	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0
>20	0	3	5	0	1	0	0	3	0	0
Already paid back	0	0	0	0	0	0	0	0	0	0

Table 34: Financial impacts of precision agriculture technologies as reported in a selection of publications.

Costs/savings	Value	Country	Year	Reference
Equipment and information cost	Basic system (with auto-steering): €54,500 farm^{-1}, i.e. €18 ha^{-1} y^{-1} (500 ha farm), €4.5 ha^{-1} y^{-1} (2000 ha farm)	Australia	2007	(Jochinke *et al.* 2007)
Equipment and monitoring cost	Advanced system: €135,000 farm^{-1} + €9 ha^{-1}y^{-1}, i.e. €42 ha^{-1} y^{-1} (500 ha farm), €16 ha^{-1} y^{-1} (2000 ha farm)	Australia	2007	(Jochinke *et al.* 2007)
Equipment and monitoring cost	Basic system (with auto-steering): €4,000 farm^{-1}, i.e. €1 ha^{-1} y^{-1} (500 ha farm), €0.2 ha^{-1} y^{-1} (2000 ha farm)	Australia	2007	(Robertson *et al.* 2007)
Equipment and monitoring cost	Medium system: €21,500 farm^{-1}, i.e. €8 ha^{-1} y^{-1} (500 ha farm), €2 ha^{-1} y^{-1} (2000 ha farm)	Australia	2007	(Robertson *et al.* 2007)
Equipment and monitoring cost	Advanced system: €49,000 farm^{-1}, i.e. €18 ha^{-1} y^{-1} (500 ha farm), €4 ha^{-1} y^{-1} (2000 ha farm)	Australia	2007	(Robertson *et al.* 2007)
Equipment and monitoring cost	Medium system: €11,000 farm^{-1}, i.e. €24 ha^{-1} y^{-1} (70 ha farm), €7 ha^{-1} y^{-1} (230 ha farm)	UK	2015	(Eory *et al.* 2015)
Equipment cost	Basic system (±30cm): €1,700	US	2009	(Groover and Grisso 2009)
Equipment cost	Basic system (±10cm): €4,500	US	2009	(Groover and Grisso 2009)
Equipment cost	Mechanical steering system (±10cm): €6,000	US	2009	(Groover and Grisso 2009)
Equipment cost	Entry-level autopilot system (±2cm): €36,000	US	2009	(Groover and Grisso 2009)
Equipment cost	Basic system (without auto-steering): €5,000 farm^{-1}; Advanced system: €13,000 - €18,000 farm^{-1}	UK	2001	(Godwin *et al.* 2003)
Equipment cost	Guidance system: €13,500 for 4,000 ha use	US	2013	(Smith *et al.* 2013)
Equipment cost	Automatic section control system: €9,000 for 4,000 ha use	US	2013	(Smith *et al.* 2013)
Monitoring cost	€8 ha^{-1} y^{-1}	UK	2001	(Godwin *et al.* 2003)
Training cost	€350 farm^{-1} in every 5 years	UK	2001	(Godwin *et al.* 2003)
Training cost	€600 farm^{-1} in every 5 years	UK	2015	(Eory *et al.* 2015)
Maintenance cost	3.5-7.5% of capital cost	UK	2001	(Godwin *et al.* 2003)
Maintenance and signal cost	€850 farm^{-1}, i.e. €13 ha^{-1} y^{-1} (70 ha farm), €3 ha^{-1} y^{-1} (230 ha farm)	UK	2015	(Eory *et al.* 2015)
Savings in variable costs	€25 ha^{-1} y^{-1}	UK	2001	(Godwin *et al.* 2003)
Savings in variable costs	€41 ha^{-1} y^{-1}	UK	2015	(Eory *et al.* 2015)
Net benefits of guidance system	€0.90 – €1.56 ha^{-1} depending on the shape of the field	US	2013	(Smith *et al.* 2013)
Net benefits of automatic section control system	€ -0.14 – €4.78 ha^{-1} depending on the shape of the field	US	2013	(Smith *et al.* 2013)

A large range is present in the difference between the net impacts calculated with pessimistic and optimistic assumptions, spanning from 1,526 €/farm/y to 72,488 €/farm/y, and at an area basis (relative to the whole area of the farm) between 49 and 513 €/ha for MG. The farm level differences between optimistic and pessimistic calculations range from 1,649 €/farm/y to 72,488 €/farm/y (and 49 to 377 €/ha/y) for VRNT uptake.

A comparison of the two technologies reveals that the overall VRNT has a more pronounced positive effect on annual farm finances. With pessimistic assumptions, the net impacts are in all cases unfavourable for the farms for MG uptake (due to the prevalence of "No effect", which is assumed to be -4% in the pessimistic scenario), while for VRNT in half of the cases the impacts are positive. The central MG net impact is between -689 and 9,200 €/farm/y (negative value in one case) while the central VRNT net impact is between -303 and 25,478 €/farm/y (negative value in two cases).

The uptake of MG predominantly reduces labour requirements in with all three impact assumptions, the highest reduction is 12% (small Greek what farms), while the highest increase is 8% (small German wheat farms). VRNT has a less clear positive effect on labour requirement; with the central impact assumption labour is increased for nine farm categories (up to 6%) and reduced for seven farm categories (the largest reduction is –8%). This difference is due to the effect on time spent with fieldwork: training and management time are affected favourably by both technologies, but full adopters usually report an increased amount of field time.

4.5 Conclusions

A range of impacts were found which vary by region and technology. Overall, the uptake of the two technologies can affect annual farm finances and labour requirements significantly, both relative to the net margin of the farms and as a net impact at the farm and area level (note that capital costs of the technologies are not included in these calculations). It seems that MG+VRNT tends to increase the net income more than MG, though for both technologies this is very low, and even negative net impacts can be found for some farm categories. The overall labour impact shows an opposite trend, that is MG technology seems to reduce labour requirements more than MG+VRNT.

