GREENSCOPE

Precision Agriculture's Impact on Water Resources and the Environment

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Abstract

With population forecasted towards 10 billion by 2050 (FAO, 2019) and climate change continuing its path to change the environment around us, attaining sustainable food security stands out as a global issue that must be addressed. Agriculture as a sector is currently the largest freshwater consumer and responsible for vast amounts of pollution. Water, fertilisers, and pesticides are all inefficiently used within agriculture due to inadequate technology commercially available and historically cheap fertiliser/pesticide costs. This paper has focused on the impact and potential that precision agriculture (PA) can have on increasing resource use efficiency through minimising inputs and maximising yields compared to conventional strategies. Over 60 studies were collated and showed that when compared to conventional strategies, PA was able to achieve a 28.5% average in water savings, a $67.2/ha average cost benefit relating to fertiliser inputs, and an average pesticide saving of 50%. Despite the proven ability of PA from an environmental and agronomical perspective, there is a lack of PA uptake – this is due to a lack of farmer confidence and high upfront capital costs. However, with rising fertiliser prices – previous views supporting the rejection of PA technologies must be reconsidered. A coordinated effort between government, researchers, and farmers must take place to boost PA adoption.

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1. Introduction

Throughout history, agriculture has remained the focal point of societal and economic growth, and now has the responsibility of food security for almost 8 billion people globally. By 2050, it is estimated that the population will reach 9.7 billion and food demand worldwide is expected to grow by over 50% (FAO, 2019; Anon, 2019). Food security is essential for any society to flourish, and with growing population increasing food demand, the agricultural sector must adapt to meet consumption needs whilst adhering to sustainable objectives focused on reducing emissions.

Currently, 25% of croplands worldwide are being irrigated using 70% of global freshwater resources (FAO, 2020a). It is predicted that a 10% increase in water usage will be required for agriculture to sufficiently provide for increased food demand in 2050 (FAO, 2020b). The sector is also one of the key contributors of emissions, particularly pertaining to nitrogen and phosphorus pollution in water bodies through both point and non-point sources. With fertiliser being historically cheap and improving yields substantially, inefficient management of the substance has become the norm and has led to environmental issues effecting both wildlife, human health, and environmental degradation. The rise of pesticides also gave way to agriculture's inevitable growth due to the impacts it has on crop waste reduction, however the use of the substance has been directly linked to unnatural chemicals being found across both water bodies and living organisms worldwide. The efficiency of water, fertiliser, and pesticide usage across the sector has been relatively low, considering societies technological advancement throughout the 20th and 21st century.

Understanding the technology required to improve efficiency across agriculture, whilst reducing emissions, is therefore of the upmost importance. A key concept that can be the solution to challenges faced ahead is precision agriculture (PA), a management concept that relies on observations, measurements, and response to crop variability across fields. The goal of PA is to ensure that returns are optimised, and inputs are efficiently reduced.

The aim of this report is to understand the benefits that PA has shown through research and the potential it can provide for the agriculture sector to improve crop production and reduce emissions.

Key objectives that are the focal point of this report is as follows:

- Understand the general framework behind precision agriculture
- Collate and convey the results of research completed on PA implementation within water, fertiliser, and pesticide usage
- Understand the key strategies and reasons for differing magnitudes of PA results compared to conventional practice
- Evaluate PA benefits and drawbacks from an agronomic, environmental, and economic perspective.
- Provide an insight into directions and key developments within precision agriculture

2. The purpose of precision agriculture

Four components make up precision agriculture as a management tool: geographic location, information collecting, decision support, and variable-rate treatment. A fifth element may be yield mapping, which gives farmers the ability to track the real results of varying inputs (Pedersen 2003). The goal of these systems should be to provide farmers the potential to enhance yield, decrease inputs, and replace intensive manual labour with an effective decision-support model and sensor system that can boost farm economics and lower emissions. Precision agriculture follows other advances that cut costs and require less labour, such as minimal tillage and genetically modified (GM) crops; the latest advancements in sensor systems, drone technology, and autonomous vehicles are expected to hasten this process even more.

Inputs are often dispersed evenly throughout the whole field in conventional farming, with a constant input per unit area across the site. To maximise productivity from a given field or to reduce input costs, precision farming entails dispersing inputs site-specifically. Since all fields have a variety of production potential or input saving potential, precision farming should be able to take advantage of this heterogeneity. Although each unit has a unique yield potential, changing the application of inputs may not always result in an extra marginal economic benefit; this is dependent on the marginal net benefit of implementing further inputs on a site-specific basis and the extent to which the site-specific data required to make that decision is available (Pederson et al. 2017).

Figure 1 represents the general technical structure of a precision agriculture system. Geographical positioning technologies, such as GPS, are used to provide a location-based map of the field. This map is then linked to an information gathering tool, such as ground based sensors or aerial pictures through drone technology. Both location and sensor-based tools will be inputted into a decision support model that will control a variable rate technology to follow in order to maximise yields and minimise inputs.

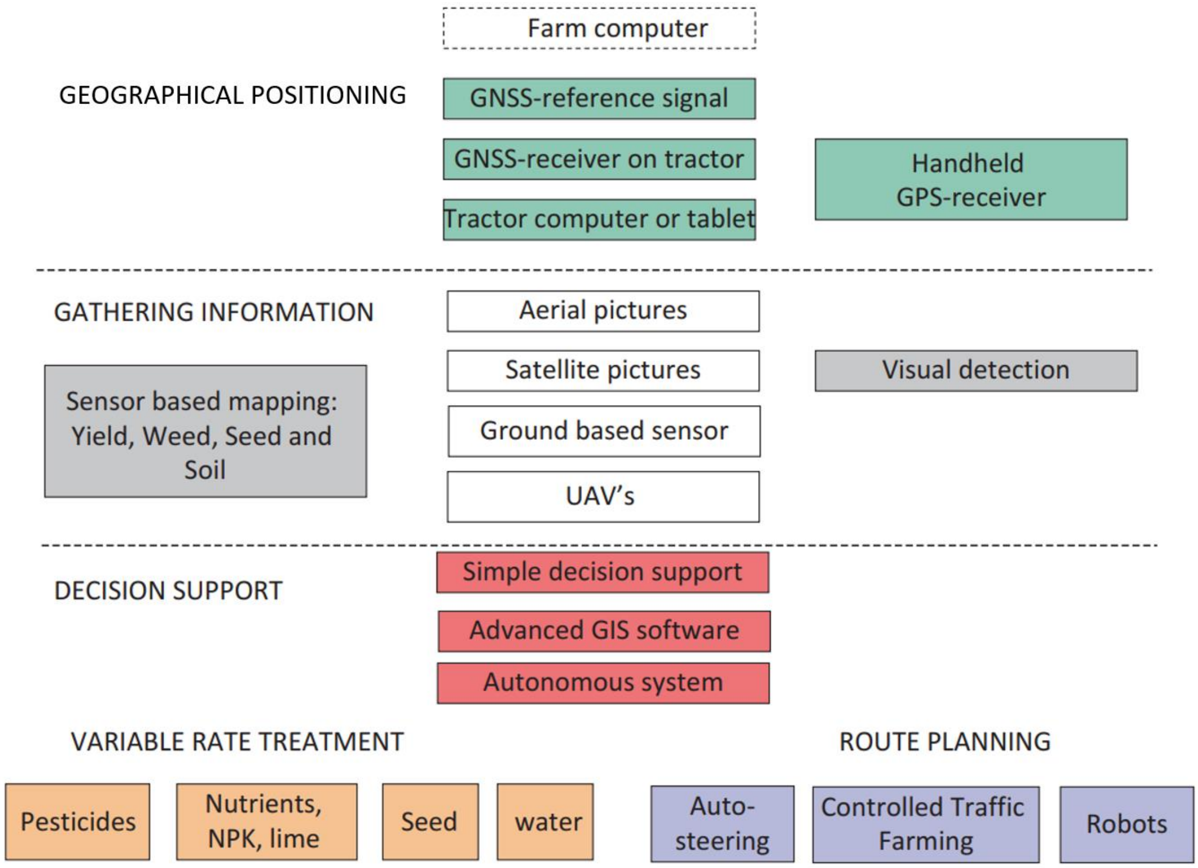

Figure 1: different technical systems and sensors in precision agriculture (Pederson et al., 2017)

Variable rate technologies (VRT) can optimise a variable element of a system (e.g. water usage, fertiliser usage, or pesticide usage) based on the characteristics of the system itself (e.g. weather, topography, plant density etc.). The optimum amount of input is determined through models based on specific/multiple characteristics to maximise yields (such as crop production). VRT is a commercially available technology across the globe, however issues around the accessibility and affordability of the technology have hindered the adoption of the technology – this will be discussed later in the report. Precision technology falls within a broader scope of precision management, such as management zones (MZ).

A management zone (MZ) is a small region with generally uniform topography and soil characteristics, they are implemented to conveniently record the geographical distribution of yield-influencing factors throughout the season. To assist farmers in increasing input usage effectiveness, agricultural sustainability, and environmental protection - dynamic prescription maps may combine information on the geographical and temporal development of pressures with site-specific irrigation systems. When defining MZ for the use of precision agriculture, several parameters such as soil characteristics, sensor-based information, management practise, crop properties, weed control, and landscape attributes should be included into a decision support model (Khosla, 2010).

This report focuses on precision agriculture that incorporates VRT, since we are more concerned with the environmental impacts of PA technologies, rather than the labour-intensive aspect of the industry.

3. Irrigation

3.1. Global agricultural water usage

The largest consumer of global available fresh water supplies is agriculture (FAO, 2016). There are already 300 million acres of irrigated land worldwide with projections to 2050 indicate an increasing scarcity of water supplies for agriculture (FAO, 2020). Water is considered renewable; however the problem is that in water scarce regions, demand outstrips the ability of the hydrological cycle to replenish supplies. The severity of global poverty, climate change, and food insecurity has increased because of this predicament.

Table 1 shows that agriculture currently accounts for 69% of all freshwater usage globally. With water resources looking uncertain in the future, the agriculture sector must increase water use efficiency if the almost 8 billion people around the world are to sustainably consume food (UN, 2017).

	Agricultural (km^3/yr)	Municipal (km^3/yr)	Industrial (km^3/yr)
Africa	184	33	9
North America	261	87	305
South America	154	36	26
Asia	2,069	234	253
Europe	84	69	181
Oceania	16	5	4
World	**2,768**	**464**	**778**

Table 1: Freshwater usage by sector and region (FAO, 2016)

Rainfall only accounts for 1% of the overall demand for crop evapotranspiration (ET), which is more of a problem in arid countries where irrigation relies on subterranean water sources such as aquifers (Mauget et al., 2017). Numerous aquifers have been depleted due to intensive irrigation. For instance, in certain wells in the Texas High Plains region, up to 78 m of water depth was drained when looking at the water table of the Ogallala aquifer from 1950-2013 (McGuire, 2013). This is over 12 times the 4.5 metre average drop for the whole aquifer basin. According to predictions, this pace of depletion will render 35% of the Southern High Plains incapable of supporting irrigation in 30 years. Solutions for water conservation in agriculture are required since other alternative water resources throughout the globe are running out with little replenishment (Mauget et al., 2013). To effectively preserve water and increase water usage efficiency in agriculture, more effective water management is necessary.

3.2. Status of PA management of irrigation

3.2.1. Motivations for precision irrigation

Because of the expansion of agriculture, producers have had to specialise, and for many of them, investing in irrigation has shown to increase farm profitability. Farmers now must take into account the benefits of heterogeneous irrigation strategies on crop yields and quality due to rising labour and energy expenses. Changing patterns in food consumption trends towards more meat and dairy within diets due to economic growth has led to a further increase in grain feed production and thus further stress on water usage within agriculture.

Irrigated agricultural sectors will have to work harder with less resources in the event of decreased water supply, more frequent droughts, and climatic uncertainty. This indicates that water use efficiency needs to be raised. Even though irrigation has been used for centuries, the industry has only lately been forced to adapt to public expectations for less water allocation and more efficiency. In this situation, precision irrigation, defined as site-specific irrigation management using VRT, emerges as a viable means of boosting irrigated agriculture's output while minimising its emissions. It will need a coordinated worldwide effort to put technology into place that are suitable for various agricultural systems, reducing water/energy usage whilst enhancing crop output.

In Europe, overhead irrigation using high-pressure rain guns, pivots, or sprinklers is the predominant method of irrigation. These may utilise excessive amounts of water and electricity. Less than 5% of all irrigated agriculture worldwide uses drip irrigation (micro-irrigation) (Thenkabail, 2012). The percentage of precision agriculture implementation throughout Europe varies, with Spain (28%) and Italy (14%) leading the countries, whilst multiple eastern European countries have failed to adopt precision agriculture at all. The expense of setting up and maintaining systems and infrequent applications when additional irrigations are used, limits the utilisation of micro irrigation outside of dry regions. In fact, many farmers in these regions are switching from typical portable sprinkler systems to semi-permanent (seasonal) solid-set systems as a replacement for drip irrigation. The development of precision irrigation for overhead systems is anticipated to result in the biggest short-term increases in water efficiency.

Figure 2: Overhead irrigation systems - rain gun, sprinkler, centre pivot

Most field-scale irrigation methods utilised today unintentionally do not evenly distribute the same water depth over a field. Pressure fluctuation in ground slopes and laterals, wind distortion, and lack of overlap of sprinkler impact area all have a negative impact on sprinkler irrigation systems (Lamaddalena et al., 2007). Similarly, wind may affect hose reel systems, which are used for most of the agricultural irrigation in northern Europe. Boom-based hose reel systems are becoming more common for field-scale horticulture irrigation because they provide a better URI than guns, although they are still susceptible to pressure variations and irregular pull-in speeds. None of the technologies in use now are more flexible than PA to handle spatially variable water application.

