Scotland's Rural College

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Review

Precision Agriculture Technologies positively contributing to GHG emissions mitigation, farm productivity and economics

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Abstract: Agriculture is one of the economic sectors that affects climate change contributing to greenhouse gas emissions directly and indirectly. There is a trend of agricultural greenhouse gas emissions reduction, but any practice in this direction should not affect negatively farm productivity and economics because this would limit its implementation, due to the high global food and feed demand and the competitive environment in this sector. Precision agriculture practices using high-tech equipment has the ability to reduce agricultural inputs by site-specific applications, as it better target inputs to spatial and temporal needs of the fields, which can result in lower greenhouse gas emissions. Precision agriculture can also have a positive impact on farm productivity and economics as it provides higher or equal yields with lower production cost than conventional practices. In this work, the precision agriculture technologies that have the potential to mitigate greenhouse gas emissions are presented providing a short description of the technology and the impacts that have been reported in literature on greenhouse gases reduction and the associated impacts on farm productivity and economics. The technologies presented span between all agricultural practices, including variable rate sowing/planting, fertilizing, spraying, weeding and irrigation.

Keywords: Precision Agriculture Technologies, Greenhouse Gas Emissions, Farm Productivity, Variable Rate Nutrient Application, Variable Rate Irrigation, Variable rate pesticide application, Variable rate planting/seeding, Precision Physical Weeding

1. Introduction

Climate change affects all processes on the Earth, including agriculture that will have to adapt to new climatic conditions over the coming years. Agriculture is liable for climate change as its activities accounts for nearly 13.5% of the total global anthropogenic Greenhouse Gas (GHG) emissions [1]. 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 global climate commitments. The main distribution of agricultural GHG emissions is related to cropland soil, enteric fermentation and manure management [2].

The application of precision agriculture (PA) practices, using the large reservoir of Precision Agriculture Technologies (PATs) in agricultural field operations could positively contribute to GHG emission reduction due to the ability of soils to operate as carbon stock reserve [2], the reduction of fuel consumption (direct GHG decrease) and the reduction of inputs (indirect GHG decrease) for the agricultural field operations [3]. On the other hand, these practices affect farm productivity by optimizing agricultural inputs that is reflected in higher or equal yields with lower cost than conventional practices. 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.

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 [4]. 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, PATs are currently taking up again, because technology problems have been gradually resolved both in terms of software and hardware with less compatibility issues, while more tangible economic results at farm level have been shown to practitioners that have 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 in 2014 on a global level, with expected growth at an annual growth rate of 12% through 2020 with the mature US and European markets considered as the most promising [5,6].

However, most practitioners do not have a clear perspective of the benefits of PATs in agricultural production and do not consider the environmental reimbursements that their use could provide [7-9] developing the need to produce evidence of the actual impact of these technologies on GHG emissions, farm productivity and economics. Therefore, the objective of this paper was to identify and describe the PATs that possess the capacity to have positive impact on GHG emissions produced from the agricultural sector in combination with farm productivity and income sustenance or improvement.

In the first section, the main sources of GHG emissions in the agricultural sector are described, while the second section analyses the GHG mitigation practices. Subsequently, the typology PATs is presented in order to sort the PATs that have a potential direct positive impact on GHG emission mitigation combined with improved or at least stable farm productivity and economics. Then, a list of the most influencing PATs is presented with a short description of the technical characteristics of each PAT and subsequently its environmental impacts (focusing on GHG emissions). 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 using PATs. Subsequently, the farm productivity and economic impacts of acquiring and using PATs are analyzed and discussed. Finally, a discussion is underlined of the importance of PATs on both reducing GHG emissions and maintaining or increasing farm productivity and income.

2. Main Sources of Agricultural GHG emissions

The major GHGs produced in the agricultural sector are methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_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; 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 [10].

The agricultural sector contributes to the production of 25% of CO_2, 50% of CH_4, and 70% of N_2O emissions in a global basis summing up to nearly 13.5% of the total global anthropogenic GHG emissions [1]. However, in OECD member countries agriculture produces 8% of the total GHG emissions with a decline 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. 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” [11].