Clearly, these results do indicate significant variability. Previous studies, summarised in detail in Table 34, clearly are site and technology specific. They are difficult to provide comparisons for this study as the price of the technology is decreasing and the technology itself is advancing. It would seem that these effects are driven by farm specific factors and Section 3 highlights both the attitudes of the farmer and the physical characteristics of the land as potential constraints to optimal operation of these technologies. In addition, Section 3 identifies training as a popular incentive to uptake more PATs in the future. Accordingly, this may infer issues of how post-sales support are provided from private companies and how the public or private sector may have a role in supporting improved operation of these PATs to maximise impacts.

Table 35: Estimated net financial impact of MG uptake on farms (negative values mean a reduction in farm margin).

Country	Farm type	Farm Size	Net impact	Net impact	Net impact	Net impact	Net impact	Net impact
			€/farm/y	€/farm/y	€/farm/y	€/ha	€/ha	€/ha
			Pessimistic	Central	Optimistic	Pessimistic	Central	Optimistic
BEL	wheat	large	-4,029	3,250	10,529	-24	20	64
BEL	wheat	medium	-2,854	1,199	5,253	-46	19	84
BEL	wheat	small	-1,931	0	1,931	-56	0	56
BEL	potato	large	-22,096	2,488	27,071	-141	16	172
BEL	potato	medium	-10,604	1,237	13,078	-144	17	177
BEL	potato	small	-7,405	643	8,691	-236	20	277
DEU	wheat	large	-9,423	9,200	27,823	-23	22	68
DEU	wheat	medium	-652	2,180	5,011	-9	30	70
DEU	wheat	small	-2,514	-689	1,069	-67	-18	29
DEU	potato	large	-23,312	0	23,312	-121	0	121
DEU	potato	medium	-7,281	1,114	9,509	-99	15	129
DEU	potato	small	-4,258	876	6,011	-128	26	181
ELL	wheat	large	-685	2,522	5,729	-5	19	44
ELL	wheat	medium	-448	1,641	3,729	-6	24	54
ELL	wheat	small	-148	614	1,377	-7	28	62
ELL	cotton	large	-2,229	2,054	6,336	-21	19	59

Country	Farm type	Farm Size	Net impact	Net impact	Net impact	Net impact	Net impact	Net impact
			€/farm/y	**€/farm/y**	**€/farm/y**	**€/ha**	**€/ha**	**€/ha**
			Pessimistic	**Central**	**Optimistic**	**Pessimistic**	**Central**	**Optimistic**
ELL	cotton	medium	-1,377	1,898	5,172	-22	30	83
ELL	cotton	small	-767	636	2,040	-41	34	110
NED	wheat	large	-10,367	1,262	12,892	-69	8	85
NED	wheat	medium	-14,379	583	15,545	-232	9	251
NED	wheat	small	-2,462	522	3,506	-62	13	88
NED	potato	large	-31,070	2,340	35,750	-170	13	196
NED	potato	medium	-13,736	811	15,358	-190	11	212
NED	potato	small	-4,283	1,177	6,637	-129	36	200
UKI	wheat	large	-11,732	0	11,732	-51	0	51
UKI	wheat	medium	-3,101	566	4,233	-34	6	47
UKI	wheat	small	NaN	NaN	NaN	NaN	NaN	NaN
UKI	potato	large	-36,244	0	36,244	-128	0	128
UKI	potato	medium	-4,283	0	4,283	-52	0	52
UKI	potato	small	NaN	NaN	NaN	NaN	NaN	NaN

NaN: data not available

Table 36: Estimated financial impact and labour impact of MG uptake on farms (negative value in net/gross margin means a decrease in the net income regardless whether the net income is positive or negative).

Country	Farm type	Farm Size	Impact on net margin	Impact on net margin	Impact on net margin	Impact on gross margin	Impact on gross margin	Impact on gross margin	Impact on labour	Impact on labour	Impact on labour
			%	%	%	%	%	%	%	%	%
			Pessimistic	Central	Optimistic	Pessimistic	Central	Optimistic	Pessimistic	Central	Optimistic
BEL	wheat	large	-9%	8%	24%	-2%	2%	5%	-2%	-5%	-8%
BEL	wheat	medium	-30%	13%	55%	-4%	2%	7%	-2%	-5%	-8%
BEL	wheat	small	-13%	0%	13%	-4%	0%	4%	-2%	-5%	-8%
BEL	potato	large	-15%	2%	18%	-5%	1%	6%	-1%	-3%	-6%
BEL	potato	medium	-31%	4%	38%	-5%	1%	6%	-2%	-5%	-8%
BEL	potato	small	-12%	1%	15%	-5%	0%	6%	-2%	-5%	-8%
DEU	wheat	large	-45%	44%	132%	-3%	3%	8%	-2%	-5%	-8%
DEU	wheat	medium	-108%	362%	831%	-1%	3%	8%	-1%	-3%	-6%
DEU	wheat	small	-68%	-19%	29%	-7%	-2%	3%	11%	8%	5%
DEU	potato	large	-32%	0%	32%	-6%	0%	6%	4%	0%	-4%
DEU	potato	medium	-30%	5%	40%	-5%	1%	7%	6%	2%	-2%
DEU	potato	small	-23%	5%	33%	-5%	1%	7%	-2%	-5%	-8%
ELL	wheat	large	-6%	22%	49%	-1%	5%	11%	-7%	-11%	-15%
ELL	wheat	medium	-6%	22%	51%	-1%	5%	12%	-2%	-5%	-8%