Leaching in agriculture refers to the soil's loss of water-soluble plant nutrients because of excessive irrigation. When leaching causes groundwater pollution, it poses a threat to the natural environment. Chemicals may dissolve when water seeps into the earth from rainfall, floods, or other causes, contaminating underground water supplies. Leaching concerns in agriculture are especially high for excess fertiliser and biocides (such as pesticides, fungicides, insecticides, and herbicides). Figure 3 provides a diagram representation of the leaching process. The reduction of deep percolation and runoff, which may result in an excessive loss of nutrients, is one of the environmental advantages of having a system that regulates water application spatially. Overwatering often causes water to drain below the rootzone and leach chemicals into the groundwater. Runoff, which may result in soil erosion and non-point source pollution owing to the movement of nutrients, particularly nitrogen and phosphorus, is a second important consequence of excessive water application. The best management practises (BMPs) that maximise water use efficiency and safeguard water quality must be chosen by producers to ensure PA is being implemented to its full potential.

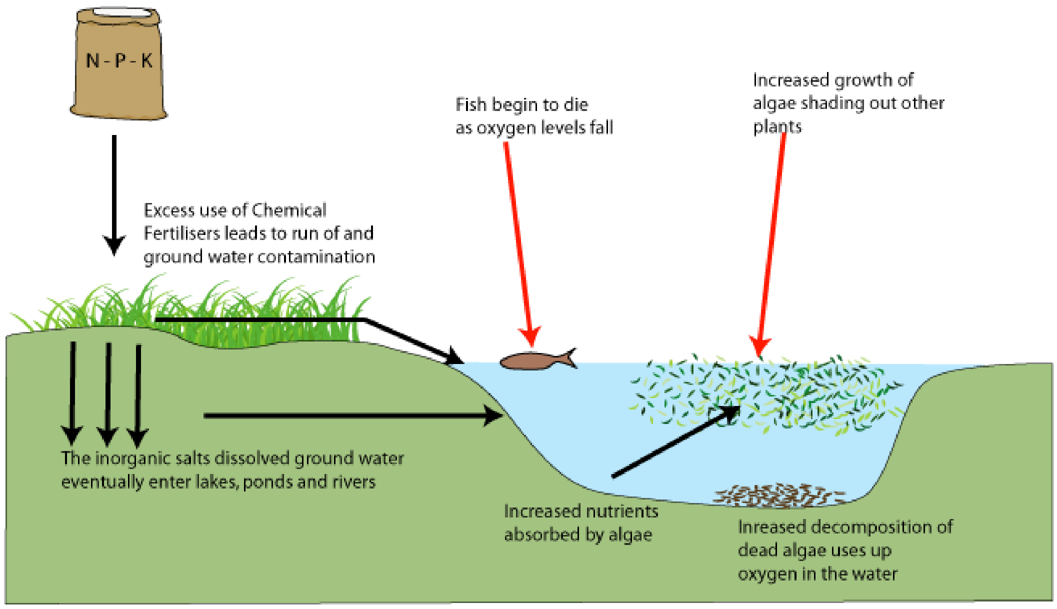

Figure 3: Explanation of nutrient leaching process (Alissa, 2016)

3.2.2. Precision water management strategies

To increase agricultural output when there is a water shortage, many precision irrigation systems have been created, however the effectiveness and profitability of site-specific technology is only as good as the precision irrigation management that it falls within. For many years, site-specific management has been carried out utilising the determination and deployment of MZ using spatial and temporal knowledge of numerous agronomic parameters. The creation of prescription maps using AI for site-specific water management has also increased in popularity in recent years.

In an investigation for potatoes in Idaho, site-specific irrigation was compared to traditional URI (King et al., 2006). A 2.9-ha field was split into nine MZ using the soil's available water-holding capacity. The findings demonstrated that site-specific management increased production in six out of nine MZ. The research made clear how vital it is to integrate all known variables that impact yield when deciding irrigation MZ for site-specific irrigation management. For instance, the number and location of soil moisture sensors used to calculate irrigation requirements may vary depending on the size and cost, both of which are factors when calculating the number of MZ in the field.

Numerous studies have defined MZ for the use of variable rate irrigation (VRI) using crop attributes such as yield maps. The nutrient variability in the field may be successfully captured by the MZ that were established using yield data from numerous years. However, since geographical and temporal variation in yield is dependent on several variables, using yield maps for site-specific management is challenging. Information from remote and proximal sensing (e.g. digital photography and airborne imagery), can be an effective method for both predetermined estimates of water requirements and more recently, it has been demonstrated that it can be used as a method of real-time sensing in precision agriculture. Throughout the season, action choices may be made using zone information together with crop response models and early season environmental indicators. Figure 4 below provides an image of a plot that has been split into MZ based on a parameter, which leads to the best management zone – this parameter could be anything used to distinguish the heterogeneity of the plot.

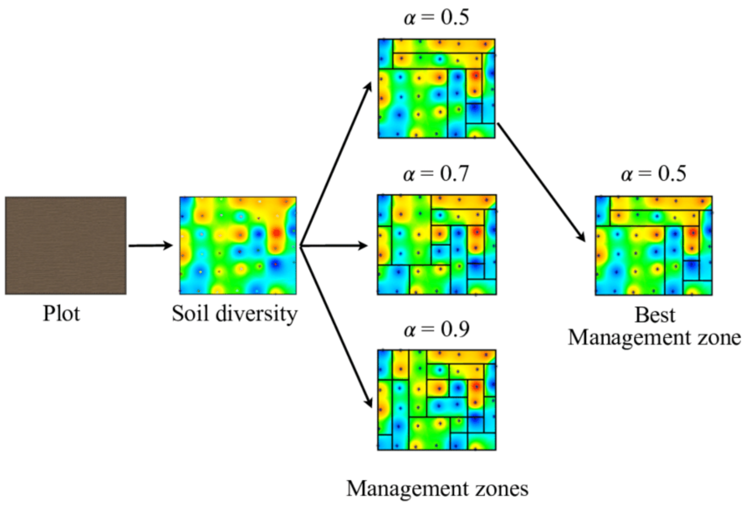

Figure 4: Example of MZ being created from a plot and leading to a best management zone (Albornoz et al., 2015)

Correct and efficient management strategy is necessary for putting VRI technology into practice. The ultimate yield or profitability may not always be favourable when technology is used in the field. For example, research has shown that from an economic perspective, the use of VRI may result in overall reduced profitability within a region of high rainfall throughout the growing season (Evans et al. 2012). Several approaches might be used to save energy and water in the field to increase crop yields. Some of the techniques include growing multiple crops in the same field, bypassing irrigation in uncultivated regions, reducing irrigation in low-water-use areas (ET), and collecting rainwater in places with high water-holding capacity (Neupane and Guo, 2019). Modern irrigated agricultural cropping systems need new methods, like adapting the present irrigation system for site-specific chemical and water treatments (O'Shaughnessy et al., 2014). Throughout the growth season, management techniques like as location and timing are essential for maximising irrigation. Deficit irrigation (DI) is a supplementary technique that conserves irrigation water by selectively scheduling watering during periods of slower growth. In this technique, irrigation is used while a crop is in its drought-sensitive growth stages. In phases less susceptible to drought, irrigation is used in accordance with precipitation and the water availability for upkeep

Current site-specific management employs a variety of control strategies, including computer modelling of crop output or the environment, sensor feedback used for site-specific water flow, optimising irrigation application timing, as well as using model prediction which determines the optimal input (Neupane and Guo, 2019). Also, the use of AI which incorporates machine learning and big data to choose water application parameters for optimal irrigation is growing (McCarthy et al., 2014).

3.3. Examples of PA management of irrigation

3.3.1. Water utilisation under PA systems compared to conventional irrigation practice

Crop	Country	Control System	Key findings	Reference
Tomato	China	Soil moisture sensing	30% increase in water savings	(Renkuan et al., 2020)
Ornamental crop	US	Soil moisture sensing	50% reduction in irrigation volume	(William et al., 2020)
Plum crop	China	Soil moisture sensing	Improved water savings across all MZ	(Doudou et al., 2020)
Cotton	Spain	Soil moisture sensing	Improved water savings across all MZ	(Cruz-Blanco et al., 2014)
Strawberry	Mexico	Soil moisture sensing	58.8% water saving	(Lozoya et al., 2019)
Cantaloup Plant	Malaysia	Weather-based scheduling	30% water savings	(Abioye et al., 2021)
Baby Pakchoi	China	Weather-based scheduling	Guarantee crop water requirements were met	(Doudou et al., 2020)
Maize	Spain	Weather-based scheduling	Yield and IWP were kept to satisfactory levels	(Cruz-Blanco et al., 2014)
Rye winter cover crop	US	Plant-based scheduling	10% reduction in irrigation water	(Calvin et al., 2020)
Maize	New Zealand	Soil moisture sensing	26.3% water savings	(O'Shaughnessy et al., 2019)
Soybean	US	Soil electrical conductivity mapping	25% water savings and 2.8% higher yields	(Evett et al., 2019)
Corn	US	Soil electrical conductivity mapping	25% water savings and 0.8% higher yields	(Evett et al., 2019)

Table 2: Collated research on PA technology water savings compared to conventional irrigation practice

3.3.2. Topographic factors influencing PA results compared to conventional practice

Large agricultural fields often exhibit topographic variation, which causes spatial heterogeneity in soil water and, eventually, crop productivity. In the same area, topography can result in over 50% of variations in water availability and affects both hydrologic features and processes (Hanna, et al. 1982). The heterogeneity in soil and topography features may also account for between 28-85% of the variation in yield (Jiang et al., 2004). For VRI applications, it is crucial to characterise the variability of terrain features and soil qualities. There may be variances in crop output of up to 69% at various sites in the field because of this, which may have a substantial impact on crop growth and yield (Brubaker, et al. 1993). According to research done in central Illinois and eastern Indiana, geography alone may account for around 20% of yield variability (Kravchenko and Bullock, 2000). As a result, results of studies focused on PA should take into account topographic impacts.

Site elevation	Cotton lint output was shown to be adversely linked with site elevation in a 7.4 hectare field study in Texas Southern High Plains (Guzman et al. 2011). The buildup of run-off water and nitrate eroded from the upper slope sections may have contributed to the increased lint production and nitrogen (N) absorption in bottom slope positions compared to upslope. Relative elevation accounted for up to 49% of the difference in soil water content and 32% of the variation in field lint production (Guzman et al. 2011).
Field curvature	The concentration of surface water is determined by the curvature of the field surface (Kaspar et al. 2003). Water flow is concentrated on concave surfaces with negative curvatures, whereas flow of water is dispersed on convex surfaces with positive curvatures. Up to 15% of variability in crop productivity can be attributed to the curvature of the soil surface. Another study (Silva et al. 2008) found a link between surface curvature and corn yield. Concave curves produced 14 percent more corn than convex sections in this study.
Soil texture	As a result, it has an impact on how water is distributed for field irrigation needs and plant development. The best water-holding capacity is often found in fine sandy loams and silts, while a rise in either clay or sand content in the soil profile reduces water-holding capacity (Duncan et al. 2012). According to a research, the amount of clay in the soil can alter how much water is available for crop growth, accounting for up to 17% of the variation in winter wheat production (Boenecke et al. 2018). Since soil texture affects crop productivity and water availability, it should be taken into account when planning and implementing VRI (Hake et al. 2010).
Soil organic matter (SOM)	Due to SOM's affinity for water, its impact on water-holding capacity plays a key role in VRI (Ball, 2001). SOM has a favourable impact on yield, and this impact is stronger in soils with low levels of organic matter (Kravchenko et al. 2000). Understanding the distribution of organic matter in the field may therefore aid in estimating the irrigation needs for the field and should be taken into account when creating site-specific water management.

Table 3: Topographic characteristics causing discrepancies in different PA results for yield improvements and water savings

Table 3 provides a summary of site elevation, field curvature, soil texture, and soil organic matter impacts on yields – which will produce varying degrees of VRI impact for each field (Pokhrel et al., 2018).

3.4. Evaluation of precision irrigation management strategies

3.4.1. Agronomic and economic evaluation of variable rate irrigation application

The results of the research show that producers can more effectively manage water resources and comply to regulatory water allocation laws by using VRI to apply irrigation scheduling both temporally and spatially. Integrated water management may also have favourable effects on a farmer's economy (saving time, convenience), society, and the environment. Limited watering quantities may be applied to regions that pond under full irrigation or to locations that have traditionally produced poor yields. The total net return profitability will determine how much water should be applied to the low-producing sectors.

VRI may also be used to redirect irrigation water away from fields with consistently poor yields and toward those with higher yields when water is not considered as the constraint. An example of this is redirecting water away from a poor yielding region which may have an insect infestation, resulting in reduce yields (Workneh et al., 2017).

Although there has been evidence that PA technologies are more profitable over the long run, farmers have not adopted VRI technology because of the large upfront capital requirements. A 12.6-ha field in southwest Georgia was the subject of research, which revealed that VRI produced an additional $16/ha in return above traditional uniform rate irrigation (URI), however even with these profits, high upfront costs reduced the confidence in farmers to implement this technology (Nijbroek et al., 2003),. Additionally, Sui and Yan (2017) evaluated irrigation quantities with URI and employed VRI technology to administer irrigation to match the temporal and geographical variability in soil and plant parameters within a field. Each variety of MZ had a set of three soil water sensors attached to monitor the levels of soil water content. When the soil water content fell to 74% of the field's capacity, irrigation commenced. In comparison to the URI, the VRI system utilised 25% less water, which greatly increased profitability. Profits were found to have increased by 27.1%, 56.9%, 96.4%, and 49.2% in Temple, Kunnunura, Hyderabad, and Saskatchewan, respectively.

More research at the landscape level is required to determine the percentage of fields that will be responsive to VRI since certain fields benefit from this technology while others do not. Most of the recent research on VRI concentrate on the field-scale level, which is not realistic to many producers – therefore further research will need to be implemented, although the results strongly suggest that VRI is a positively impactful technology.

3.4.2. Further opportunities and constraints within variable rate irrigation

If the advantages are shown on a "real farm," producers are more willing to embrace VRI. The majority of earlier research on VRI was done in tiny, misrepresentative areas that were used for experiments or other purposes (Sadler et al., 2005). To guarantee that management practises and study objectives are in harmony, this form of research requires tight coordination between the researcher and farmer. Large-scale data and information acquisition is expensive and time-consuming. Additionally, the absence of suitable tools that combine traditional statistical techniques with spatial analysis makes the statistical analysis of on-farm data difficult. This makes it difficult to comprehend how crop development and its surroundings interact when using site-specific irrigation. For information on real-world VRI uses, further on-farm investigations are required. Additional barriers to the use of precision agricultural technologies include the farmer's lack of understanding of temporal variation and environmental effects (McBratney et al., 2005).