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).

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 later in this paper). This concerns nitrogen mineral fertilisers, manure spreading and nitrogen from crop residues incorporated into the soil or lixiviation of surplus nitrogen. N_2O has high Global Warming Potential (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 [12]. 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 CH_4 producer. CH_4 is also produced during manure storage (decomposition). There are several studies targeting on CH_4 measurements [13] and its mitigation from rice fields, mainly through water [14], fertiliser, and manure managements [15]. CH_4 emissions increase when mulching and organic manure are applied in soils [16]. On the other hand, midseason drainage can cut CH_4 emissions significantly [17]. Aerobic soils may act as CH_4 sinks [13,18] or sources [19].

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 CO_2 emissions from processing of inputs at farm level showed that this gas can represent between 10 and 20% of the total GHG emissions in agriculture [2].

3. Greenhouse Gases mitigation practices

Climate change can be mitigated through the reduction of GHG emissions, the enhancement of GHG removals and the avoidance or displacement of emissions [18]. Mismanagement of carbon (C) and nitrogen (N) flows in the agricultural system is the reason for GHG overproduction. There are methods and technologies that reduce GHG emissions, such as the timely and accurate application of nitrogen fertilization that reduces N_2O [20,21]. Regarding enhancing GHG 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 [22]. GHG emissions can be avoided or displaced by the conversion of residual agricultural biomass into biofuel of any type [23,24] 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 [25,26]. For instance, no-tillage practices, which can potentially reduce GHG emissions by 20.6-23.7% compared to conventional tillage [27] may have unanticipated and unwanted effects on other sources or sinks of GHG. 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 [28].

Smith et al. (2008) [18] listed the GHG emissions mitigation measures in seven categories that include different practices. More particularly, cropland management (nutrient management, tillage/residue management, water management, rise management, agroforestry, set-aside, land-use change), grazing land management/pasture improvement (grazing intensity, increased productivity through fertilisation, nutrient management, fire management, species introduction including legumes), management of organic soils (avoid drainage of wetlands), restoration of degraded lands (erosion control, organic amendments, nutrient amendments), livestock management (improved feeding practices, specific agents and dietary additives, longer term structural and management changes and animal breeding), manure/biosolid management (improved storage and handling, anaerobic digestion, more efficient use as nutrient source) and 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. 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 [29]. They considered four (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_2-eq/ha.

Another report [30] indicated some mitigation methods in order to reduce agricultural production emissions in the UK by 3 $MtCO_2$-eq until 2020 compared to 2007 and showed that the most promising for GHG reduction (it can reach 1.4 $MtCO_2$-eq) in high extend is nutrient management, followed by the use of plants with improved nitrogen use efficiency (potential of 0.8 $MtCO_2$eq) and improved land and soil management (up to 0.45 $MtCO_2$-eq). This work shows the potential of PA practices that are directly connected with nutrient, land and soil management.

The European Commission Climate Action 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. It is anticipated 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.

4. Typology of Precision Agriculture Technologies

In the literature there are only three attempts to provide a typology of PATs. One of the most prominent studies on PA [7] 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).

Zarco-Tejada et al. (2014) [9] categorised PATs for crop and livestock farming in a linear manner following the timeline of use of the technologies ending up in three categories, namely *Remote sensing*; *Guidance systems*; *Variable rate applications*. Finally, Schwarz et al. (2011) [31] have provided the most comprehensive typology of PATs (selected to be used in this work), divided into three main categories: *Guidance systems* (i.e. hard- and software that guide tractors and implements over a field), which include all forms of automatic steering/guidance for tractors and self-propelled agricultural machinery, such as driver assistance, machine guidance, controlled traffic farming; *Recording technologies* (i.e. sensors mounted on ground-based stations, rolling, airborne or satellite platforms, gathering spatial information), which include soil mapping, soil moisture mapping, canopy mapping, yield mapping, etc.; *Reacting technologies* (i.e. implements, hard- and software that together can vary the placement of agricultural inputs in the field), which include technologies like variable rate irrigation and weeding and variable rate application of seeds, fertiliser and pesticides.