Country	Farm type	Farm Size	Impact on net margin	Impact on net margin	Impact on net margin	Impact on gross margin	Impact on gross margin	Impact on gross margin	Impact on labour	Impact on labour	Impact on labour
			%	%	%	%	%	%	%	%	%
			Pessimistic	Central	Optimistic	Pessimistic	Central	Optimistic	Pessimistic	Central	Optimistic
ELL	wheat	small	-7%	30%	66%	-1%	4%	8%	-9%	-12%	-17%
ELL	cotton	large	-6%	6%	18%	-7%	6%	19%	-2%	-5%	-8%
ELL	cotton	medium	-5%	7%	19%	-4%	5%	13%	-2%	-5%	-8%
ELL	cotton	small	-9%	8%	24%	-5%	4%	13%	-5%	-7%	-10%
NED	wheat	large	-11%	1%	14%	-3%	0%	4%	-2%	-5%	-8%
NED	wheat	medium	-23%	1%	25%	-10%	0%	10%	-2%	-5%	-8%
NED	wheat	small	-17%	4%	24%	-3%	1%	4%	-2%	-5%	-8%
NED	potato	large	-22%	2%	25%	-5%	0%	5%	4%	0%	-4%
NED	potato	medium	-20%	1%	22%	-5%	0%	5%	-2%	-5%	-8%
NED	potato	small	-9%	2%	14%	-3%	1%	5%	-2%	-5%	-8%
UKI	wheat	large	-37%	0%	37%	-7%	0%	7%	-2%	-5%	-8%
UKI	wheat	medium	-30%	5%	41%	-4%	1%	5%	-5%	-7%	-10%
UKI	wheat	small	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
UKI	potato	large	-973%	0%	973%	-7%	0%	7%	4%	0%	-4%
UKI	potato	medium	-159%	0%	159%	-8%	0%	8%	4%	0%	-4%
UKI	potato	small	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

NaN: data not available

Table 37: Estimated net financial impact of MG+VRNT uptake on farms (negative values mean a reduction in farm margin).

Country	Farm type	Farm Size	Net impact	Net impact	Net impact	Net impact	Net impact	Net impact
			€/farm/y	€/farm/y	€/farm/y	€/ha	€/ha	€/ha
			Pessimistic	Central	Optimistic	Pessimistic	Central	Optimistic
BEL	wheat	large	NaN	NaN	NaN	NaN	NaN	NaN
BEL	wheat	medium	3,551	6,537	9,523	57	105	153
BEL	wheat	small	736	2,223	3,710	21	64	107
BEL	potato	large	NaN	NaN	NaN	NaN	NaN	NaN
BEL	potato	medium	11,319	19,506	27,694	154	265	376
BEL	potato	small	5,388	11,304	17,220	172	360	549
DEU	wheat	large	-20,463	0	20,463	-50	0	50
DEU	wheat	medium	-2,563	355	3,273	-36	5	46
DEU	wheat	small	NaN	NaN	NaN	NaN	NaN	NaN
DEU	potato	large	-18,324	4,157	26,637	-95	22	138
DEU	potato	medium	-6,886	1,444	9,773	-94	20	133
DEU	potato	small	NaN	NaN	NaN	NaN	NaN	NaN
ELL	wheat	large	2,984	6,082	9,380	23	46	72
ELL	wheat	medium	7,963	10,255	12,962	115	148	187
ELL	wheat	Small	-397	418	1,252	-18	19	56
ELL	cotton	Large	2,423	6,225	10,145	22	57	94

Country	Farm type	Farm Size	Net impact	Net impact	Net impact	Net impact	Net impact	Net impact
			€/farm/y	€/farm/y	€/farm/y	€/ha	€/ha	€/ha
			Pessimistic	Central	Optimistic	Pessimistic	Central	Optimistic
ELL	cotton	medium	702	3,630	6,558	11	58	105
ELL	cotton	small	-1,795	-303	1,191	-96	-16	64
NED	wheat	large	-8,874	2,506	13,887	-59	17	92
NED	wheat	medium	15,495	25,478	35,461	250	411	573
NED	wheat	small	-2,462	522	3,506	-62	13	88
NED	potato	large	-22,550	9,440	41,430	-123	52	227
NED	potato	medium	9,720	20,358	30,996	134	281	428
NED	potato	small	-4,283	1,177	6,637	-129	36	200
UKI	wheat	large	1,332	10,887	20,441	6	48	90
UKI	wheat	medium	-3,269	-51	3,167	-36	-1	35
UKI	wheat	small	NaN	NaN	NaN	NaN	NaN	NaN
UKI	potato	large	-36,244	0	36,244	-128	0	128
UKI	potato	medium	87	3,249	6,412	1	40	78
UKI	potato	small	NaN	NaN	NaN	NaN	NaN	NaN

NaN: data not available

Table 38: Estimated financial impact and labour impact of MG+VRNT uptake on farms (negative value in net/gross margin means a decrease in the net income regardless whether the net income is positive or negative).

Country	Farm type	Farm Size	Impact on net margin	Impact on net margin	Impact on net margin	Impact on gross margin	Impact on gross margin	Impact on gross margin	Impact on labour	Impact on labour	Impact on labour
			%	%	%	%	%	%	%	%	%
			Pessimistic	**Central**	**Optimistic**	**Pessimistic**	**Central**	**Optimistic**	**Pessimistic**	**Central**	**Optimistic**
BEL	wheat	large	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
BEL	wheat	medium	38%	69%	101%	5%	8%	12%	9%	6%	3%
BEL	wheat	small	5%	15%	24%	1%	4%	7%	6%	2%	-2%
BEL	potato	large	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
BEL	potato	medium	33%	57%	81%	6%	10%	14%	9%	6%	3%
BEL	potato	small	9%	19%	29%	4%	8%	12%	6%	2%	-2%
DEU	wheat	large	-97%	0%	97%	-6%	0%	6%	4%	0%	-4%
DEU	wheat	medium	-425%	59%	543%	-4%	1%	5%	6%	2%	-2%
DEU	wheat	small	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
DEU	potato	large	-25%	6%	37%	-5%	1%	7%	4%	0%	-4%
DEU	potato	medium	-29%	6%	41%	-5%	1%	7%	4%	0%	-4%
DEU	potato	small	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
ELL	wheat	large	26%	52%	80%	6%	12%	19%	5%	1%	-3%
ELL	wheat	medium	109%	140%	177%	26%	33%	42%	2%	-1%	-4%