Data and information from soil physical and chemical qualities, crop growth conditions, meteorological parameters, and the interplay between these components are needed for precision irrigation management. A thorough decision-support system that can process multiple layers of data is necessary for the effective deployment of precision irrigation moving forward (Miller et al., 2017). The minimal amount of farmer-friendly decision support tools, like those creating dynamic prescription maps, continues to be a problem for the implementation of PA (Barker et al., 2018). Many decision support systems are available, but because of their complexity, manufacturers are hesitant to use them to their fullest extent. Additionally, the information that scientists and engineers believe should be included in the decision support system do not consider enough, the use of farmers' implicit knowledge or meet their demands in the actual world. The absence of learning incentives are some other factors that prevent the widespread usage of various decision assistance technologies (Lindblom et al., 2017).

4. Fertilisers

4.1. Global fertiliser consumption

Worldwide fertiliser consumption differs significantly by geography, with East and South Asia using the most and Africa using relatively less (Kotschi 2015). Table 4 shows the global fertiliser consumption projected for 2022 to surpass 200 million tonnes for the first time (FAO, 2019)..

Year	2016	2017	2018	2019	2020	2021	2022
Nitrogen, N	105 148	105 050	105 893	107 424	108 744	110 193	111 591
Phosphorus, as P_2O_5	44 481	45 152	45 902	46 587	47 402	48 264	49 096
Potassium, as K_2O	35 434	36 349	37 171	37 971	38 711	39 473	40 232
Total ($N+P_2O_5+K_2O$)	**185 063**	**186 551**	**188 966**	**191 981**	**194 857**	**197 930**	**200 919**

Table 4: Historic and projected global fertiliser consumption (thousand tonnes) from 2016-2022 (FAO,2019)

China is the world's biggest producer of grains and one of the top users of fertilisers, with the highest levels of phosphate and nitrogen usage for agriculture (Reuters 2010; FAO 2020b) (FAO 2020b). China has produced more than eight times as much grain since the 1960s, but its consumption of nitrogen fertiliser has climbed by roughly 55 times (Reuters 2010). Together, East Asia, South Asia, and Latin America account for more than 70% of the global need for fertiliser. About 69% of the world's fertiliser is used in Asia, with China making up most of that usage. According to Skowroska and Filipek (2014), 10.5 million tonnes of N, 2.4 million tonnes of P_2O_5, and 2.7 million tonnes of K_2O were consumed as fertiliser in the EU-27 nations in 2011–2012.

The demand for nitrogen, phosphate, and potash in the globe increased annually between 2014 and 2016 by 2%; however, the demand for fertiliser decreased by 1% between 2017 and 2019. (FAO,2020). This decrease in consumption is due to a factors such as worsening global economies, trade disputes, and war (IFA 2019).

With yearly growth rates of 1.2% for nitrogen, 1.7% for phosphates, and 1.8% for potash, the forecasted global demand for fertilisers may be well over 200 million tonnes by 2024 (Quinn 2020), and it is anticipated to reach over 324 million tonnes in 2050. (Drescher et al. 2011). In 2007, the USA (24%), China and other adjacent Asian nations (18%), and Africa (17%) accounted for the majority of the world's mineral P demand. The remaining 41% of mineral P supplies were consumed by the rest of the globe (Villalba et al. 2008). By 2050, farmland is expected to need 22–27 million tonnes of P fertilisers annually, while grassland will use an additional 4–12 million tonnes (Mogollon et al. 2018; Bindraban et al. 2020).

The ratio of nitrogen in our crops' harvested products relative to our inputs (fertilisers or manure) is known as the "nitrogen usage efficiency," and it may be used to determine how effectively nitrogen is being utilised (NUE). If our crops' NUE was 60%, it meant that our crops contained 60% of the nitrogen that was provided to them as inputs. The crops didn't consume the remaining 40% of the nitrogen. A low NUE is not good. This indicates that the amount of nitrogen we apply is seldom ever absorbed by the crops. If the NUE was 20%, then 80% of the applied nitrogen was converted to pollution.

Since 1980, the efficiency of nitrogen utilisation has been poor worldwide, ranging between 40% and 50%. (Lassaletta et al., 2014). This is surprisingly low. It implies that our crops only absorb less than half of the nitrogen we apply to them. The remainder is surplus waste that seeps into the ecosystem. However, as the figure illustrates, NUE varies significantly over the globe, as seen in figure 5. Some nations only reach a NUE of less than 40%. For instance, the efficiency of both China and India is merely a third. But some nations do far better. The efficiency of France, Ireland, the UK, and the US is more than two-thirds (Lassaletta et al., 2014).

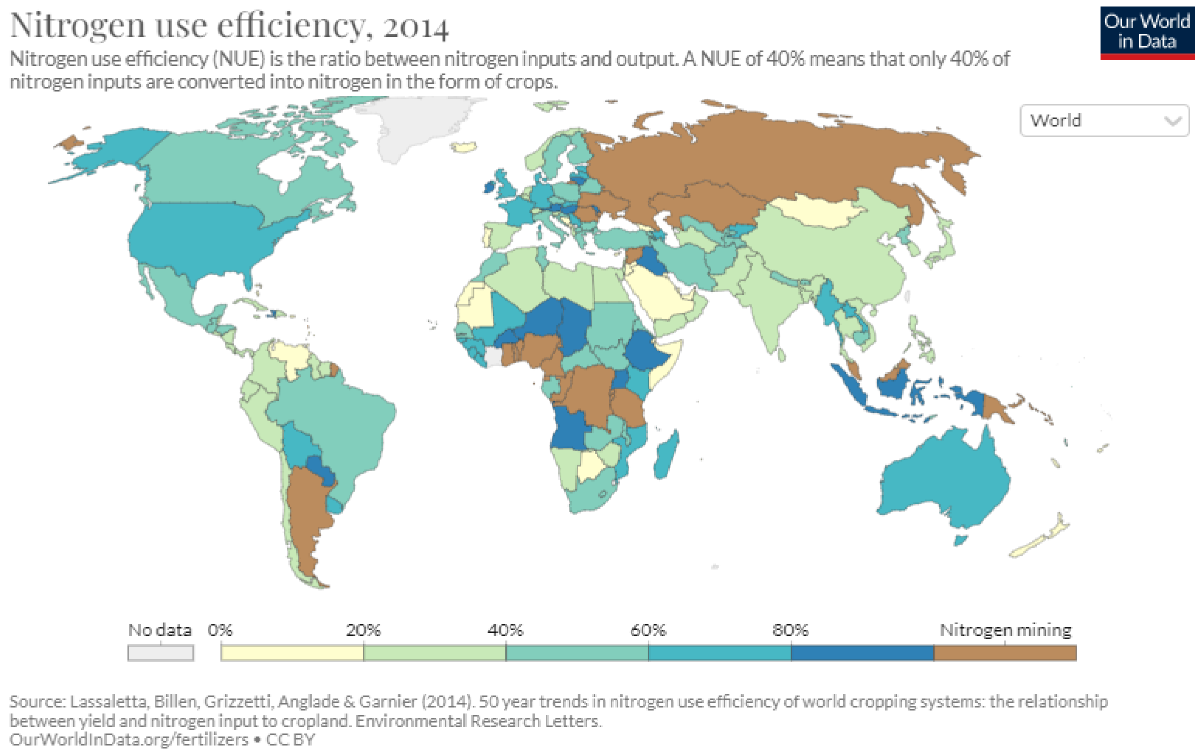

Figure 5: Global map demonstrating variation in NUE (Hannah and Max, 2013)

Between 40-50% of nitrogen has been used inefficiently over the globe since 1980. (2014) Lassaletta et al. This is astoundingly low. It suggests that the amount of nitrogen we apply to our crops is only absorbed to a lesser extent. The remaining portion is extra waste that penetrates into the environment. However, as the image shows, NUE varies widely over the world. Some countries only achieve a NUE of less than 40%. For instance, China and India are just about a third as efficient. However, some countries score notably better. More than two-thirds of the US, UK, France, Ireland, and other countries are efficient (Lassaletta et al., 2014).

4.2. Motivations for implementing PA for fertiliser

Nitrate, which is a form of Nitrogen, is a frequent contaminant in ground and surface waters. In agricultural soils, nitrate may easily drain through the root zone and into the surface or groundwater. Nitrogen leaching in irrigated areas has raised serious worries about nitrate (NO_3) pollution in surface and groundwater, and nitrous oxide, which is 300 times more impactful than carbon dioxide's contribution to climate change (Robertson and Groffman, 2009). In parts of Europe, groundwater nitrate contamination has become so severe that over 10% of the population experiences levels above WHO drinking water guidelines (FAO, 2019).

High fish mortality and algal blooms are other impacts caused by the eutrophication of reservoirs, lakes, and coastal water bodies - this is due to the enrichment of N from fertilisers as non-point source pollution. Additionally, can lead to a negative effect on the contribution of rural income and aquaculture to food security in developing countries. Nitrate stimulates phytoplankton production in surface waters, which causes eutrophication, resulting in biodiversity loss and hazardous algal blooms that may affect whole ecosystems (Bartley et al., 2003). Some regions have seen increases in N flows of up to 15 times, which has significantly accelerated coastal eutrophication. Similarly, the two main outcomes of phosphatic fertilisers are phosphorous (P) fixation and runoff which causes eutrophication (Howarth, 2008).

The use of nitrogen fertiliser has expanded dramatically over the previous 50 years, contributing to a 40% increase in grain yield per capita (Mosier et al. 2001). Synthetic nitrogen is estimated to provide roughly 40% of the world's dietary protein, and reliance on N fertiliser will increase in coming decades (Smil, 2004). Leaching losses in dry and semi-arid locations are minor. Nitrate leaching has been shown to be a problematic issue especially in sandy soil with a variation of climatic conditions (Wang et al. 2014). N shortage in agricultural soils may result in restricted growth and lower crop output in deficient environments (Zhu et al. 2019). The technique used to apply nitrogen fertiliser is certainly a factor in controlling N losses in soils.

Croplands make up 60% of the regions with increased levels of nitrate in ground water worldwide (Shukla et al., 2018). The amount of fertiliser N used, and the amount of nitrate lost through irrigated farmland to water bodies is substantially larger compared to rain-fed agriculture as 20% of cultivated area consists of irrigated agriculture, accounting for 40% of global food supply (UNESCO, 2021). Although there are many variables that affect the regional and temporal profile of nitrate in ground water below farmland, one important effect of elevated levels is the linear rise in N fertiliser use, shown in figure 6, due to rising demand for cereal grains and meat-based food.

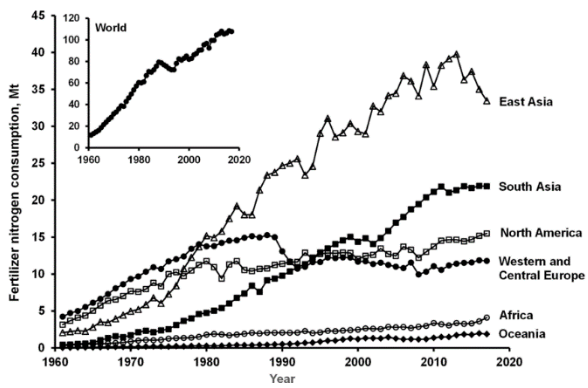

Figure 6: Fertiliser nitrogen consumption globally from 1960-2020

As further nitrate reaches the watersheds and onto the main river basins, the effects of non-point source pollution brought on by fertiliser usage in agro-ecosystems will continue to worsen. Due to the possibility of coastal water becoming eutrophic, it subsequently becomes a regional problem (van Drecht et al., 2001). The world's largest rivers' N intakes are shown in table 5, along with their N exports to coastal seas. In the instances of the Amazon and Zaire, the minor contributions of agriculture to the N flows indicate limited agricultural growth, while the Chinese rivers and the Ganges represent the region's increased usage of fertiliser obtained from agriculture during the previous several decades.

River (Country)	N input into rivers		N export to coastal waters	
	Annual input, kg N km^{-2}	Contribution of agriculture, %	Annual input, kg N km^{-2}	Contribution of agriculture, %
Mississipi (USA)	7489	89	597	63
Amazon (Brazil)	3034	17	692	6
Nile (Egypt)	3601	67	268	37
Zaire (Zaire)	3427	18	632	9
Zambezi (Zambia, Zimbabwe, Mozambique)	3175	47	330	2
Rhine (Germany)	13,941	77	2795	49
Po (Italy)	9060	81	1841	56
Ganges (India)	9366	81	1269	55
Changjiang (China)	11,823	92	2237	83
Huanghe (China)	5159	88	214	24

Table 5: N inputs/exports of major water bodies worldwide

Crop production is the primary cause of nitrogen cycle disruption worldwide. According to estimates, fertiliser provided 50% of the 136.6 Tg of annual nitrogen flows into agricultural land (Liu et al., 2010). Leaching and soil erosion account for 23 Tg N/year and 24 Tg N/year, respectively, of the 148 Tg N/year N outflows (Liu et al., 2010).

In the EU, agriculture is responsible for 20–40% of the phosphorus and 40–80% of the total nitrogen that pollutes surface water resources (Tudi et al., 2021). The United States Department of Agriculture estimates that nitrogen contamination causes groundwater pollution in more than half of the nation's counties. This problem is made more difficult by the heterogeneity of the field's growth characteristics, such as soil texture and water availability, which affects nitrogen absorption and plant growth across the field. Precision technology can match local plant demand with nitrogen supply by modifying fertiliser application rates within the field.

Recent years have seen a significant increase in concern over the extent of the world's phosphorus reserves. It has been estimated that, at the present pace of extraction, the commercially mineable deposit will be depleted in 60 to 100 years. According to a recent study, the PR's exploitable reserves might last 300–400 years assuming no changes to demand (Tudi et al., 2021).

Currently, 85% of phosphorus that is extracted yearly is treated for use in agriculture, generally as animal feed (about 5–10%) and fertiliser to apply to land (about 80%). (Tudi et al., 2021). However, there is a growing consensus that P is inefficiently used because multiple studies have shown that only 10-15% of application amount is used by crops, and rarely as much as 25% (Hilton et al., 2010).