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.

All the PATs that are included in the typology of Schwarz et al. (2011) [31] together with their interconnection are summarized in Figure 1. All three categories of PATs require the use of Global Navigation Satellite Systems (GNSSs), as shown in the figure.

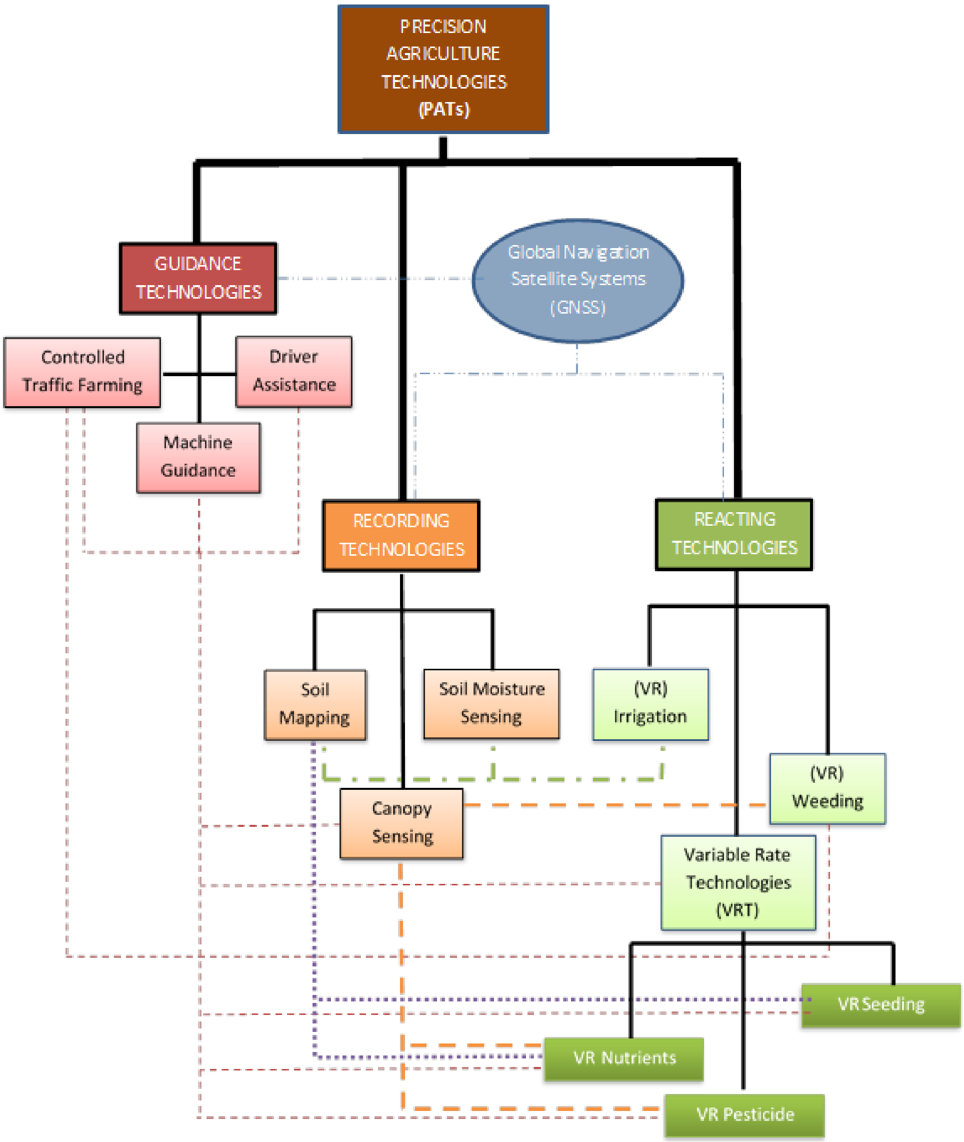

Figure 1. Precision agriculture technologies overview

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 paper. For the same reasons GNSSs were also excluded from further analysis. Hence, reacting technologies and guidance systems were selected to be analysed and their potential to reduce GHG emissions and improve farm productivity and income was assessed.