Country	Farm type	Farm Size	Impact on net margin	Impact on net margin	Impact on net margin	Impact on gross margin	Impact on gross margin	Impact on gross margin	Impact on labour	Impact on labour	Impact on labour
			%	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
			Pessimistic	**Central**	**Optimistic**	**Pessimistic**	**Central**	**Optimistic**	**Pessimistic**	**Central**	**Optimistic**
ELL	wheat	small	-19%	20%	60%	-2%	3%	8%	-5%	-8%	-10%
ELL	cotton	large	7%	18%	29%	7%	19%	31%	5%	1%	-3%
ELL	cotton	medium	3%	13%	24%	2%	9%	17%	6%	2%	-1%
ELL	cotton	small	-21%	-4%	14%	-11%	-2%	8%	4%	0%	-4%
NED	wheat	large	-9%	3%	15%	-3%	1%	4%	-1%	-3%	-6%
NED	wheat	medium	25%	41%	57%	10%	17%	24%	4%	0%	-4%
NED	wheat	small	-17%	4%	24%	-3%	1%	4%	-3%	-6%	-9%
NED	potato	large	-16%	7%	29%	-3%	1%	6%	-1%	-3%	-6%
NED	potato	medium	14%	29%	44%	3%	7%	11%	4%	0%	-4%
NED	potato	small	-9%	2%	14%	-3%	1%	5%	-5%	-8%	-10%
UKI	wheat	large	4%	35%	65%	1%	6%	12%	6%	2%	-2%
UKI	wheat	medium	-31%	0%	30%	-4%	0%	4%	4%	0%	-4%
UKI	wheat	small	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
UKI	potato	large	-973%	0%	973%	-7%	0%	7%	4%	0%	-4%
UKI	potato	medium	3%	121%	238%	0%	6%	12%	-2%	-5%	-8%
UKI	potato	small	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

NaN: data not available

5 *Analysis of EU-wide environmental impact assessment of PATs using MITERRA-Europe*

5.1 Introduction

This analysis is part of Task 6 Agronomic, socioeconomic and environmental analysis. The objective of this task is to assess the agronomic, socioeconomic and environmental impacts of the selected promising precision agriculture techniques (PATs). The MITERRA-Europe model will be used to assess the EU wide potential for using the promising PATs and assess the environmental impact of its implementation, with a focus on the GHG emissions. This will be based on the information and data collected during the project in the different tasks.

5.2 Methodology

5.2.1 MITERRA-Europe

MITERRA-Europe, developed by Wageningen Environmental Research (Alterra), is an environmental assessment model, which calculates GHG (CO2, CH4 and N2O) emissions, soil organic carbon stock changes and nitrogen emissions from agriculture on a deterministic and annual basis. MITERRA-Europe is based on the CAPRI and GAINS models, supplemented with a nitrogen leaching model, a soil carbon module and a module for representing mitigation activities (Velthof et al., 2009; Lesschen et al., 2011; de Wit et al., 2014). MITERRA-Europe covers the agriculture sector at different spatial scales, i.e. Member State scale and NUTS2 scale. The model assesses all agricultural greenhouse gasses until the farm-gate. In addition other environmental impacts on air, water and soil quality are assessed, which can identify and assess potential negative spill-over effects of using the PATs. Greenhouse gas emissions are calculated based on emission factors as derived from the IPCC 2006 guidelines.

The MITERRA model comprises a large database with information on crop production (areas, yields) and calculates the inputs (fertilizer, manure) and contains detailed biophysical data (e.g. LUCAS soil properties and climate data). In addition, land management data from the Survey on Agricultural Production Methods (SAPM) is included in the model. Based on the results of the previous task, the most relevant and promising PAT's will be parameterised in MITERRA, similar as done in previous projects for other measures, i.e. agronomic climate mitigation measures in PICCMAT and nitrogen related measures in NitroEurope.

5.2.2 Selected PATs

Based on the analysis and literature reviews from the previous tasks a selection of PATs with direct GHG reduction potential was made. Based on this analysis the main PAT for GHG reduction is the variable rate application of nitrogen, which potential N2O emission reductions from the application and N2O and CO2 reductions from the fertilizer production.

Variable rate irrigation has a moderate potential, but no specific data on reduction of N2O emissions are available. In general irrigated fields have higher N2O emissions than non-irrigated fields (50-140% higher), in theory the variable rate irrigation can reduce N2O emissions, but data is too limited to include this effect in the current analysis.

Controlled traffic farming and machine guidance have limited potential according to the analysis, but as adoption of especially machine guidance is higher and increasing, we did include machine guidance in the analysis. Machine guidance might also lead to more efficient fertilizer application, which can result in reduced N2O emissions.

5.2.3 Parameterisation

For both variable rate nitrogen application and machine guidance we assumed that this could be used for most arable crops. The following crops were included, cereals (soft wheat, durum wheat, barley, rye, oats, grain maize, rice and other cereals), rapeseed, sunflower, soybeans, pulses, potato, sugar beet and textile crops. Together these crops account for 75 million ha in the EU-28, which is 41% of the total utilized agricultural area (UAA).

5.2.3.1 Variable rate nitrogen application

The main source of information for the parameterisation is the survey of this study that was held amongst arable farmers. Based on the analysis of the farmers survey (Barnes et al., 2017b) we obtained the following parameterisation, as shown in Table 39 for the perceived effects, again for an pessimistic, average and optimistic scenario. The values are the average of the observations of all groups (country, crop and farm size).

Table 39: Parameterisation for VRNT, based on survey results

	Pessimistic	**Average**	**Optimistic**
Yield	0.8%	4.1%	7.4%
Fuel use	0.6%	-5.4%	-6.3%
N applied	-4.6%	-8.0%	-11.7%

To compare these results, we also looked at other studies, which were identified in the previous deliverables, including the literature review.

Site-specific fertilisation can reduce the total amount of fertiliser used (Koch et al., 2004), indicating an increase in Nitrogen Use Efficiency (NUE). Raun et al. (2001) found an average NUE increase of more than 15% in winter wheat in Oklahoma, USA. (D1. page 80);

Variable rate application can save 2-20 kg N per ha, based on results from the FutureFarm project;

Presentation Ulrich Adam (CEMA) states 5-30% reduction in fertiliser use due to precision fertilization;

Presentation from Wilfried Winiwarter (JRC workshop Sevilla, 2015) showed that Variable rate application can reduce fertilizer application on average by 24% (range 8-40%), based on several US studies. In their GAINS modelling the assume emission reductions from 6-18% on top of a 6% efficiency increase in the baseline.