Additionally, P residue is fixed in soil and cannot be used by subsequent crops. Such projections demonstrate the need of using phosphorus in agriculture effectively (Hilton et al., 2010).

4.3. Fertiliser PA technology and management systems within PA

4.3.1. Key management systems

Treatment mapping:

Precision management is available to be implemented once yield-influencing factors, such as N and P status, has been evaluated using sampling and analysis techniques. Then, correlations between N and other variables that affect grain production may be found using statistical methods. The objective is to create a site-specific treatment map that demonstrates the exact position/rate of required treatment across the site. The variation throughout the site may be addressed by using this strategy to operate variable-rate applicators. The yield-map output and soil condition variability in each specific field area may be used by the map-based fertilisation approach to optimally match fertiliser application rates (Plant, 2001).

Real-time and in-season determination sensing:

Another strategy that can be used instead of treatment maps is real-time and in-season determination sensing through the use of a range of sensing technologies, from infra-red cameras to UAV's This makes varying the N input without the need for considerable previous data analysis possible. Canopy reflectance devices/sensors are able to be attached on fertiliser applicators that have computer processing and VR controllers. Throughout the growing season, tractor-mounted equipment provides real-time crop growth detection, and fertiliser may be applied in a single dose (Kitchen et al. 2010). A control system determines the input requirements based on continuous data and sends information to a controller, providing the input to sensor's identified location.

Systems for determining homogeneous zones:

Another method of regulating fertilisation is superimposing map images and categorising areas of the field according to important factors affecting yields, allowing a single dose of crop input to be delivered in a uniform manner within the management zone. Song et al. (2009) defined management zones on the basis of a combination of soil/yield data and remote sensing information, also known as Quickbird imagery. All three of these techniques reduced the variability of wheat spectral characteristics, crop nutrients, and yield within the various zones. Research revealed that management zone delineation using satellite remote sensing data was accurate and practicable across multiple crops (Song et al, 2009). A useful web-based precision technology has also been created, utilising satellite imagery and field data to automatically estimate the ideal number of management zones and define them (Zhang et al., 2010). Other precision technologies are outlined in Table 6 below.

Nutrient Expert	Using a decision-support tool, fertiliser recommendations are dependant on growing environmental characteristics, soil fertility indicators, soil tests for P or K, management of crop inputs, and farmer's practise. The methodology promotes adopting the 4R nutrient management approach for site-specific nutrition management.
QUEFTS	Software that uses a model to examine how crops produced in tropical soils are affected by nitrogen, phosphorus, and potassium limitations. Procedure is completed in four steps: determine potential supply of N, P, and K; determine actual expected nutrient absorption; establish three yield ranges based on actual absorptions of N, P, and K; determining the final estimate of yield (Janssen et al., 1990).
Nutrient Manager for Rice	A decision-making tool composed of questions without the need for soil investigation. Using the methods and algorithms outlined by Buresh et al., the answers to the questions can create P and K recommendations.
SST Summit	The SST Summit enables using soil fertility data to produce maps of nutrient availability and recommendations for fertiliser application at various rates. Additionally, it permits the development of sowing maps at various rates (SST, 2019).
RISSAC-RIA	A computerised system of recommendations is intended to assist farmers in making economical and logical use of the food resources at their disposal. For 48 major crops, the system provides fertiliser recommendations.

Table 6: Different examples of PA technologies in use today

4.3.2. 4R strategy process

The 4R strategy relates to the best management practice of fertiliser use and highlights four key aspect of management that must be "right" to achieve optimal yields, reduced inputs, and minimal environmental damage. These four "right" aspects are: source, rate, time, and place – the table below briefly highlights where PA can fit into the 4R's.

	Reasoning	PA Implications
Rate	A rate that is too low will limit crop output and quality, while a rate that is too high would harm crops and have a detrimental influence on the environment. Application of nutrients either in excess or insufficiently will reduce economic profitability.	By applying fertiliser at a variable rate, it is possible to control the spatial variance in the field's nutrient requirements. It is possible to adapt variable-rate treatment, within the field, to different crop demands by taking into account nutrient requirement differences based on soil testing.
Time	Application of nutrients at the proper time will maximise nutrient retention and boost crop output.	The best way to do this is with VRF models that combine sensors and field cameras that can accurately record field topography. N and P application timing must be determined with careful regard to slope, soil type, climate conditions, and other topographic variabilities.
Place	The proper placement of nutrients allows plant roots to be able to always take up enough nutrient throughout the growth season.	By using soil testing, yield maps, and other techniques to evaluate the variations in yield potential, placement systems may be utilised to place fertiliser in proportion to the developing roots that have been discovered.
Source	Throughout the growth season, a balanced supply of key nutrients must be available in plant-accessible forms for when the crop needs them.	Little impact that PA technologies can do to optimise this process.

Table 7: 4R's management strategy and PA's role fitting in

4.4. Examples of PA fertiliser management

4.4.1. Nitrogen utilisation under PA systems compared to conventional practice

Crop	Country	Control/Model	Key findings	Economic benefit	Reference
Corn	USA	Topsoil depth	In over 75% of cases, VRT was more profitable than uniform rates.	\$75/ha	(Butchee et al., 2011)
Corn	USA	N leaching estimate	Reduced N leaching by 4.48kg/ha	\$3/ha	(Li et al., 2009)
Wheat, Barley	Germany	Chemical loading	Lowered N usage by 36% whilst maintaining high yields	NA	(Biermacher et al., 2006)
Corn	Canada	N-leaching simulation	Reduced nitrate leaching by 13% on average	NA	(Raun et al., 2002)
Potatoes	USA	N leaching simulation	No difference in N applied, N losses, or environmental benefits	0	(Scharf et al., 2011)
Corn	USA	Soil sensors	Unrecovered N amounts decreased in least productive soils	\$24/ha	(Wade et al., 2009)
Winter Wheat	USA	Soil sensors	82% reduction in fertiliser usage and 31.7% yield improvement	NA	(Jon et al., 2006)
Winter Wheat	USA	Plant sensors	59% reduction in fertiliser usage and 10.3% yield improvement	NA	(Jon et al., 2006)
Winter Wheat	USA	Soil sensors	6% yield improvement	NA	(Wade et al., 2009)
Winter Wheat	China	Optical sensor	28% reduction in fertiliser usage	\$90/ha	(Li et al., 2009)
Spring Wheat	UK	Airborne imagery	No difference in N applied, but a 0.46 t/ha increase in yields	\$400/ha	(Welsh et al., 2003)
Winter Wheat	USA	Optical sensor	Can increase NUE by 15% more than uniform rate technology	NA	(Raun et al., 2004)
Winter Wheat	USA	Optical sensor	Reduced N by 22 kg/ha whilst producing similar yields	\$14/ha	(Butchee et al., 2011)
Wheat	USA	Soil sensors	Reduced pre-plant N input by 59-82%	\$50/ha	(Biermacher et al., 2006)
Wheat	USA	Plant sensors	Mixed results of VRT economic benefits	\$32/ha	(Biermacher et al., 2009)
Wheat	Mexico	Optical sensor	Average savings of 69 kg ha^{-1} of N without a reduction in yields	\$48 /ha	(Raun et al., 2002)
Corn	USA	OPM-based	Increased yields by 110 kg/ha and reduced N by 15 kg/ha	\$10/ha	(Scharf et al., 2011)
Coffee	Brazil	Soil sensors	Yield increase of 34% with savings of 23% in phosphate fertilizer	NA	(Welsh et al., 2003)

Table 8: Key findings from research of PA fertiliser management

4.4.2. Evaluation of PA systems in the management of fertilisers

Adopting specific nitrogen fertiliser recommendations may increase fertiliser effectiveness, reducing environmental effects due to N losses and lowering the price of unnecessary inputs for producers of cereal crops (Arregui et al., 2006).

Ma et al. (2014) demonstrated that compared to uniform rate (UR) and single-dose pre-planting treatment, N's VR techniques needed less fertiliser to achieve an identical yield and had a higher nitrogen utilisation efficiency (NUE). Improvements in yield and NUE in the variable rate method was due to both a second topdressing application and a variate N application rate. In addition, compared to the treatments, variable rate application techniques lower the variability of mineral soil N spatially and the variability of yield. This is very important to farmers, as a survey showed that a top priority of farmers is the predictability and consistency of income (Ma et al, 2014).

A key limitation on the current research papers focused on precision nutrient application, is the lack of regional diversity – especially within developing countries where farming practices are considerably less efficient compared to western Europe and north America.

The most successful fertiliser management strategy for preventing nitrate leakage from soil-plant systems is the application of prescribed fertiliser N rates. Nitrate leaching outside of the root zone of crops may be decreased by adjusting the timing of fertiliser N application to match the N absorption pattern of crops. Predictive models for N enrichment of acquifers have shown that the optimum distribution of spatially variable fertiliser input in agricultural watersheds reduces nitrate pollution by over 22% (Ma et al. 2017). This method relies heavily on information, but it could be countered by practical considerations like the comparatively high actual and opportunity costs of agricultural labour.

Throughout the research, there has been clear evidence of a reduction in N leaching under VRT. In areas with high potential for leaching, VR application of pre-plant fertiliser was related to decreased soil NO_3 concentration. Additionally, when VRT was applied, NO_3-N leaching was significantly reduced by up to 28% in sensitive areas, such as valleys (Drechsel et al., 2015). Additionally, it was shown in most studies that VR application had negligible impacts on crop yields, in contrast to UR that resulted in a decrease in yields.

Thrikawala et al. (1999) used an N fertiliser simulation which presupposed that all surplus N applications were lost via leaching into groundwater to demonstrate the environmental advantages of VRT in maize. Large decreases in N inputs kept yield levels constant and pollution was reduced in all scenarios, ranging from 4.2%-36.3%. They also discovered that when average soil fertility increased, the environmental advantages of VRT decreased. However, it should be emphasised that the research suggests that VRT has little impact if there is either a relatively low or high average of field soil fertility. A specific range of average soil fertility should be considered before implementing certain PA strategies to have an optimal effect.

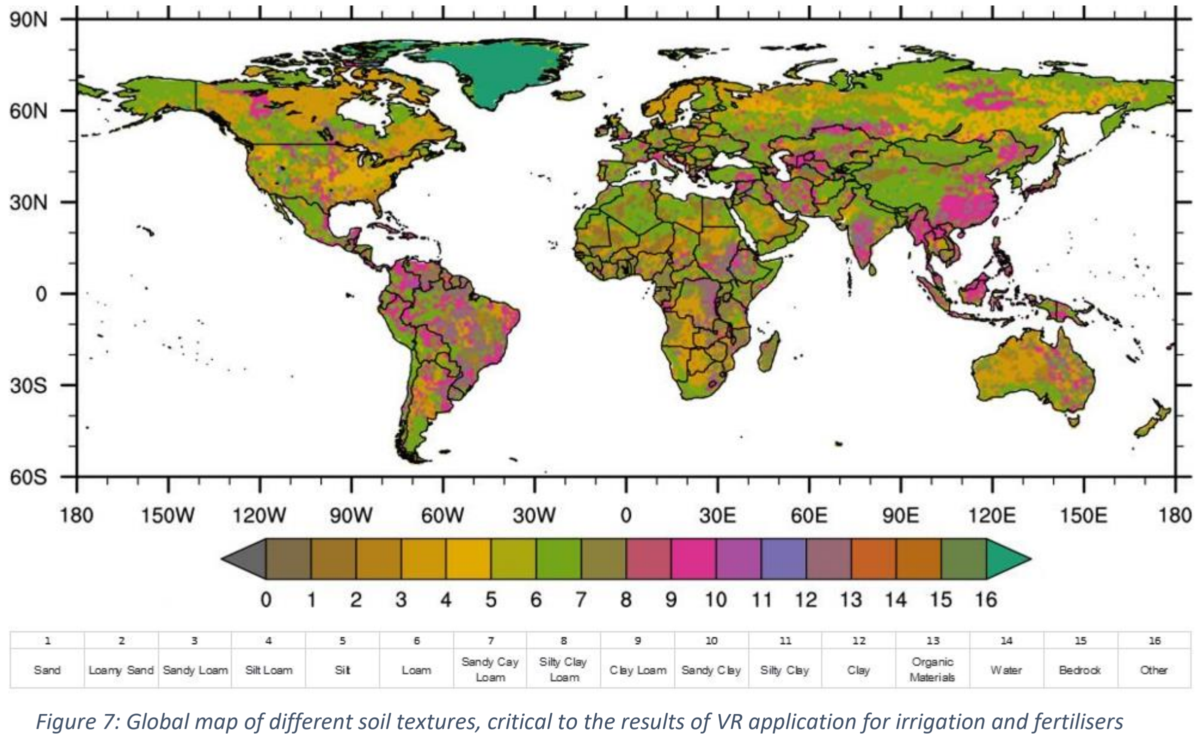

Figure 7: Global map of different soil textures, critical to the results of VR application for irrigation and fertilisers

The possible environmental impacts of PA in nutrient management were explored by Larson et al. in 1997. It was found that field texture played an important role in PA results with sandy loams to loamy sands, having a nitrogen leaching reduction of up to 60 kg/ha and 99 kg/ha respectively (Larson et al., 1997). This experiment showed that generally PA technology seems to be more effective in environments that consist of loamy sands instead of sandy loam type soils – the different soil types have been presented in figure 7.

Throughout many reports researched, a key theme that was discussed was the reduced inputs, and thus, the reduced costs that farmers would experience in the use of PA. However, most reports neglected the upfront cost that farmers would have to pay to implement the new technology. According to Blackmore et al. (1994), PA has the potential to significantly improve agricultural practises by reducing emissions, particularly from N fertiliser. They issued a warning that financial impacts on farmers would need to be compensated by grants or subsidies if PA were to be employed in a farming policy that was motivated by environmental concerns. The financial risks to the farmers might escalate if only environmental concerns are given more weight when determining input level.

The model's capacity to recognise the time of fertiliser administration and correlate it with the time taken for nutrient loss processes was a critical distinction between the impacts of different PA technologies. For mobile soil nutrients (e.g. N), timing of input is critical, compared to nutrients retained in the soil, such as P and K. There are many loss processes with regards to N. In general, wetter conditions result in more leaching and denitrification losses (Bausch et al., 2005). Any crop that uses nitrogen should have it applied as quickly as possible and before full crop absorption in order to meet the crop's growth demands. When it comes to P and K, most of the nutrients will be maintained in the soil even during periods of severe rainfall, therefore the scheduling of application has little effect on crop absorption. However, if P surface treatments are made only a few weeks before a runoff event, they may have a significant negative water quality (Drechsel et al., 2015).