5. 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. 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 Annex.

5.1. Variable rate nutrient application (VRNA)

5.1.1. Description of VRNA technologies

Variable rate nutrient application (VRNA) 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).

VRNA 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 [32,33]. VRNA 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 VRNA is executed by spreading the material using an adjustable controlled air stream through a piped boom [34].

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 [35-36]. VRNA 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 [35-36].

5.1.2. GHG emissions reduction potential through VRNA

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 [10,29,37].

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 [37]. 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.

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 [37].

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.

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).

Nitrification is the oxidation of ammonium to nitrate. 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 [37]. Therefore, when soils start to dry out, more N_2O is emitted.

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 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).

A number of studies have concluded that many farmers apply nitrogen in excess of crop nutrient needs [38,39,40]. According to Eurostat (2016) [41] 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 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.

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 VRNA technologies are interconnected to other PA technologies (GNSS, soil mapping, canopy sensors, on-the-go sensors, 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 VRNA. However, there is significant work on the impact of lower nitrogen field input to N_2O emissions. Bates et al. (2009) [42] identified an abatement potential of 5% reduction in the baseline GHG emission rate that is assigned to mineral fertiliser application. They 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) [39] 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 [43,44] and the relationship of N_2O emissions to nitrogen application rate increases proportionally with the application rate [21]. Another study estimated that an average of 1.19% of nitrogen added to soils is released as N_2O [45]. Paustian et al. (2004) [46] 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 could be reduced directly by approximately 1.25% of nitrogen inputs saved. . Sehy et al. (2003) [47] examined the use of VRNA and GPS in field nitrogen application and found out that N_2O emissions decreased by up to 34% in low-yielding areas.

5.1.3. Impacts of the use of VRNA 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) [48] 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 [49].

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 [40]. 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 [50].

Several authors have analysed the impact of VRNA on farm productivity and economics. Tekin (2010) [51] estimated that VRNA 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) [52] found also similar results (6-46%) in nitrogen savings in corn fields in northeastern Colorado, USA. According to ICF International (2013) [50], 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) [53] 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 m^2 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 [49,54]. Mamo et al (2003) [55] found a profit increase of 7 to 20.25 €/ha for corn when using VR fertilizer application compared to uniform application due to reduction in the use of fertiliser. Koch et al. (2004) [52] found an increase of 25.6 to 38.6 €/ha in net returns for VRNA 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 VR equipment (GPS receiver, on-board computer, software, VR 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 VR equipment to be spread over a larger area, and therefore decrease the expense of VR equipment per hectare. VR application based on grid soil sampling has as a result the lowest net return, primarily due to increased fertiliser uses and soil sampling costs [52].

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 [56]. 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 [57]. 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 [58]. 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 and financial value [57]. It should be noted that some VR manure systems can be retrofitted to the tankers that farmers already have [36], 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 [59]. 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 [60]. 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 [60]. Under-application of lime can cause large yield losses. Over-application of lime can be as detrimental as under-liming [59], 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 [59,60]. 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 [61], 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 [59].Weisz et al. (2003) [59] 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.

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 [62]. In 75% of the studies (4 in total) reviewed by Lambert and Lowenberg-DeBoer (2000) [63] 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 [59]. Kuang et al. (2014) [60] 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) [64] found an increase of €6.51/ha for Indiana corn and soybean production systems.

5.2. Variable rate irrigation (VRI)

5.2.1. Description of VRI technologies

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 [65]. 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% [66].

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 [67,68] or multiple manifolds; each valved separately [69,70]. 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 [71,72,73]. 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 [74].

The most common site-specific sprinkler irrigation systems in use today are speed control systems [75]. 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.

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 [76]. 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.

5.2.2. GHG emission reduction potential through VRI

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% [75] 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) [77] 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.

5.2.3. Impacts of VRI 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 [78]. LaRue and Evans (2012) [79] 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 [53] 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. They also calculated that VRI adoption in drip irrigation may cost up to 40€ per ha.