5.2.3.2 Machine guidance

Based on the analysis of the farmers survey we obtained the following parameterisation for machine guidance, as shown in Table 40. As the survey did not result in clear differences amongst the five case study countries, we used these values for all EU member states, again for a pessimistic, average and optimistic scenario.

Table 40: Parameterisation for machine guidance, based on survey results

	Pessimistic	**Average**	**Optimistic**
Yield	-4.0%	0.0%	4.0%
Fuel use	-2.4%	-5.4%	-8.3%
N applied	0.5%	-2.9%	-6.4%

To compare these results, we also looked at other studies, which were identified in the previous deliverables, including the literature review.

- From the literature survey was found that Controlled Traffic Farming (CTF) can lead to improved fertiliser use efficiency, uptake of fertiliser can be improved by around 15%;
- Presentation Ulrike Kloeble (JRC workshop Sevilla, 2015) stated that parallel tracking and auto-guidance can save 2-5% of N fertiliser and also 2-5% fuel use, based on results from the FutureFarm project;
- Wösten et al. (2016): Fuel consumption can be reduced by 5-10% by using guidance systems.

5.2.3.3 Emission sources

The following GHG sources with potential reduction have been taken into account:

- Direct soil N_2O emissions from lower fertilizer application;
- Indirect N_2O emissions (from N volatilisation and N leaching);
- GHG emissions from fertilizer production;
- GHG emissions from fuel use for field operations.

The last two emissions sources are not reported within the UNFCCC sector Agriculture, but under the Energy and Industrial processes sectors. In addition, we also included the potential reductions of ammonia (NH_3) emissions and nitrate leaching and runoff.

For the direct and indirect N_2O soil emissions due to the application of N fertiliser, the emission factors from the IPCC 2006 guidelines have been used. For N leaching and runoff location specific factors are used, as described in Velthof et al. (2009). For fertiliser production the emission factors from Brentrup and Palliere (2008) have been used, which are values for European average technique of 2006. These emission factors might be too high for the year 2010 as in the recent years most fertiliser companies in Europe installed de-N_2O catalytic systems, which significantly reduce the N_2O emissions from ammonium and nitrate based fertiliser production. In the modelling a distinction is made between urea based fertilisers and other nitrogen fertilisers.

5.2.3.4 Scenarios

The adoption rate is one of the most important, but also unknown parameter for a scenario assessment of the impact of the precision agriculture techniques. As the survey was set-up as a case study based survey, the average adoption rate cannot be directly derived from the data. However, based on the survey profiles of adopters versus non-adopters might be made and these profiles could be used for the extrapolation to all European farmers.

The outcome of the survey did not provide very clear patterns of adopters versus non-adopters for the variables that could be used for the EU-wide scenario analysis. For most of the five case study countries differences were small, or for some parameters also contradictory. One variable that seems important for adoption is farm area. The analysis of the survey data showed quite distinct differences for this variable, at least for countries where the average farm size is relatively small (Netherlands and Belgium). For partial (only machine guidance) and full adopters (variable rate technology and machine guidance) the farm area was larger than for the non-adopters. As data on farm size is available at NUTS2 level from Eurostat, we decided to use this indicator as main parameter for potential adoption.

Table 41: Average arable farm land area (ha) for non-, partial and full adopters, based on survey results

	Belgium	**Germany**	**Greece**	**The Netherlands**	**United Kingdom**
Non-adopters	25	105	67	49	166
Partial adopters (only MG)	57	538	82	152	210
Full adopters (MG + VRNT)	40	847	153	211	253

We used NUTS2 level data from the 2010 FSS survey as derived from Eurostat (*ef_m_farmleg*) to derive the share of farm size for the different regions. Based on the available information three classes of farm area were derived: less than 50 ha, 50 – 100 ha and more than 100 ha. This information was combined for two main arable farm types: "Specialist cereals, oilseed and protein crops" and "General field cropping". The total farm area in the EU-28 for these two farm types was 88 million ha, which is 48% of the total utilized agricultural area (UAA) in the EU. The other part of the UAA will be mainly grassland and livestock based farms, where arable crops cover in general only a minor fraction of the farm area. In Figure 8 the potential implementation share per member states is shown, this is based on the area of farms with at least 50 ha of farm area. For most countries the PA techniques could be introduced at least at 50% of the potential area, only Cyprus, Malta, Poland and Slovenia, have lower potential, due to small farm areas.

Based on the survey we defined the following six scenarios:

1. Machine guidance (partial for arable farms with minimum area of 100 ha;
2. Machine guidance for arable farms with minimum farm area of 50 ha;
3. Machine guidance for all arable farms (maximum application);
4. Variable Rate Nitrogen Technology for arable farms with minimum farm area of 100 ha;
5. Variable Rate Nitrogen Technology for arable farms with minimum farm area of 50 ha;
6. Variable Rate Nitrogen Technology for all arable farms (maximum application).

Figure 8 provides a graphical impression on the potential implementation of PATs based on the share of farms with more than 50ha. Figure 9 provides a geographical overview of the share of farms with more than 50ha and more than 100ha.