Variable-rate applications of fertigation have not been extensively studied. Crop yield responses to both nitrogen and water are not uniform within a field (King et al., 2009), highlighting the need of researching how water and fertiliser interact during variable-rate irrigation. Remote sensing and irrigation combined with site-specific N application can result in a 50% reduction in N inputs and an 85% reduction in leaching whilst having no impact on yields (Bausch et al., 2005).

4.4.3. Implications of fertiliser price increase for PA adoption

Prices of major fertilisers such as ammonium nitrate have jumped 200% compared to 2021, forcing farmers to spend more to grow crops. The present crisis has been brought on by a number of causes, including the war in Ukraine, as Russia, Belarus, and Ukraine are all major exporters. Additionally, rising gas prices due to the war have put further pressure on nitrogen fertilisers, as many are produced via energy intensive methods. China, responsible for 30% of the world’s phosphate production, banned the export of fertilisers last year in attempt to combat mounting domestic prices – further spurring on price hikes internationally (FAO, 2020). Meanwhile, the world’s single biggest fertiliser producer, the Canadian company Nutrien, has struggled to export its product due to rail strikes.

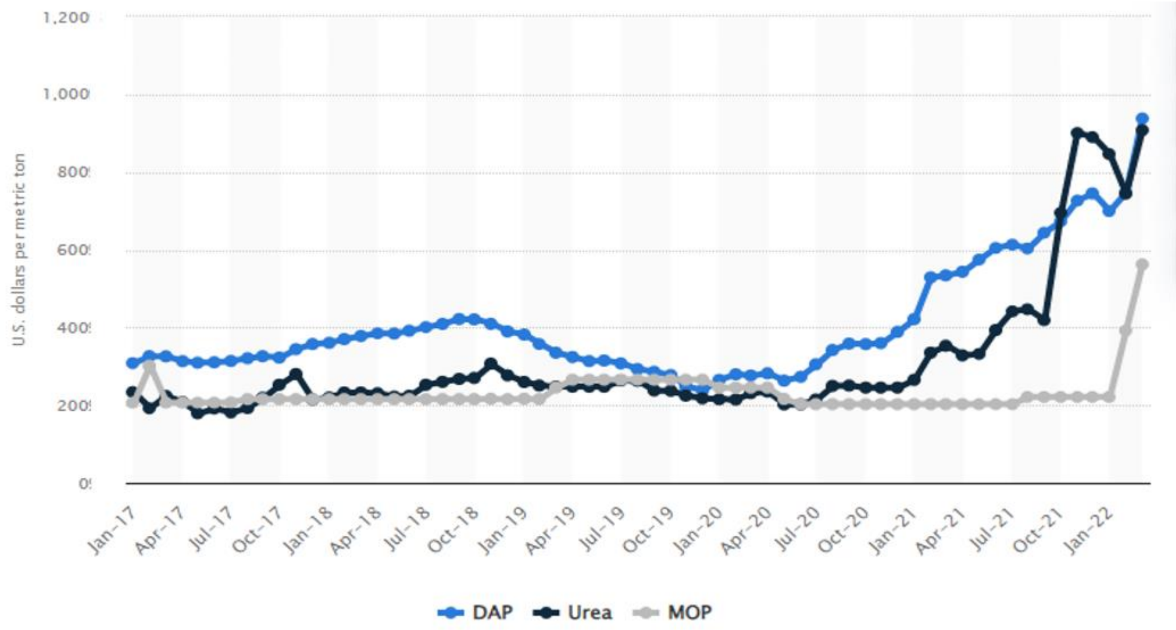

Figure 8: Fertiliser price change 2017-2022 (Statista, 2022)

The crisis clearly demonstrates a need for the implementation of PA technologies. Accurate nitrogen recommendations may increase fertiliser effectiveness, lowering unnecessary input costs for producers and the negative effects of nitrate leaching to the environment (Arregui et al., 2006). Shanahan et al. (2008) claims that N management techniques are still ineffective, and over 66% of nitrogen fertilisers used in production systems are being lost to leaching and runoff.

$$Price\ per\ tonne\ of\ fertiliser\ N = \$907.89$$

$$\%\ lost\ of\ fertiliser = 66\%$$

$$2022\ annual\ consumption = 201{,}000{,}000\ tonnes$$

$$Annual\ agricultural\ N\ loss\ cost = \$907.89 \times 66\% \times 201{,}000{,}000$$

$$Annual\ agricultural\ N\ loss\ cost = \$120.44\ billion$$

Theoretically, if PA technologies were rolled out across the globe and the entire agricultural industry used the technology to ensure maximum use efficiencies, the annual savings would amount to $120.44 billion.

This change of cost in fertiliser prices has made a significant impact on the way we view prior studies. Many studies, such as Leiva et al. (1997), deemed PA technologies as cost inefficient due to intensive capital costs for small changes in fertiliser production revenue. However, due to this increase in fertiliser price, we will see a dramatic increase in the positive view of PA technologies from a farmer's economic viewpoint, which will increase technology adoption levels worldwide.

FIGURE 32
Rice vs fertilizer prices

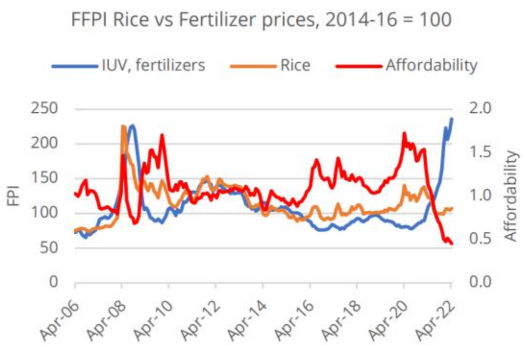

FIGURE 33
Sugar vs fertilizer prices

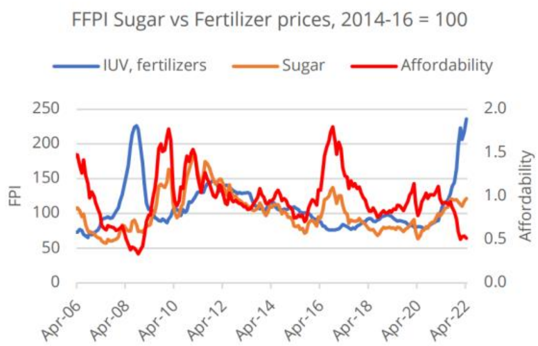

Figure 9: Graphs showing side-by-side analysis of the affordability of rice and sugar alongside fertiliser prices

Figure 9 above show that there is a need for government initiatives to be implemented for affordability of essential items to rise again – through the improvements in yield form the research conducted, policies should be aimed towards higher uptake of PA technologies.

5. Pesticides

5.1. Definition and use of pesticides

5.1.1. Defining pesticides

Insecticides, fungicides, and herbicides are all included in the category of substances known as pesticides (Bernardes et al., 2015). It is well acknowledged that pesticides have a significant role within agricultural as they lower product losses and raise food quality and production at an affordable level (Aktar et al., 2008). Global output of pesticides climbed 11% annually, from 200,000 tonnes to over 5 million tonnes from 1950-2000 (Carvalho, 2017). Annually, 3 billion kg of pesticides were used across the globe, however just 1% of those pesticides are successfully employed (Bernardes et al., 2015). The substantial quantities of pesticides that are still present permeate or reach non-target plants and the surrounding environment.

Functional groups, chemical classes, and toxicity are some of the categories used to distinguish pesticides (Garcia et al., 2012). The diverse targets, such as fungicides, herbicides, and insecticides are a crucial categorization. For instance, insecticides are to eradicate insects, herbicides are to eradicate weeds, and fungicides are used to eradicate fungus.

5.1.2. Importance of pesticides on waste reduction

Pesticides are vital in the production of agricultural products. Farmers have employed them to manage weeds and insects in agricultural operations, and the usage of pesticides has been linked to remarkable gains in agricultural output (Bernardes et al., 2015). Pesticides are used in around one-third of agricultural goods globally. Without pesticides, the output of grains, vegetables, and fruits would decline by 32%, 54%, and 78% respectively (Lamichhane et al., 2017). Therefore, pesticides are essential for lowering disease rates and increasing agricultural yields all around the globe.

There are fifty thousand species of plant diseases responsible for 13% of crop waste, nine thousand pest species responsible for 14% of crop waste, and over eight thousand weed species that are responsible for 13% of crop waste (Pimentel, 2009a). When insecticides were employed, crop loss due to pests decreased by 35-42%, and today over 80% of crops in the US use fungicides – apples economic worth grew by $1.2B with the use of fungicides (Guo et al., 2007). Without pesticides there would be a 27% fall in the US wheat, cotton, and soybean export supply (Zhang et al., 2011).

5.2. Global outlook on pesticide use

In the three main categories of pesticides (insecticides, fungicides/bactericides, and herbicides) from 2007 to 2008, herbicides came out on top (Anket et al. 2019). Fungicides and bactericides had a sharp rise and were ranked second. As shown in table 9, Asia is now largest user of pesticides in the world, with Europe being second. The top pesticide producers, users, and traders globally are China, the US, Brazil, France, and Japan. Maize is the most pesticide treated crop, mostly herbicides, in industrialised nations.

Africa		Total pesticide usage (kg)	Pesticide usage density (kg/ha)
	Congo	71,053,500	3,030
	Sudan	4,715,170	250
	Cameroon	5,800,392	1,220
	Zimbabwe	2,071,012	530
	Malawi	710,904	600
	Togo	141,963	250
	Rwanda	416,569	1,470
	Burundi	52,885	190

Asia		Total pesticide usage (kg)	Pesticide usage density (kg/ha)
	China	1,807,000,000	18,829
	India	56,120,000	1,707
	Malaysia	49,199,000	14,916
	Pakistan	27,885,000	3,162
	Thailand	21,800,000	4,249
	Vietnam	19,154,000	5,775
	South Korea	19,788,000	19,747
	Bangladesh	15,833,000	10,665

Europe		Total pesticide usage (kg)	Pesticide usage density (kg/ha)
	France	21,504,366	3,900
	Spain	16,698,678	3,350
	Sweden	3,239,741	720
	Germany	13,572,384	3,800
	Italy	19,435,011	6,450
	Greece	3,404,052	2,580
	Portugal	6,263,251	6,840
	Austria	2,004,206	2,390
	Czech Republic	1,143,557	1,450
	Ireland	1,995,753	2,840
	Denmark	315,900	710
	Netherlands	4,062,123	9,860
	Belgium	2,358,423	7,730

Other			
	USA	500,000	5,084
	Brazil	500,000	5,871
	Argentina	236,000	8,488
	Australia	80,000,000	1,033,429

Table 9: Breakdown by continent and countries of pesticide use globally in 2014 (Anket et al. 2019)

The major drivers of rising pesticide usage are population increase and climate change, with future projections predicting larger worldwide pesticide output (Tirado et al. 2010). Although pesticides significantly increase agricultural yields and help produce food that is both inexpensive and of high quality, their widespread usage has severe detrimental impacts on the environment (Miraglia et al. 2009). Environmental pollution is caused by the spread of pesticide contamination from target plants. Pesticides are able to travel by wind, water, runoff, leaching, or air.

The risk of a dramatic increase in pesticide usage in emerging nations may escalate in the years to come as their economies improve. It is a difficult effort to maintain or enhance the downward trend of pesticide usage in developed nations. Developing nations, as shown in Figure 10, often employ extremely harmful chemical pesticides, whereas industrialised nations typically utilise low-toxic, low-residual insecticides, herbicides, and bio-pesticides. Thus, the implementation of PA regarding pesticides is far more important in developing nations.

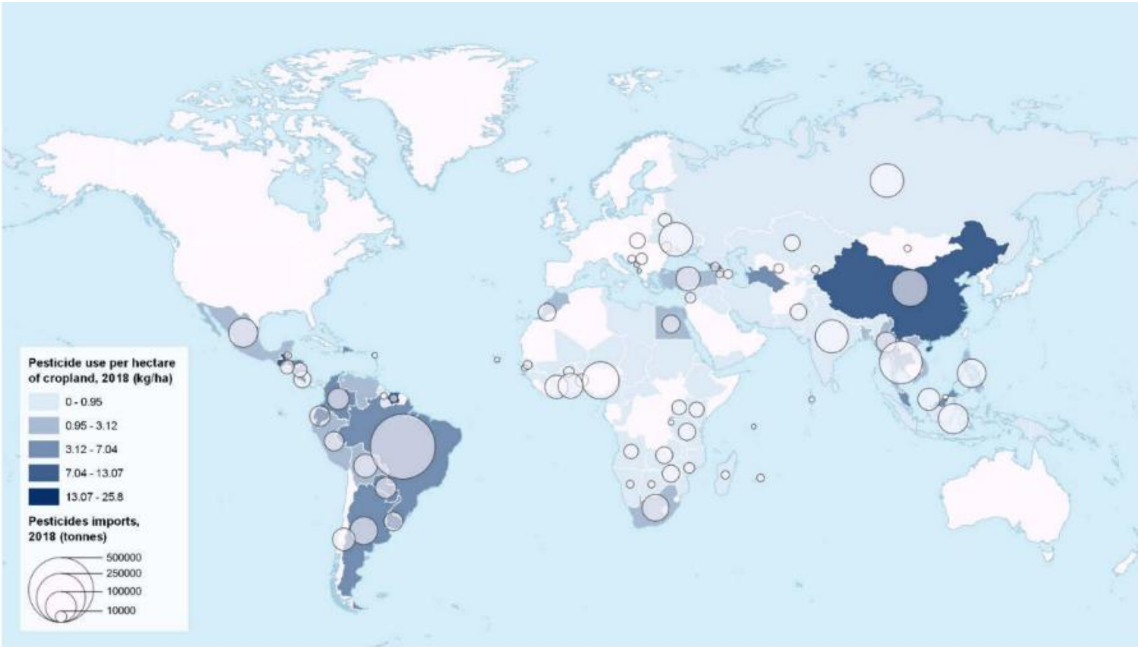

Figure 10: Breakdown of developing countries' pesticide use per hectare in 2018

5.3. Pesticide environmental impact and the push for PA adoption

When pesticides leak from agricultural fields, groundwater becomes contaminated (Ben Salem et al. 2016). Surface water systems, such as lakes, streams, reservoirs, and rivers are vulnerable to pesticide build-up as they are small sinks for the emissions (Ansara-Ross et al. 2012). The hydrologic cycle connects surface water systems to atmospheric water and groundwater. In addition, seepage of the soil may allow pesticides present in surface water to enter the groundwater. Evaporation and transpiration are other ways that they get into the atmosphere (Adams et al. 2016). Surface waters may be refilled by both groundwater and atmospheric water.