Few hard figures are available about the economics of variable rate irrigation. LaRue and Evans (2012) [79] 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) [80] 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 [81].

Lambert and Lowenberg-DeBoer (2000) [63] 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 [78,82,83]. For water use reduction, Hedley and Yule (2009) [84] tested different scenarios for New Zealand and showed significant potential water savings of 21.8–26.3% for VRI, while these potential water savings suggest that VRI will become more affordable as irrigation costs increase. Daccache et al. (2015) [85] estimated the benefit to the grower in the reduced cost of water and energy to be typically around 30 €/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. Machine guidance (MG)

5.3.1. Description of MG technologies

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.

5.3.2. GHG emissions reduction potential through MG

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 [86] 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) [87] 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% [88].

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. Impacts of MG use 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 [88].

In peanut digging operations a study revealed average net returns between 83 and 612 €/ha for the use of auto-steering [89]. 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 [90]. 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 [91]. 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 [91].

5.4. Controlled Traffic Farming (CTF)

5.4.1. Description of CTF technology

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.

5.4.2. GHG emission reduction potential through CTF

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) [92]. 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) [93] 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.

5.4.2. Impacts of the use of CTF 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. CTF typically releases 57-115 €/ha extra profit including the required investment, cost savings and increased yields [94]. 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% [93]. Horsch (2016) [95] pointed out that fuel use for crop establishment with CTF is reduced by at least 35%, while Jensen et al. (2012) [92] estimated that it may be possible to reduce costs of fuel by 25-27% in cereals due to less overlap. Horsch (2016) [95] also mentioned that time and energy for crop establishment can even be reduced by 70%, while he 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. A 1400 ha wheat/oilseed rape rotation farm converted from minimum tillage farming to CTF no tillage was studied and it was found out that yield was increased by 4% in wheat and 7.5% in oilseed rape [96].

In addition, machinery costs are reduced as lighter machines with less power are needed. Some farmers in Australia have cut their machinery costs by as much as 75% while their crop yields have risen [96]. Horsch (2016) [95] 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) [97] 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. A 1400 ha wheat/oilseed rape rotation farm converted from minimum tillage farming to CTF no tillage was examined and it was found out that farm profit was increased by 8% and the return on capital investment was 14% [96]. It was also shown that €290,000 savings on machinery investment was achieved. The cost of UK consultants for providing farm survey to the farmer, including the present production constraints, the machinery and equipment requirements to apply CTF was estimated to €927 plus expense and VAT. If the farmer requires a full action plan to install CTF the service cost is increased to €1,390 plus expense and VAT [96].

5.5. Variable rate pesticide application (VRPA)

5.5.1. Description of VRPA technologies

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 [98]. In some cases, they can also be used to apply fertiliser at variable rates [99].

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 [34]. 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 [98]. VR pesticide application technologies use other PATs (GNSS, machine guidance, crop sensing, and leaf wetness sensors) to apply the optimum pesticide quantity site-specifically.

5.5.2. GHG emission reduction potential through VRPA

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 [100]. 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 [101]. There is significant work on the saved pesticide quantity that ranges from 11 to 90% for herbicide use in different arable crop types [100,102,103,104]. Other work recorded pesticide use reduction in perennial crops between 28- 70% [105,106,107,108]. VR pesticide application can also cause reductions in insecticide use by 13.4% in winter wheat [109]. They also reduce significantly spray overlap that can also reduce the total pesticide use [110].

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 [111].

5.5.3. 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) [112] 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 [100].

Swinton (2003) [113] 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) [100] 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) [110] 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) [114] 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) [104] 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 VRPA 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 [110]. Gerhards and Sökefeld (2003) [114] 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) [110] 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) [100] 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) [114] estimated the cost of a camera system for weed detection at €40,000, whereas Dammer and Wartenberg (2007) [104] used an optoelectronic weed sensor of about €2,000. The latter could however not distinguish between crops and weeds and was therefore limited in its operations. In a study 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 [115].