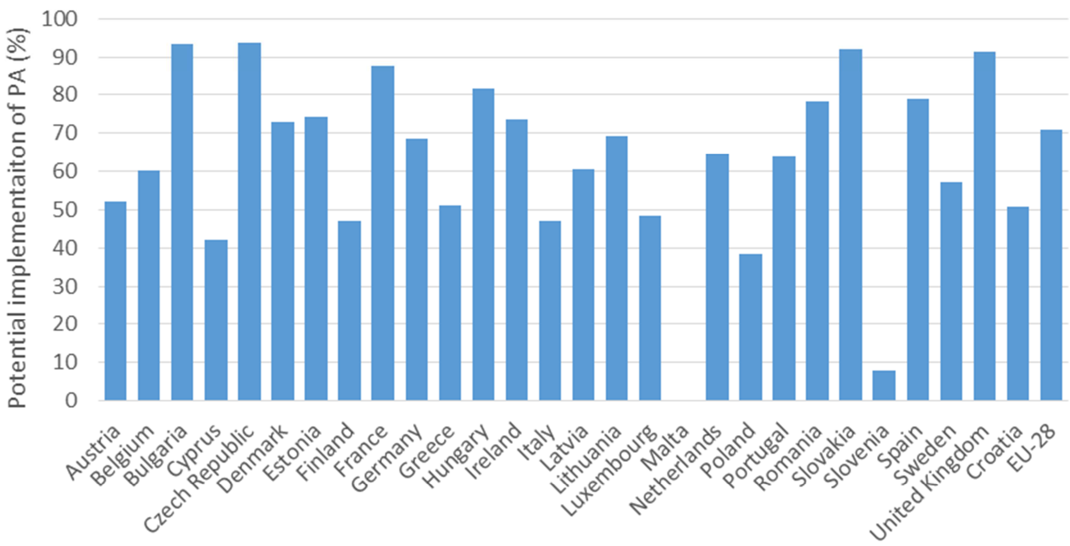


Figure 8: Potential implementation of PA techniques based on share of arable farms with more than 50 ha (in Annex 2 the potential implementation can be found for all three adoption scenarios).

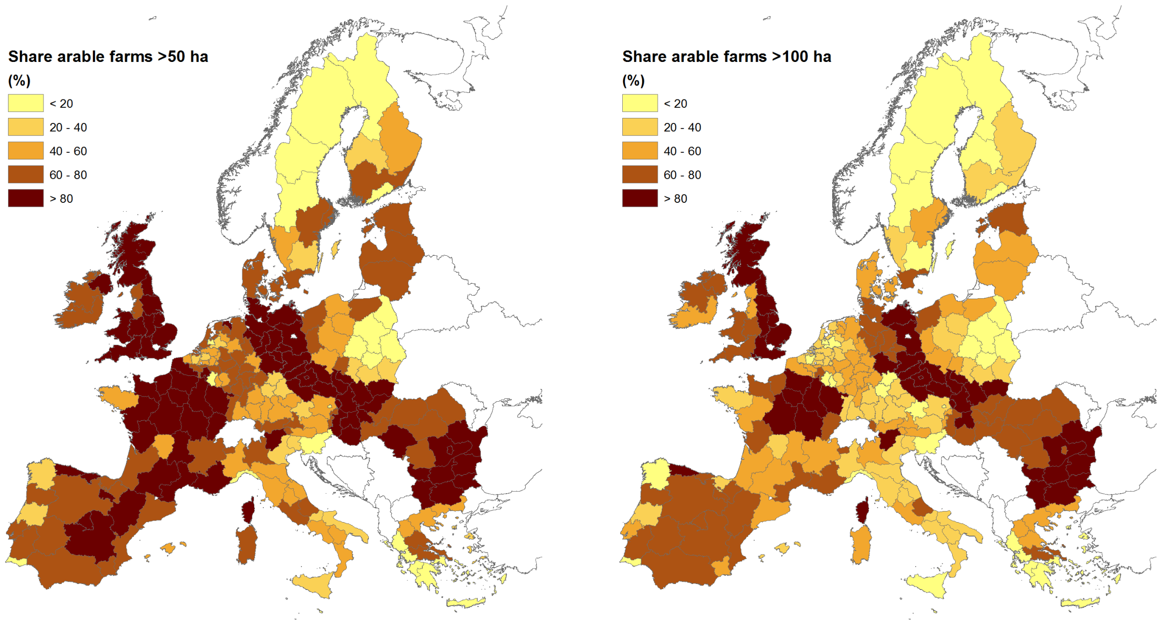


Figure 9: Maps of regional share of arable farms of >50 ha arable land (left) and > 100 ha (right).

The scenarios were simulated with data for the year 2010. For this year, a consistent data set is currently available for the MITERRA-Europe model. Another reason to use this year is that the survey, on which the fertiliser and fuel reduction percentages are based, is based on information obtained in the past years, for which 2010 is probably more representative than 2020. However, in a baseline scenario for 2020 the fertiliser application will be reduced compared to 2010 due to autonomous improvements in fertiliser management, e.g. due to action plans following the Nitrates Directive, which will increase the fertiliser use efficiency. Eurostat data also shows a reduction in N surplus, from on average 51 kg N/ha in 2005-2008 to 48 kg N/ha in 2009-2012.

This means that the calculated potential might be somewhat overestimated, on the other hand farm size is likely to increase in 2020 compared to 2010, which means the potential area on which the precision agriculture techniques can be implemented will increase.

5.3 Results

Table 42 shows the main results of the environmental impact assessment with the potential GHG savings of MG and VRNT for pessimistic, average and optimistic scenarios at EU level. Total GHG savings for MG are in the range of 125-4410 kton CO_2-eq per year and for VRNT 2549-6919 kton CO_2-eq per year.

The main results for the six scenarios at EU-28 level are shown in Table 44 and Table 45. The main driving factor for the differences in the result is the area on which machine guidance or VRNT is applied, which is shown in Table 43. In Table 46 the GHG savings for the six scenarios are shown at member state and in Figure 10 also the regional results at NUTS2 level are presented for application of machine guidance and VRNT.

Table 42: Annual GHG savings at EU-28 level for the MG and VRNT optimistic, average and pessimistic scenarios, based on adoption on farms > 50 ha (results for other adoption scenarios are provided in Annex 3).

Savings	**MG**			**VRNT**		
[kton CO_2-eq]	**Pessimistic**	**Average**	**Optimistic**	**Pessimistic**	**Average**	**Optimistic**
Direct N_2O	-98	413	1258	904	1572	2299
Indirect N_2O	-21	87	263	190	327	471
Fuel use	363	891	1370	363	891	1370
Fertilizer production	-119	499	1520	1092	1899	2778
Total GHG savings	*125*	*1889*	*4410*	*2549*	*4689*	*6918*

Table 43: Arable area on which PA can be applied for the scenarios.