Just 1% of insecticides sprayed worldwide are deemed effective and 99% of pesticides used make their way to non-target locations, such as soils, the atmosphere, and water bodies - these pesticides are then consumed by all animals unintentionally. get a-that are discharged into non-target soils, water bodies, and the environment (Zhang et al. 2011). Nearly all wells in the US were found to contain one or more of the 127 pesticides used globally (EPA, 2015). An Indiana University study team examined 90 locations and focused on tree barks, ranging across different climates and geographies, and found pesticide residues at every location (EPA, 2015). All of this suggests that PA technology must be used to effectiveness of pesticide application.

The samples of water taken from Pakistan's Rawal Lake, the main supply of drinking water for the surrounding areas, were discovered to have pyrethroid pesticide residue levels that were four times higher than the acceptable threshold. The primary cause of the residues were runoff pollution from surrounding agricultural areas (Khan et al. 2020). Over 90% of water samples tested had pesticides in them, either in little amounts or in large amounts (Kole et al. 2001). In a recent research, 34 chemicals from pesticides of three distinct categories—herbicides, fungicides, and insecticides—were identified and quantified in the Louros River in Greece (Kapsi et al. 2019). Since nearly 95% of the world's population depends on groundwater, contamination is an issue that must be addressed, especially in agricultural regions where pesticides are regularly utilized (Singh et al. 2018).

Several pesticides were discovered by the United States Geological Survey (USGS) in more than 90% of the water and fish samples taken from US streams (Rose et al. 2018). 37,000-500,000 m2 of wetlands in Saskatchewan, Canada, were contaminated by herbicides to levels higher than the national threshold (Mazlan et al. 2017). According to a 2013 Greenpeace investigation, 70% of pesticides applied in China did not reach plants as intended and instead leaked into the groundwater and soil (Fan, 2017).

5.3.1. Conventional pesticide application practices

Airborne pesticide contamination is a significant source of pollution that has dangerous effects on human health, plants and animals (Liu et al. 2015). Agricultural pesticides are constantly sprayed into the air, with the residues often being made up of either spraying application or the volatilization of pesticides from soil or plants (Langenbach et al. 2017).

One way to apply pesticides is via pesticide sprays. The fan projects the pesticide as water droplets, and after passing through the canopy in a turbulent manner, they are both pulled into the earth by gravity and spread by atmospheric activity like wind (Durisi et al. 2010). Three significant techniques of spraying— aerial spraying, surface application, and subsurface application —generally are utilised in the current agricultural growth process. However, many impoverished nations still implement hand sanitizer use (de Jong et al. 2008).

All pesticide application techniques have the risk of being ineffective, resulting in air pollution, and exposing the people to pesticides (Aktar et al. 2009). 25% of pesticide losses is down to drifting (Pan et al. 2020). This procedure has negative effects on the global environment in addition to causing pollution in the local area (Kim et al. 2017). For instance, pesticides were applied to farms in the southern United States, where they volatilized, were carried by atmospheric processes, condensed in cooler regions, and then were dropped from the sky into the Canadian Great Lakes (Sultana et al. 2014). As a result, the rate and distance of drifting pesticide residues make it very difficult to evaluate pesticide air pollution.

The use of pesticides in 3D crops, where spray is directed both upwards and laterally into the canopy by means of air support, leads to soil, water, and air contamination (Grella et al., 2017). Trees can not be considered a vertical plane which can be uniformly sprayed, therefore, applying airborne pesticide spray to 3D crop canopies, such as vineyards, is a complicated procedure (Walklate et al., 2003). The European Green Deal's which aligns policies for a more sustainable continent has set policies regarding the decrease in pesticide usage in agriculture by 50% by 2030 (European Commission, 2019).

5.4. Examples of PA management of pesticides

5.4.1 Pesticide utilisation under PA systems compared to conventional practice

Crop	Country	Year	Control	Savings	Reference
Apple/Pear	U.S.A	1999	Tree Row Volume	23.0%	(Doruchowski et al., 1999)
Apple	U.S.A	2013	Canopy/Foliage Based	73.0%	(Chen et al., 2013)
Apple	U.S.A	2009	Canopy Height Based	40.0%	(Landers, 2010)
Olive	Spain	2020	Tree Crown Volume	38.0%	(Lizana et al., 2021)
Vineyard	Spain	2007	Tree Row Volume	58.0%	(Gil et al., 2007)
Merlot	Spain	2012	Tree Row Volume	21.9%	(Gil et al., 2013)
Olive	Spain	2006	Tree Width	70.0%	(Solanelles et al., 2006)
Pear	Spain	2006	Tree Width	28.0%	(Solanelles et al., 2006)
Apple	Spain	2006	Tree Width	39.0%	(Solanelles et al., 2006)
Apple	Slovenia	2012	Tree Density	48.2%	(Stajnko et al., 2012)
Tempranillo	Spain	2010	Vine Row Volume	77.0%	(Llorens et al., 2010)
Apple	Slovenia	2011	Tree Row Volume	20.2%	(Jejcic et al., 2011)
Apple	Spain	2021	Tree Row Volume	60.7%	(Xun et al., 2022)
Orange	Spain	2017	Leaf Area Density	31.0%	(Garcera et al., 2017)
Vineyard	Spain	2009	Vine Row Volume	58.0%	(Llorens et al., 2010)
Vineyard	Spain	2019	Map-based	25.3%	(Roman, 2020)
Wheat	Germany	2001	Grass Weed Control	90%	(Timmermann et al., 2003)
Barley	Germany	2001	Grass Weed Control	78%	(Timmermann et al., 2003)
Sugar beet	Germany	2001	Grass Weed Control	36%	(Timmermann et al., 2003)
Wheat	Germany	2001	Broadleaf Weed Control	60%	(Timmermann et al., 2003)
Barley	Germany	2001	Broadleaf Weed Control	11%	(Timmermann et al., 2003)
Sugar beet	Germany	2001	Broadleaf Weed Control	41%	(Timmermann et al., 2003)
Corn	U.S.A	1999	Weed Control	42%	(Tian et al., 2000)
Cereals	Germany	1997	Weed Control	47-80%	(Tian et al., 2000)
Corn	U.S.A	1994	Real-time sensing	30-72%	(Mortensen et al., 1995)
Corn	U.S.A	1994	Broadleaf Weed Control	71%	(Mortensen et al., 1995)
Corn	U.S.A	1994	Grass Weed Control	94%	(Mortensen et al., 1995)
Cereals	Denmark	1996	Weed Control	47%	(Doruchowski et al., 1999)
Cereals	U.K	1996	Grass Weed Control	40-60%	(Chen et al., 2013)

Table 10: Collated research on pesticide savings using PA compared to conventional methods

5.4.2 Evaluation of PA effectiveness for pesticide use

PA offers a range of technologies that make it possible to lessen any environmental issues that might arise from pest control. These technologies include spatial/temporal field maps consisting of weed dispersion, a diagnostic tool of yield maps for weed impacts, and administering herbicide on regions of weed infestation through VRT. The same techniques may be used to treat weeds, illnesses, and insects (Hatfield, 2000). Before PA can be included into preferred pest control systems, pesticide management models must balance the costs of applying VRT with the advantages of lower herbicide expenses and the societal/environmental benefits of decreased herbicide use.

Weed density and soil characteristics that influence the transport of herbicides were studied for two years in a corn-soybean rotation plant in soil (Khakural et al., 1998). Runoff flow and silt content in several water bodies were detected using sensors with auto samplers to assess pesticide leaching. It was discovered that soil characteristics including pH, coefficient of pesticide adsorption, organic matter, weed density, and texture parameters all differed geographically.

Clay et al. (1998) studied a soybean field's weed spatial variability in the US. The efficiency of weed control, crop yield, and financial success were calculated and compared to a producer's general herbicide treatment at each location. The treatments consisted of computer-generated suggestions, the grower's customary application of herbicide, and an untreated control. The bio-economic model suggested solutions $82/ha cheaper than conventional producer practice, with superior yields, economic returns, and weed control - benefitting both the farmer and society.

Johnson et al. (1997) used a conceptual framework to show how site-specific weed control might improve environmental outcomes by using less pesticide overall. They demonstrated that spot treatments prevented the development of herbicide resistance. Johnson et al. (1995) discovered that employing VRT reduced the need for pesticides by 50%.

Heisel et al. (1996) used weed control strategies using PA to find herbicide savings of 66–75% compared to conventional recommendations for barley in Denmark. Throughout the research, the type of weed control strategy seemed to have an impact on pesticide savings. Figure … shows that in general, across multiple crops and regions, it was found that grass weed controls generally saved 73.6% of herbicide usage, compared to 42.4% for broadleaf weed control. For most crops in which broadleaf weed control was used, grass weed control could have been used instead – therefore, a recommendation is for farmers to prioritise grass weed as a control.

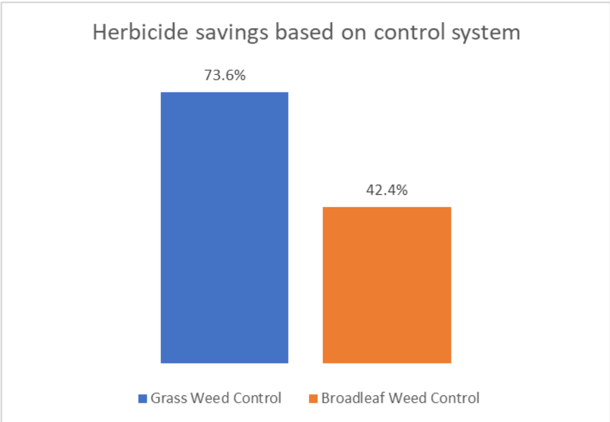

Figure 11: Comparison between different control systems in herbicide savings

In 12 Nebraska agricultural areas, Mortensen et al. (1994) performed geographic assessments of weed populations. Prior to the initial cultivation or postemergence herbicide treatment, they took samples of weed seedling populations in five soybean and seven corn fields. The findings showed that if herbicides were administered to existing populations, postemergence herbicide treatments for broadleaf and grass weeds may be decreased by 71% and 94%, respectively. They also calculated that, if in-row plant species recognition were achievable, real-time sensing might cut the usage of herbicides by an average of 30-72%. Haggar et al. (1983) predicted a postemergence VRT herbicide treatment would result in a 60% decrease. According to Shearer and Jones (1991), utilising a photoelectric sensor reduced the need for herbicides by 15%.

More than 9.7 Mha of crops in Europe are three-dimensional, including citrus, olives, and apples trees in and over 36 Mha globally (FAO, 2020). With 10.5 Mha globally, the olive tree is the most widely planted 3D crop in the world (FAO, 2020). Therefore, from an environmental and financial standpoint, applying precise dosages of pesticides to protect 3D crops becomes crucial (Román et al., 2020).

A lot of the research on prescription maps are for static VR pesti cide application (VRPA) (Garcia et al. 2022). Only a little amount of study has been done on the necessity for developing dynamic prescription maps that might take seasonal variations in crop growth and circumstances into account (Dietrich et al. 2014). To assess VRPA prescription maps or management zone creation incorporating various crop characteristics under various conditions, further study is needed. When planning pesticide applications and creating dynamic prescription maps, soil, crop information, soil, and other environmental variables may be obtained via distant/proximal sensors including thermal imaging or infrared sensors (Ahmed et al. 2016). To assess the feasibility of these type of prescription maps throughout growth season, further study must be done on how to combine such data and information.

6. Conclusion

This report has shown that widespread PA implementation is vital for agriculture moving forward. Benefits of increased yields and reduced inputs were shown in over 60 studies that focused on the comparison between PA and conventional farming practice. These studies have shown that field use efficiency of water, fertiliser, and pesticides were all significantly increased when PA was adopted across different regions globally and different crops (cereal and fruit).

In 12 studies regarding PA of irrigation, it was shown that VRI provided an average benefit of 28.5% water savings compared to that of URI – these water savings had no impact on yields and in some cases, even caused yields to increase by 2.8%. In 18 studies focused on the implementation of PA regarding fertiliser use the average economic improvement was $67.82/ha through either fertiliser savings or yield increase. In 29 studies based on PA of pesticides, through varying model control systems, an average pesticide saving of 50.0% was found. The key differences between the results of individual studies generally were found to be the site-specific topography for irrigation PA, the consideration of upfront technology costs for fertiliser PA, and different control systems for pesticide PA (such as grass weed control being more impactful than broadleaf weed control).

It is clear from the results that precision agriculture can significantly benefit both the environment and long-term economics for the farmer. However, the high upfront capital cost, complexity of the systems, and lack of farmer representation in research has led to a lack of technology adoption. For PA to be more incentivising for farmers, governments should provide short term intervention through subsidies and more research should be conducted at a larger and more realistic scale that will build farmer's trust to implement the technology. PA from a technical standpoint, certainly has proven its potential to push the agricultural sector forward to meet rising demand whilst lowering emissions – it is the adoption strategy that now must be coordinated between governments, organisations, and farmers to ensure that precision technology is widely implemented. As fertiliser prices continue to rise due to global issues, PA technologies will continue to gain popularity as field tests show better returns and farmers acknowledge the cost benefits of reduced inputs and maximised yields.

7. References

Adams, R.M.; McAdams, B.C.; Arnold, W.A.; Chin, Y.-P. (2016) Transformation of chlorpyrifos and chlorpyrifos-methyl in prairie pothole pore waters. Environ. Sci. Process. Impacts 2016, 18, 1406–1416.