5.6. Variable rate planting/seeding (VRP/VRS)

5.6.1. 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 [34]. More advanced systems have independent planting/seeding elements that can also differentiate the application rate on-the-go per row [116]. 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.

5.6.2. GHG emission reduction potential through VRP/VRS

When applying VRP/VRS it 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 [117]. 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.

5.6.3. Impacts of the use of VRP/VRS on productivity and farm economics

The main benefit from VRP/VRS 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 VRP/VRS will be low, while in heterogeneous fields with differentiated performance zones, the return on investment will be much higher. In the early years of VRP/VRS development, its economic impact was unclear.

Variable seeding rate of winter wheat can offer increase in yield from 3% compared to uniform seeding [118]. Another research showed that farmers using variable rate seeding 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% [119]. Corn yields can be increased by 6% using variable rate seeding [120]. Although VRS 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 VRS drills and planters was noticed in USA in 2007 [121].

Bullock et al. (1998) [122] 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. Another work 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 [123]. Taylor and Staggenborg (2000) [124] 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. Shanahan et al. (2004) [125] stated that "site-specific management of plant densities may be [ed: economically] feasible", most likely due to technological advances. Dillon et al. (2009) [126] 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 VRS of wheat in France is economically feasible. Hörbe et al. (2013) [117] performed two experiments that tested the economic returns of VRS 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 VR 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 VR planters among 52 fields showed a percentage of double-planted area to reach up to 15.5% and the savings from the use of VR planters ranged from €3.5 to €22.9 per ha depending on the farming operation and the field type [127].

No independent scientific research on the economic impact of multi-hybrid planting/seeding is currently available, because this technology has been developed very recently.

5.7. Precision physical weeding technology (PPW)

5.7.1. Description of PPW technology

Precision physical weeding (PPW) 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 [128]. In this work is reported the design and development of an automatic machine able to perform, at the same time, mechanical and thermal weed control on maize. Other detection system would be ultrasonic sensors that detect plant density that when it is increased the harrow treats this part more aggressively [129]. 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). A hybrid physical/chemical weeding system is mentioned by Norremark (2010) [130]. 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.

5.7.2. GHG emission reduction potential through PPW

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 [129]. 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.

5.7.3. Impacts of PPW 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 €/ha, while conventional weeding cost 297 €/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 [130]. Peruzzi et al. (2008) [131] 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 €/ha on top of the normal harvest.

6. 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 great attention 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 significant interest on the possible GHG emission mitigation through the use of PATs. However, literature is limited on data regarding the effect of PA on climate change. All categories of PATs (guidance, recording, reacting) contribute to the reduction of GHG emissions and in farm productivity and income due to their interconnections and it is difficult to separate them according to importance. Recording and GNSS technologies are supportive in the PA process, while reacting technologies and guidance systems have a direct visible result on the agricultural system that are applied on. Hence, these PATs were analysed according to their potential to reduce GHG emissions and improve farm productivity and income.

Variable rate nutrient application (VRNA) 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. They can also affect positively farm productivity and income by applying the right amount of nitrogen according to the plants' needs. Variable rate irrigation (VRI) systems follows in GHG emission reduction potential as its impact is dual; primarily the decrease of irrigated water reduces 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). In terms of productivity, the impact is also significant, particularly in dry areas, as irrigation scheduling kai dosage can be optimized resulting in economic benefits (lower pumping costs combined with higher yields). Controlled Traffic Farming (CTF) and machine guidance (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 and lower cost of production). Variable rate pesticide application (VRPA) is also expected to have GHG reduction potential due to lower pesticide application through lower GHGs coming from pesticide industrial production. However, the actual environmental effect can be extremely significant, but through lower chemical substances application that contaminates all natural resources (water, air, soil). The effect on farm economics is also major, especially in crops that receive many chemical applications, such as herbicides and fungicides. Variable rate planting/seeding (VRP/VRS) and precision physical weeding (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.

There is a necessity that more research should be carried out on the impact of PATs on GHG emissions, as there is strong evidence that PA can significantly assist in reducing GHG emissions, which will also influence the further adoption of PATs by practitioners, however this impact should be numerically justified with field experiments.

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