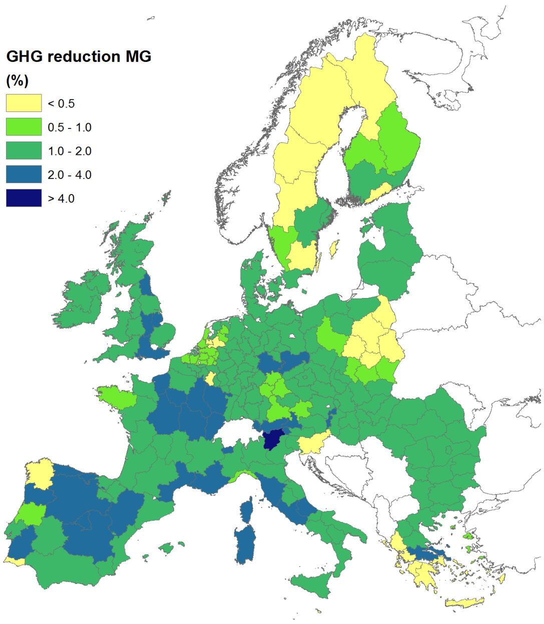
Scenario	**Arable area (million ha)**
PA on farms >100 ha	43.8
PA on farms >50 ha	53.1
PA full application	74.8

Table 44: Annual GHG savings at EU-28 level for the six PA adoption scenarios (based on average scenario, results for optimistic and pessimistic scenario are provided in Annex 3).

Adoption Scenarios	Direct N_2O emission kton CO_2-eq	Indirect N_2O emission kton CO_2-eq	Fuel use kton CO_2-eq	Fertilizer production kton CO_2-eq	Total GHG savings kton CO_2-eq
MG >100 ha	338	71	696	408	1513
MG >50 ha	413	87	891	499	1889
MG full application	561	123	1402	674	2760
VRNT >100 ha	1288	266	696	1555	3805
VRNT >50 ha	1572	327	891	1899	4689
VRNT full application	2139	458	1402	2568	6567

Table 45: Annual fertiliser, NH3 emission and N leaching and runoff reductions at EU-28 level for the six PA adoption scenarios (based on average scenario, results for optimistic and pessimistic scenario are provided in Annex 3).

Adoption scenarios	Fertilizer savings kton N	NH_3 emissions kton N	N leaching and runoff kton N
Machine guidance >100 ha	72	3	15
Machine guidance >50 ha	88	4	19
Machine guidance full application	120	6	26
VRNT >100 ha	275	13	56
VRNT >50 ha	336	16	70
VRNT full application	457	22	98



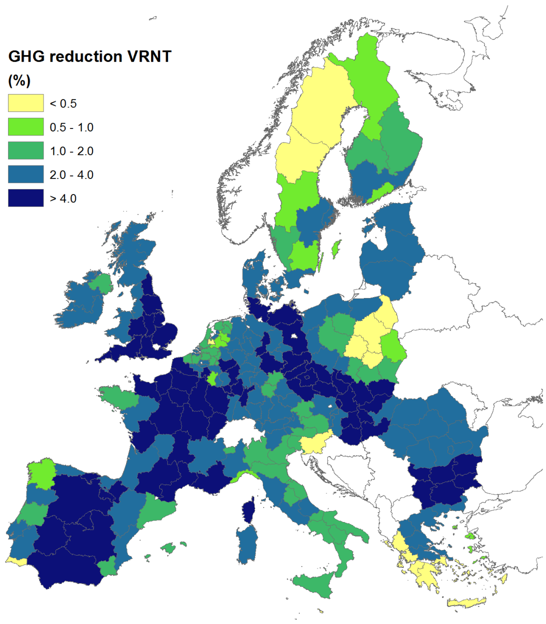


Figure 10: Maps of GHG reduction for MG (left) and VRNT (right) compared to the baseline scenario (thus only for crops where PA can potentially be applied). Both maps are based on the scenarios where precision agriculture is applied on farms with more than 50 ha of arable land.

Table 46: Total GHG savings (kton CO2-eq) per Member State for the six PA scenarios (based on average scenario).

	Machine guidance >100 ha	**Machine guidance >50 ha**	**Machine guidance full**	**VRNT >100 ha**	**VRNT >50 ha**	**VRNT full**
Austria	29	55	105	18	33	64
Belgium	27	45	72	31	52	85
Bulgaria	165	171	183	236	245	263
Cyprus	1	2	5	1	2	4
Czech Republic	88	93	99	111	117	125
Denmark	57	76	104	66	89	122
Estonia	10	11	16	10	11	14
Finland	28	58	120	34	70	143
France	663	833	936	775	972	1089
Germany	443	552	797	509	633	909
Greece	58	63	124	61	66	131
Hungary	131	146	177	171	190	231
Ireland	15	19	26	13	17	23
Italy	119	173	368	75	109	230
Latvia	14	16	26	14	16	26
Lithuania	40	49	71	43	53	76
Luxembourg	0	2	3	0	2	4
Malta	0	0	0	0	0	0
Netherlands	18	35	54	17	32	50
Poland	217	280	696	199	256	614
Portugal	14	17	26	12	15	23
Romania	106	112	143	123	130	166
Slovakia	33	34	37	44	46	50
Slovenia	0	1	7	0	1	8
Spain	270	333	422	268	331	420
Sweden	24	32	54	24	32	53
United Kingdom	259	294	321	292	331	361
Croatia	18	27	54	27	41	80

5.4 Discussion and conclusion

The results of the analysis show that the introduction of PATs has positive effects on the environment, with reductions in GHG emissions. Also other environmental impacts, such as ammonia emissions and nitrate leaching can be reduced. However, the size of the emission reduction is regionally variable due to differences in farm size, current fertiliser use and environmental conditions. Especially farm size is an important factor, as implementation of PA has more potential on larger farms (lower investment cost per ha and more effective). Highest GHG reductions are therefore found in regions in France, Germany and some Eastern European countries.

Large scale introduction of precision agriculture techniques, such as machine guidance and variable rate nitrogen application, can reduce GHG emissions from the fertiliser application, fertiliser production and fuel use. Based on the analysis for 2010, the mitigation potential for machine guidance ranges from 1.5 to 2.8 Mton CO_2-eq per year, of which 0.4 to 0.7 Mton CO_2-eq are within the UNFCCC Agriculture category. For VRNT, the potential ranges from 3.5 to 5.9 Mton CO_2-eq per year, of which 1.6 to 2.6 Mton CO_2-eq are within the UNFCCC Agriculture category.