Ahmad, W.; Noor, M.A.; Afzal, I.; Bakhtavar, M.A.; Nawaz, M.M.; Sun, X.; Zhou, B.; Ma, W.; Zhao, M. (2016) Improvement of Sorghum Crop through Exogenous Application of Natural Growth-Promoting Substances under a Changing Climate. Sustainability 2016, 8, 1330

Aktar, W.; Paramasivam, M.; Sengupta, D.; Purkait, S.; Ganguly, M.; Banerjee, S. (2008) Impact assessment of pesticide residues in fish of Ganga river around Kolkata in West Bengal. Environ. Monit. Assess. 2008, 157, 97–104.

Arregui LM, Lasa B, Lafarga A, Irañeta I, Baroja E, Quemada M (2006) Evaluation of chlorophyll meters as tools for N fertilization in winter wheat under humid Mediterranean conditions. European Journal of Agronomy 24(2):140–148. DOI: https://doi.org/10.1016/j.eja.2005.05.005

Ball, J. (2001) Soil and Water Relationships, The Samuel Robert Nobel Foundation. Available online: http://www.noble.org/Ag/Soils/SoilWaterRelationships/Index.htm

Barker, J.B.; Heeren, D.M.; Neale, C.M.U.; Rudnick, D.R. (2018) *Evaluation of variable rate irrigation using a remote-sensing-based model*. https://doi.org/10.1016/j.agwat.2018.02.022

Bartley R, Henderson A, Prosser IP, Hughes AO, McKergow LA, Lu H, Brodie J, Bainbridge Z, Roth CH (2003) *Patterns of erosion and sediment and nutrient transport in the Herbert River catchment, Queensland*. Nitrogen in Agriculture: Balancing the Cost of an Essential Resource | Annual Review of Environment and Resources (annualreviews.org)

Bausch, W.C.; Delgado, J.A. (2005) Impact of residual soil nitrate on in-season nitrogen applications to irrigated corn based on remotely sensed assessments of crop nitrogen status.

Ben Salem, F.; Ben Said, O.; Aissa, P.; Mahmoudi, E.; Monperrus, M.; Grunberger, O.; Duran, R. (2016) Pesticides in Ichkeul Lake–Bizerta Lagoon Watershed in Tunisia: Use, occurrence, and effects on bacteria and free-living marine nematodes. Environ. Sci. Pollut. Res. 2016, 23, 36–48.

Bernardes, M.F.F.; Pazin, M.; Pereira, L.C.; Dorta, D.J. (2015) Impact of Pesticides on Environmental and Human Health. In Toxicology Studies—Cells, Drugs and Environment; IntechOpen: London, UK, 2015; pp. 195–233.

Bindraban PS, Dimkpa CO, Pandey R (2020) *Exploring phosphorus fertilizers and fertilization strategies for improved human and environmental health.* https://doi.org/10. 1007/s00374-019-01430-2

Blackmore, B. S., Wheeler, P. N., Morris, J., Morris, R. M. and Jones, R.J.A. (1994) The role of precision farming in sustainable agriculture: A European perspective. In: Proceedings of the 2nd International Conference on Precision Agriculture. edited by P. C. Robert, R. H. Rust and W. E. Larson. (ASACSSA-SSSA. Madison, WI, USA) pp. 773–793.

Boenecke, E.; Lueck, E.; Ruehlmann, J.; Gruendling, R.; Franko, U. (2018) Determining the within-field yield variability from seasonally changing soil conditions. Precis. Agric. 2018, 19, 750–769.

Brubaker, S.C.; Jones, A.J.; Lewis, D.T.; Frank, K. (1993) *Soil Properties associated with landscape Position.* https://doi.org/10.2136/sssaj1993.03615995005700010041x

Clay, S., Lems, G., Clay, D., Ellsbury, M. and Forcella, F. (1998). Targeting Precision Agrochemical Applications to Increase Productivity. In: Proceedings of the 4th International Conference on Precision Agriculture, edited by P. C. Robert, R. H. Rust and W. E. Larson. (ASA-CSSA-SSSA. Madison, WI, USA) pp. 1699–1707.

Duncan, H.A. (2012) Locating the Variability of Soil Water Holding Capacity and Understanding Its Effects on Deficit Irrigation and Cotton Lint Yield. 2012. Available online: http://trace.tennessee.edu/utk_gradthes/1286

Đuriši´c-Mladenovi´c, N.; Škrbi´c, B.; Cvejanov, J. (2010) Organochlorine Pesticides in Soil and Sediment from an Urban Zone of Novi Sad, Serbia. In Survival and Sustainability: Environmental Concerns in the 21st Century; Springer: Berlin/Heidelberg, Germany, 2010; pp. 1469–1481.

de Jong, F.M.; de Snoo, G.R.; van de Zande, J.C. (2008) Estimated nationwide effects of pesticide spray drift on terrestrial habitats in the Netherlands. J. Environ. Manag. 2008, 86, 721–730.

De Schampheleire, M., Spanoghe, P., Brusselman, E., Sonck, S., (2007) Risk assessment of pesticide spray drift damage in Belgium. Crop Prot. 26, 602–611. https://doi.org/10.1016/j.cropro.2006.05.013.

Dietrich, J.P.; Van Gaest, A.L.; Strickland, S.A.; Arkoosh, M.R. (2014) The impact of temperature stress and pesticide exposure on mortality and disease susceptibility of endangered Pacific salmon. Chemosphere 2014, 108, 353–359.

European Commission, 2019. The European Green Deal. COM(2019) 640 final. Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640.

Evans, R.G.; King, B.A. (2012) *Site-specific sprinkler irrigation in a water-limited future.* https://elibrary.asabe.org/abstract.asp?aid=41382

Factbook (2019) *Nutrien Factbook 2019.* https://www.nutrien.com/sites/default/files/uploads/2019-05/Nutrien%20Fact%20Book%202019.pdf

FAO (2020b) *Global trends, statistics and insights for fertilizer.* https://www.nationmaster.com/nmx/sector/fertilizer

Fan LY. (2017). China Founds Pesticide Office to Combat Pollution, Overuse. http://www.sixthtone.com/news/1000987/china-founds-pesticide-office-to-combat-pollution%2C-overuse#.

Fonte, A., Garcerá, C., Tena, A., Chueca, P., (2020). CitrusVol validation for the adjustment of spray volume in treatments against Tetranychus urticae in Clementines. Agronomy https://doi.org/10.3390/agronomy10010032

Garcia, F.P.; Ascencio, S.Y.C.; Oyarzun, J.C.G.; Hernandez, A.C.; Alavarado, P.V. (2012) Pesticides: Classification, uses and toxicity. Measures of exposure and genotoxic risks. Int. J. Environ. Sci. Toxic. Res. 2012, 1, 279–293.

Gil, E., Escolà, A., (2009). Design of a decision support method to determine volume rate for vineyard spraying. Appl. Eng. Agric. 25, 145–152. https://doi.org/ 10.13031/2013.26323.

Guo XF, Zhang HF, Li JG. (2007) The importance of fungicides/bactericides in American agriculture. World Pesticides, 9(3): 21-25

Guzman, J.G.; Al-Kaisi, M.M. (2011) Landscape position effect on selected soil physical properties of reconstructed prairies in southcentral Iowa. J. Soil Water Conserv. 2011, 66, 183–191.

Hake, K.D.; Grimes, D.W. (2010) Crop Water management to optimize growth and yield. In Physiology of Cotton; Springer: Dordrecht, The Netherlands, 2010; pp. 255–264.

Hanna, A.Y.; Harlan, P.W.; Lewis, D.T. (1982) *Soil available water as influenced by landscape position and aspect.* https://doi.org/10.2134/agronj1982.00021962007400060016x

Hannah Ritchie and Max Roser (2013). *Fertilizers*. https://ourworldindata.org/fertilizers

Hatfield, J. (2000). Precision Agriculture and Environmental Quality: Challenges for Research and Education. National Soil Tilth Laboratory, Agricultural Research Service, USDA, Ames, Iowa. Document available at http://www.arborday.org.

Hayes, T.B.; Hansen, M.; Kapuscinski, A.R.; Locke, K.A.; Barnosky, A. (2017) From silent spring to silent night: Agrochemicals and the anthropocene. Elem Sci Anth 2017, 5, 1–24.

Heisel, T., Christensen, S. and Walter, A. (1996). Weed managing model for patch spraying in cereal. In: Proceedings of the 3rd International Conference on Precision Agriculture. edited by P. C. Robert, R. H. Rust and W. E. Larson. (ASA- CSSA- SSSA. Madison, WI, USA) pp. 999–1007

Howarth RW (2008) *Coastal nitrogen pollution: a review of sources and trends globally and regionally.* https://doi.org/10.1016/j.hal.2008.08.015

Hruška, J.; Adão, T.; Pádua, L.; Marques, P.; Cunha, A.; Peres, E.; Sousa, A.; Morais, R.; Sousa, J.J. (2018) *Machine learning classification methods in hyperspectral data processing for agricultural applications.* https://dl.acm.org/doi/10.1145/3220228.3220242

IFA (2019) Fertilizer Outlook 2019–2023. Annual Conference, Montreal, 11–13 June 2019. PIT, Market Intelligence and Agriculture Services, IFA. https://api.ifastat.org/reports/download/12620.

l-Jamal MS, Ball S and Sammis TW. (2001) Comparison of sprinkler, trickle and furrow irrigation efficiencies for onion production. https://doi.org/10.1016/S0378-3774(00)00089-5

Johnston AE, Poulton PR, Fixen PE, Curtin D (2014) Phosphorus https://doi.org/10.1016/B978-0-12-420225-2.00005-4

Johnson, G., Cardina, J. and Mortensen, D. (1997). Site-specific weed management: current and future directions. In: The State of Site-Specific Management for Agriculture. edited by F. Pierce and E. Sadler. (ASA-CSSA-SSSA, Madison, WI., USA). Chapter 7, pp. 131–147.

J. Hilton, A.E. Johnston, C.J. Dawson. (2010) The phosphate life-cycle: rethinking the options for a finite resource.

Jiang, P.; Thelen, K.D. (2004) *Effect of soil and topographic properties on crop yield in a north-central corn-soybean cropping system.* https://doi.org/10.2134/agronj2004.0252

Khan MI, Shoukat MA, Cheema SA, Arif HN, Niazi NK, Azam M, Bashir S, Imran Ashraf I, Qadri R (2020) Contamination and exposure of pesticides in Pakistan: a review. Pak J Agric Sci 57 (1):131–149

Khakural, B., Robert, P., Mulla, D., Oliveira, R., Johnson, G. and Koskinen, W. (1998). Site-specific herbicide management for preserving water quality. In: Proceedings of the 4th International Conference on Precision Agriculture. edited by P. C. Robert, R. H. Rust and W. E. Larson. (ASA-CSSA-SSSA. Madison, WI, USA). pp. 1719–1731.

Khosla, R. (2010) *Precision agriculture: Challenges and opportunities in a flat world*. https://www.iuss.org/19th%20WCSS/Symposium/pdf/0779.pdf

King, B.A.; Stark, J.C.; Wall, R.W.; Stark, J.C.; Wall, R.W. (2006) Comparison of Site-Specific and Conventional Uniform Irrigation Management for Potatoes. http://dx.doi.org/10.13031/2013.22000

King, B.A.; Wall, R.W.; Karsky, T.F. (2009) Center-pivot irrigation system for independent site-specific management of water and chemical application.

Kitchen NR, Sudduth KA, Drummond ST, Scharf PC, Palm HL, Roberts DF, Vories ED (2010) Ground-based canopy reflectance sensing for variable-rate nitrogen corn fertilization. Agron J 102:71–84. doi:10.2134/agronj2009.0114

Kitchen, N.R.; Hughes, D.F.; Sudduth, K.A.; Birrell, S.J. (1995) *Comparison of variable rate to single rate nitrogen fertiliser application: Corn production and residual soil NO3-N.* https://doi.org/10.2134/1995.site-specificmanagement.c29

Kim, K.-H.; Kabir, E.; Jahan, S.A. (2017) Exposure to pesticides and the associated human health effects. Sci. Total Environ. 2017, 575, 525–535.

Kole RK, Banerjee H, Bhattacharyya A (2001) Monitoring of market fish samples for Endosulfan and Hexachloro cyclohexane residues in and around Calcutta. Bull Environ Contam Toxicol 67:554–559

Kapsi M, Tsoutsi C, Paschalidou A, Albanis T (2019) Environmental monitoring and risk assessment of pesticide residues in surface waters of the Louros River (N.W. Greece). Sci Total Environ 650:2188–2198. https://doi.org/10.1016/j.scitotenv.2018.09.185

Kaspar, T.C.; Colvin, T.S.; Jaynes, D.B.; Karlen, D.L.; James, D.E.; Meek, D.W.; Pulido, D.; Butler, H. (2003) Relationship between six years of corn yields and terrain attributes. Precis. Agric. 2003, 4, 87–101.

Kotschi J (2015) *Adverse impacts of mineral fertilizers in tropical agriculture, a soiled reputation.* https://www.boell.de/en/content/soiled-reputation-adverse-impacts-mineral-fertilizers-tropical-agriculture

Kravchenko, A.N.; Bullock, D.G. (2000) *Correlation of corn and soybean grain yield with topography and soil properties*. https://doi.org/10.2134/agronj2000.92175x

Lamichhane, J.R. (2017) Pesticide use and risk reduction in European farming systems with IPM: An introduction to the special issue. Crop. Prot. 2017, 97, 1–6.

Lamaddalena N,Fratino U and Daccache A. (2007) On-farm sprinkler irrigation performance as affected by the distribution system. https://doi.org/10.1016/j.biosystemseng.2006.09.002

Langenbach, T.; Mano, D.; Campos, M.M.; Cunha, A.L.; De Campos, T.M. (2017) Pesticide dispersion by spraying under tropical conditions. J. Environ. Sci. Health Part B 2017, 52, 843–849.

Larson, W., Lamb, J., Khakural, B., Ferguson, R. and Rehm, G. (1997) Potential of Site-Specific Management for Nonpoint Environmental Protection. In: The State of Site-Specific Management for Agriculture. edited by F. Pierce and E. Sadler, (ASA-CSSA-SSSA, Madison, Wisconsin, 1997), Chapter 15, pp. 337–367.

Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., & Garnier, J. (2014). *Lassal Environmental Research* https://iopscience.iop.org/article/10.1088/1748-9326/9/10/105011/meta

Lindblom, J.; Lundström, C.; Ljung, M.; Jonsson, A. (2017) *Promoting sustainable intensification in precision agriculture: Review of decision support systems development and strategies*. https://link.springer.com/article/10.1007/s11119-016-9491-4

Liu J, You L, Amini M, Obersteiner M, Herrero M, Zehnder AJB, Yang H (2010) A high-resolution assessment on global nitrogen fows in cropland. https://doi.org/10.1073/pnas.0913658107

Liu, Y.; Mo, R.; Tang, F.; Fu, Y.; Guo, Y. (2015) Influence of different formulations on chlorpyrifos behavior and risk assessment in bamboo forest of China. Environ. Sci. Pollut. Res. 2015, 22, 20245–20254.

Ma B-L, Wu T-Y, Shang J (2014) On-farm comparison of variable rates of nitrogen with uniform application to maize on canopy reflectance, soil nitrate, and grain yield. Journal of Plant Nutrition and Soil Science 177(2): 216– 226. DOI: https://doi.org/10.1002/jpln.201200338

Mauget, S.; Leiker, G.; Nair, S. (2013) *A web application for cotton irrigation management on the U.S. Southern High Plains. Part I: Crop yield modeling and profit analysis.* http://dx.doi.org/10.1016/j.compag.2013.10.003

Mauget, S.A.; Adhikari, P.; Leiker, G.; Baumhardt, R.L.; Thorp, K.R.; Ale, S. (2017) *Modeling the effects of management and elevation on West Texas dryland cotton production.* https://www.sciencedirect.com/science/article/abs/pii/S0168192317302253

Mazlan, N.; Ahmed, M.; Muharam, F.M.; Alam, M.A. (2017) Status of persistent organic pesticide residues in water and food and their effects on environment and farmers: A comprehensive review in Nigeria. Semin.-Cienc. Agrar. 2017, 38, 2221–2236.

McBratney, A.; Whelan, B.; Ancev, T.; Bouma, J. (2005) *Future directions of precision agriculture*. https://link.springer.com/article/10.1007/s11119-005-0681-8

McCarthy, A.C.; Hancock, N.H.; Raine, S.R. (2014) *Development and simulation of sensor-based irrigation control strategies for cotton using the VARI wise simulation framework.* https://doi.org/10.1016/j.compag.2013.12.014

McGuire, V.L. (2014) *Water-level changes and change in water in storage in the High Plains aquifer, predevelopment to 2013 and 2011–2013.* https://pubs.er.usgs.gov/publication/sir20145218

Miller, K.A.; Luck, J.D.; Heeren, D.M.; Lo, T.; Martin, D.L.; Barker, J.B. (2017) *A geospatial variable rate irrigation control scenario evaluation methodology based on mining root zone available water capacity*. https://link.springer.com/article/10.1007/s11119-017-9548-z

Miraglia, M.; Marvin, H.; Kleter, G.; Battilani, P.; Brera, C.; Coni, E.; Cubadda, F.; Croci, L.; De Santis, B.; Dekkers, S.; et al. (2009) Climate change and food safety: An emerging issue with special focus on Europe. Food Chem. Toxicol. 2009, 47, 1009–1021.

Mogollon JM, Beusen AHW, van Grinsven HJM, Westhoek H, Bouwman AF (2018) Future agricultural phosphorus demand according to the shared socioeconomic pathways. https://doi.org/10.1016/j.gloenvcha.2018.03.007

Mortensen, D., Johnson, G., Wyse, D. and Martin, A. (1994). Managing spatially variable weed population. In: site-specific management for agricultural systems. Proceedings of the 2nd International Conference on Precision Agriculture. edited by P. C. Robert, R. H. Rust and W. E. Larson. (ASA-CSSA-SSSA. Madison, WI, USA) pp. 397–415.

Mosier A, Bleken M, Chaiwanakupt P, Elllis EC, Freney JR, Howrath RB, Matson PA, Minami K, Naylor R, Weeks KN, Zhu ZL (2001) *Policy implications of human-accelerated nitrogen cycling.* Policy implications of human-accelerated nitrogen cycling | SpringerLink

Nijbroek, R.; Hoogenboom, G.; Jones, J.W. (2003) *Optimizing irrigation management for a spatially variable soybean field.* https://doi.org/10.1016/S0308-521X(02)00127-0

Neupane, J.; Guo, W. (2019) Agronomic Basis and Strategies for Precision Water Management: A Review. *Agronomy* **2019**, *9*, 87. https://doi.org/10.3390/agronomy9020087

Oenema O, van Liere L, Schoumans O (2005) *Effects of lowering nitrogen and phosphorus surpluses in agriculture on the quality of groundwater and surface water in the Netherlands.* https://doi.org/10.1016/j.jhydrol.2004.07.044

O'Shaughnessy, S.A.; Rush, C. (2014) *Precision agriculture: Irrigation. In Encyclopedia of Agriculture and Food System.* https://ia903402.us.archive.org/7/items/encyclopedia_202104/Encyclopedia of Agriculture and Food Systems_compressed.pdf

O'Shaughnessy, S.A.; Evett, S.R.; Colaizzi, P.D. (2015) Dynamic prescription maps for site-specific variable rate irrigation of cotton. https://doi.org/10.1016/j.agwat.2015.06.001

Pan, D.; He, M.; Kong, F. (2020) Risk attitude, risk perception, and farmers' pesticide application behavior in China: A moderation and mediation model. J. Clean. Prod. 2020, 276, 124241.

Pedersen SM, Fountas S, Blackmore S, Pedersen JL, Pedersen HH. (2003) *Adoption of precision farming in Denmark.* https://www.cabdirect.org/cabdirect/abstract/20033117780

Pedersen, S.M., Lind, K.M. (2017). Precision Agriculture – From Mapping to Site-Specific Application. In: Pedersen, S., Lind, K. (eds) Precision Agriculture: Technology and Economic Perspectives. Progress in Precision Agriculture. Springer, Cham. https://doi.org/10.1007/978-3-319-68715-5_1

Pedersen, S.M., Lind, K.M. (2017) *Precision Agriculture – From Mapping to Site-Specific Application.* https://doi.org/10.1007/978-3-319-68715-5_1

Pimentel D. (1997) Techniques for Reducing Pesticide Use: Environmental and Economic Benefits. John Wiley and Sons, Chichester, USA

Pimentel D. (2009a) Pesticides and pest control. In: Integrated Pest Management: Innovation-Development Process (Vol. 1) (Rajinder P, Dhawan A, eds). 83-87, Springer, Netherlands

Pimentel D. (2009b) Environmental and economic costs of the application of pesticides primarily in the United States. In: Integrated Pest Management: Innovation-Development Process (Vol. 1) (Rajinder R, Dhawan A, eds). 88-111, Springer, Netherlands

Plant RE (2001) Site-specific management: the application of information technology to crop production. Comput Electron Agric 30:9– 29

Price, J. A., Workneh, F., Evett, S. R., Jones, D. C., Arthur, J., & Rush, C. M. (2010). *Effects of wheat streak mosaic virus on root development and water-use efficiency of hard red winter wheat.* https://doi.org/10.1094/pdis-94- 6-0766

Quinn R (2020) Global fertilizer outlook – 6 global fertilizer demand bright. https://www.dtnpf.com/agriculture/web/ag/crops/article/2020/01/03/global-fertilizer-demand-bright

Redulla, C., Havlin, J., Kluitenberg, G., Zhang, N. and Schrock, M. (1996) Variable N management for improving groundwater quality. In: Proceedings of the 3rd International Conference on Precision Agriculture. edited by P. C. Robert, R. H. Rust and W. E. Larson. (ASA-CSSA-SSSA. Madison, WI, USA) pp. 1101–1110.

Reuters (2010) *China needs to cut use of chemical fertilizers: research.* https://www.reuters.com/article/us-china-agriculture-fertiliser/china-needs-to-cut-use-of-chemical-fertilizers-researchidUSTRE60D20T20100114

Robertson GP, Groffman PM (2009) *Nitrogen in agriculture: balancing the cost of an essential resource. https://www.annualreviews.org/doi/abs/10.1146/annurev.environ.032108.105046*

Rose, C.E.; Coupe, R.H.; Capel, P.D.; Webb, R.M. (2018) Holistic assessment of occurrence and fate of metolachlor within environmental compartments of agricultural watersheds. Sci. Total Environ. 2018, 612, 708–719.

Sadler, E.J.; Evans, R.G.; Stone, K.C.; Camp, C.R. (2005) *Opportunities for conservation with precision irrigation*. https://www.jswconline.org/content/60/6/371

Schepers, A.R.; Shanahan, J.F.; Liebig, M.A.; Schepers, J.S.; Johnson, S.H.; Luchiari, A. (2004) *Appropriateness of management zones for characterizing spatial variability of soil properties and irrigated corn yields across years.* https://acsess.onlinelibrary.wiley.com/doi/abs/10.2134/agronj2004.1950

Shukla S, Saxena A (2018) Global status of nitrate contamination in groundwater: its occurrence, health impacts, and mitigation measures. https://doi.org/10.1007/978-3-319-58538-3_20-1

Sigua, G. C., Stone, K. C., Bauer, P. J., Szogi, A. A., & Shumaker, P. D. (2017). *Impacts of irrigation scheduling on pore water nitrate and phosphate in coastal plain region of the United States.* Agric. Water Manag., 186, 75-85. https://doi.org/10.1016/j.agwat.2017.02.016

Singh NS, Sharma R, Parween T, Patanjali PK (2018) Pesticide contamination and human health risk factor. In: Oves M et al (eds) Modern age environmental problems and their remediation, pp 49–68. https://doi.org/10.1007/978-3-319-64501-8-3

Silva, J.R.M.; Silva, L.L. (2008) Evaluation of the relationship between maize yield spatial and temporal variability and different topographic attributes. Biosyst. Eng. 2008, 101, 183–190

Skowroñska M, Filipek T (2014) *Life cycle assessment of fertilizers: a review.* https://doi.org/10.2478/intag-2013-0032

Smil V (2004) Enriching the earth: Fritz Haber, Carl Bosch, and the transformation of world food production. https://mitpress.mit.edu/books/enriching-earth

Solanelles, F., Escolà, A., Planas, S., et al., (2006). An electronic control system for pesticide application proportional to the canopy width of tree crops. Biosyst. Eng. 95, 473–481. https://doi.org/10.1016/j.biosystemseng.2006.08.004.

Song X, Wang J, Huang W, Liu L, Yan G, Pu R (2009) The delineation of agricultural management zones with high resolution remotely sensed data. Precis Agric 10:471–487. doi:10.1007/s11119-009-9108-2

Sultana, J.; Syed, J.H.; Mahmood, A.; Ali, U.; Rehman, M.Y.A.; Malik, R.N.; Li, J.; Zhang, G. (2014) Investigation of organochlorine pesticides from the Indus Basin, Pakistan: Sources, air–soil exchange fluxes and risk assessment. Sci. Total Environ. 2014, 497, 113–122.

Tirado, M.; Clarke, R.; Jaykus, L.; McQuatters-Gollop, A.; Frank, J. (2010) Climate change and food safety: A review. Food Res. Int. 2010, 43, 1745–1765

Thenkabail PS, Knox JW, Ozdogan M, Gumma MK, Congalton R,Wu Z,et al. (2012) Assessing future risks to agricultural productivity, water resources and food security: how can remote sensing help? https://www.researchgate.net/publication/232735085_Assessing_future_risks_to_agricultural_productivity_water_resources_and_food_security_How_can_remote_sensing_help

Thrikawala, S., Weersink, A., Kachanoski, G. and Fox, G. (1999) ''Economic feasibility of variable rate technology for nitrogen on corn''. American Journal of Agricultural Economics 81, 914–927.

Tudi, M.; Daniel Ruan, H.; Wang, L.; Lyu, J.; Sadler, R.; Connell, D.; Chu, C.; Phung, D.T. (2021) Agriculture Development, Pesticide Application and Its Impact on the Environment. https://doi.org/10.3390/ijerph18031112

United Nations. (2017) *World Population Prospects: The 2017 Revision, Key Findings and Advance Tables.* https://population.un.org/wpp/publications/files/wpp2017_keyfindings.pdf

van Drecht G, Bouwman AF, Knoop JM, Meinardi C, Beusen A (2001) Global pollution of surface waters from point and nonpoint sources of nitrogen. https://doi.org/10.1100/tsw.2001.326

Villalba G, Liu Y, Schroder H, Ayres RU (2008) Global phosphorus flows in the industrial economy from a production perspective. https://doi.org/10.1111/j.1530-9290.2008.00050.x

Von der Leyen, U., (2019) A union that strives for more. My agenda for Europe. https://ec. europa.eu/commission/sites/beta-political/files/political-guidelines-next-commission_en.pdf.

Wang C, Wang X, Liu D, Wu H, Lü X, Fang Y, Yin H (2014) *Aridity threshold in controlling ecosystem nitrogen cycling in arid and semi-arid grasslands. https://www.nature.com/articles/ncomms5799*

Workneh, F., O'Shaughnessy, S., Evett, S., & Rush, C. M. (2017). *Relationships between early wheat streak mosaic severity levels and grain yield: Implications for management decisions.* https://doi.org/10.1094/pdis-02-17-0176-re

Zhang X, Shi L, Jia X, Seielstad G, Helgason C (2010) Zone mapping application for precision-farming: a decision support tool for variable rate application. Precis Agric 11:103–114. doi:10.1007/s11119-009-9130-4

Zhang WJ. (2011) Constructing ecological interaction networks by correlation analysis: hints from community sampling. Network Biology, 1(2): 81-98

Zhang W, Jiang F, Ou J. (2011). Global pesticide consumption and pollution: With China as a focus. (1) (PDF) Global pesticide consumption and pollution: With China as a focus (researchgate.net)

Zhu L, Yang H, Zhao Y, Kang K, Liu Y, He P, Wei Z (2019) *Biochar combined with montmorillonite amendments increase bioavailable organic nitrogen and reduce nitrogen loss during composting.* https://www.sciencedirect.com/science/article/abs/pii/S0960852419314543