Given that the survey reported the effects as a range (e.g. no effect: between -5% and +5%), pessimistic, central and optimistic scenarios were considered for the impacts. Even for a pessimistic scenario the GHG savings are still 0.1 Mton CO_2-eq per year for MG and 2.1 Mton CO_2-eq per year for VRNT, whereas GHG savings for a positive scenario can be about 4.4 Mton CO_2-eq per year for MG and 6.6 Mton CO_2-eq per year for VRNT.

Compared to the EU total emissions from the UNFCCC category Agriculture, 436 Mton CO_2-eq according to the latest submissions for the year 2014, this remains a small potential, of about 0.6%. However, the measures also lead to reductions of emissions in other sectors (energy and industrial processes) and have co-benefits for the environment (reduction of ammonia emission and nitrate leaching).

However, VRNT has a positive effect on the crop yields, on average +4% according to the survey, whereas machine guidance has no yield effect. The increased crop yield has not been taken into account in the analysis, as this doesn’t reduce the total emission. However, for VRNT the footprint (emissions per kg of product) will be lower compared to machine guidance, because of this yield effect.

The cost-effectiveness of emission abatement based on PA was not estimated at EU level in this study, as the costs are very different per country and the kind of system that is selected. For MG the investment costs of a fully automatic navigation system varies from €5,000 to €40,000 (see Balafoutis et al, 2016). Also the results of the partial budget (Chapter 4), which excludes the capital costs of the machinery, show very large ranges between the net impacts calculated with pessimistic and optimistic assumptions between 49 and 513 €/ha/year for MG and 49 to 377 €/ha/year for VRNT uptake. The average per area mitigation is 35 kg CO_2-eq/ha/year for MG and around 80 kg CO_2-eq/ha/year for VRNT, based on the average scenario. Assuming for MG an average capital cost of €20,000 on a farm of 200 ha and a 10-year depreciation period, the annual capital costs would be around €10 /ha/year. According to the partial budget calculation (Table 35), the average net financial impact for the central scenario is about €15/ha/year, thus MG can be a cost-effective practice. For VRNT the capital cost will be higher, assuming an average cost of €100,000, the annual capital costs would be around €50 /ha/year. According to the partial budget calculation (Table 36) the average net financial impact is about €85/ha/year, thus also VRNT can be a cost-effective practice. However, the ranges in the capital cost estimates and partial budget results are very large, therefore, this calculation should be considered as a rough estimate, which shows that under the conditions used in the calculation, both MG and VRNT can be a cost-effective practice. For smaller farms the capital costs might be too high, but if they can share their machinery, the costs per area will become lower again. According to the EcAMPA2 study and the GAINS modelling VRNT was not a cost-effective option, which might be due to other assumptions and cost estimates.

Compared to other mitigation options in arable cropping systems, such as nitrification inhibitors, use of cover crops and conservation tillage, the mitigation potential is limited. However, with the long-term climate mitigation goals as stated in the Paris Agreement, all possible reductions are required, and a range of mitigation options has to be used. PA will be one of them, and given that PA is likely to be cost-effective, it is one of the options that has the potential for good uptake. In this analysis only the use of PA for mineral fertiliser application has been considered. There might be potential as well for the use of PA for application of manure, which can increase the mitigation potential in the land-based livestock sectors as well.

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Appendix A. Potential adoption (%) of PA per country

Country	Farms > 100 ha	Farms > 50 ha	All farms
Austria	28	52	100
Belgium	36	60	100
Bulgaria	90	93	100
Cyprus	25	42	100
Czech Republic	89	94	100
Denmark	54	73	100
Estonia	66	74	100
Finland	22	47	100
France	69	88	100
Germany	55	69	100
Greece	47	51	100
Hungary	73	82	100
Ireland	58	74	100
Italy	32	47	100
Latvia	53	61	100
Lithuania	56	69	100
Luxembourg	13	48	100
Malta*	0	0	100
Netherlands	34	65	100
Poland	30	38	100
Portugal	52	64	100
Romania	74	78	100
Slovakia	88	92	100
Slovenia	5	8	100
Spain	64	79	100
Sweden	42	57	100
United Kingdom	80	91	100
Croatia	34	51	100
EU-28	59	71	100

* For Malta no farm size data were available

Appendix B. Additional scenario results environmental impact assessment

Table A3.1: Annual GHG savings (kton CO_2-eq/year) at EU-28 level for the MG and VRNT optimistic, average and pessimistic scenarios, based on adoption on farms > 100 ha.

	MG			VRNT		
	Pessimistic	Average	Optimistic	Pessimistic	Average	Optimistic
Direct N_2O	-81	338	1030	741	1288	1884
Indirect N_2O	-17	71	214	154	266	384
Fuel use	284	696	1070	-77	361	812
Fertilizer production	-97	408	1244	894	1555	2275
Total GHG savings	100	1513	3532	1700	3471	5367

Table A3.2: Annual GHG savings (kton CO_2-eq/year) at EU-28 level for the MG and VRNT optimistic, average and pessimistic scenarios, based on adoption on all farms.

	MG			VRNT		
	Pessimistic	Average	Optimistic	Pessimistic	Average	Optimistic
Direct N_2O	-134	561	1711	1230	2139	3128
Indirect N_2O	-30	123	370	265	458	660
Fuel use	571	1402	2155	-156	727	1636
Fertilizer production	-161	674	2054	1477	2568	3756
Total GHG savings	183	2760	6442	2885	5892	9110

Table A3.3: Annual fertiliser, NH_3 emission and N leaching and runoff reductions at EU-28 level for the optimistic, average and pessimistic scenario (based on adoption at farms >50 ha).

Scenarios	**Fertiliser savings**	**NH_3 emissions**	**N leaching and runoff**
	kton N	kton N	kton N
MG average	88	4	19
MG pessimistic	-21	-1	-5
MG optimistic	269	12	56
VRNT average	336	16	70
VRNT pessimistic	193	9	40
VRNT optimistic	491	23	100

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