

July 2016



## **Research Review No. 87**

# A review of the past, present and future of precision agriculture in the UK

Sajjad Awan

Agriculture and Horticulture Development Board, Stoneleigh Park, Kenilworth CV8 2TL

While the Agriculture and Horticulture Development Board seeks to ensure that the information contained within this document is accurate at the time of printing, no warranty is given in respect thereof and, to the maximum extent permitted by law, the Agriculture and Horticulture Development Board accepts no liability for loss, damage or injury howsoever caused (including that caused by negligence) or suffered directly or indirectly in relation to information and opinions contained in or omitted from this document.

Reference herein to trade names and proprietary products without stating that they are protected does not imply that they may be regarded as unprotected and thus free for general use. No endorsement of named products is intended, nor is any criticism implied of other alternative, but unnamed, products.

AHDB Cereals & Oilseeds is a part of the Agriculture and Horticulture Development Board (AHDB).



# CONTENTS

<b>1.</b>	<b>ABSTRACT .....</b>	<b>2</b>
<b>2.</b>	<b>INTRODUCTION .....</b>	<b>3</b>
<b>3.</b>	<b>PRECISION AGRICULTURE: THE COMPONENTS.....</b>	<b>4</b>
	<b>3.1. Information .....</b>	<b>4</b>
	3.1.1. Machine to machine communication.....	4
	3.1.2. Information management .....	5
	3.1.3. Data interpretation.....	5
	<b>3.2. Spatial data .....</b>	<b>5</b>
	3.2.1. Satellite navigation system.....	5
	3.2.2. Geographic Information Systems .....	6
	3.2.3. Proximal sensing.....	6
	3.2.4. Remote sensing .....	7
	<b>3.3. Yield monitoring and mapping .....</b>	<b>8</b>
	<b>3.4. Addressing variability.....</b>	<b>9</b>
	3.4.1. Soil characteristics .....	9
	3.4.2. Water and nutrients.....	10
	3.4.3. Variable rate technology (VRT).....	11
<b>4.</b>	<b>THE ECONOMIC BENEFITS OF PRECISION AGRICULTURE .....</b>	<b>11</b>
<b>5.</b>	<b>FUTURE RESEARCH AND DEVELOPMENT IN PA .....</b>	<b>13</b>
	<b>5.1. Inclusion of historical data for image/map analysis.....</b>	<b>13</b>
<b>6.</b>	<b>KEY CHALLENGES AND KNOWLEDGE GAPS.....</b>	<b>14</b>
<b>7.</b>	<b>REFERENCES .....</b>	<b>15</b>

## LIST OF ABBREVIATIONS

ADIS	Agricultural Data Interchange Standard
CTF	Controlled Traffic Farming
DGPS	Differential Global Positioning System
GIS	Geographic Information System
GLONASS	Global Navigation Satellite System (Russian system)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSM	Global System for Mobile communication
HypIRI	Hyperspectral Infrared Imager
LAI	Leaf Area Index
LiDAR	Light Detection and Ranging
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
PA	Precision Agriculture
PaRS	Photogrammetry and Remote Sensing
PEU	Perceived ease of use
SSCM	Site Specific crop Management
UAV	Unmanned Aerial Vehicle
VRT	Variable Rate Technology

## 1. Abstract

Precision agriculture (PA) as a crop management concept has the potential to address many of the increasing environmental, economic and public pressures on arable farming. Benefits are attained due to increased yields and/or reduced costs through the efficient use of resources. PA, therefore, contributes to the wider goal of sustainable intensification.

One of the key features of PA comes from satellite-controlled positioning systems, principally Global Navigation Satellite Systems (GNSS) that are a major enabler of 'precision systems'. Automatic steering systems are the most successful applications on arable land, showing clear benefits to the farmers, and there is increasing uptake of Controlled Traffic Farming (CTF) to minimise soil compaction. Development of sensor technology and access to new and historical datasets is enabling extension of PA into Variable Rate Technology (VRT), e.g. for optimising fertiliser and pesticide use. At present, the success rate varies significantly depending on the site-specific factors of application but substantial improvements are likely as technology develops.

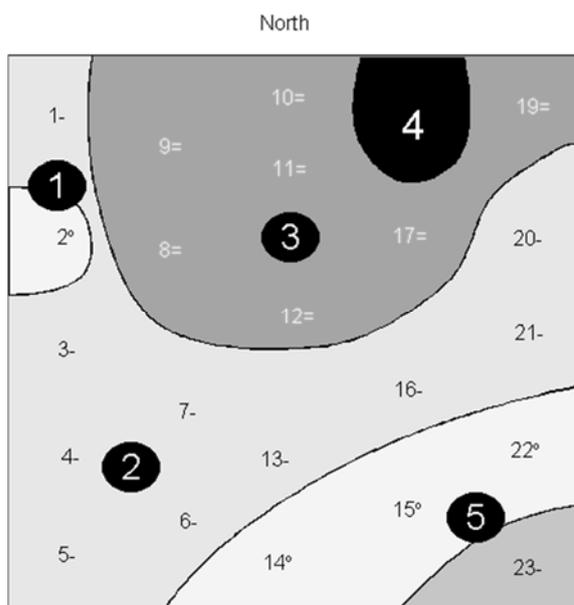
This brief review reaffirms that PA can play an important role in the UK to meet the increasing demand for food, feed, and raw materials while delivering sustainable intensification. Nevertheless, the adoption of PA presents specific challenges due to the sizes and diversity of farm structures. An assessment of the potential actions to support the adoption of PA has highlighted some key knowledge gaps including, but not limited to, the ease of use of the technology, reliability and cost effectiveness.

## 2. Introduction

An expanding human population, anticipated resource limitation, climate change projections and tougher environmental regulations are putting intense pressure on crop production systems. This pressure is driving innovation through investment in new precision agriculture (PA) technologies aimed at increasing crop production efficiency while mitigating environmental impacts. PA can deliver targeted input applications and it also helps in quantifying sowing, fertilising and spraying according to variation in soil characteristics and plant populations.

There are many definitions and applications of PA; it can vary from farm to farm, but revolves around site-specific crop management (SSCM). In general, it can be defined as “an integrated information and production based farming system that can increase the crop resource use efficiency, productivity and profitability and reduce the environmental risks associated with the farming practices” (Whelan and Taylor, 2013). According to Batte and Van Buren (1999), SSCM is not a single technology but an integration of technologies permitting the collection of data on an appropriate time scale.

Precision agriculture is based on the fact that soils and growing conditions are subject to considerable variation, even within very small plots. The earliest (to the author’s knowledge) publication on precision farming (Linsley and Bauer, 1929) noted that "the soils of this state, often within a field, vary widely in their need for limestone" (Figure 1) and "it is important, therefore, that detailed tests be made of the field so that limestone may be applied according to the need for it."



"The soils of this state, often within a single field, vary widely in their need for limestone," and "It is important, therefore, that systematic and detailed tests be made of the field so that limestone may be applied according to the need for it."

C. M. LINSLEY and F. C. BAUER in their 1929 circular No. 346 from the University of Illinois

**Figure 1.** Reproduced from the first publication concerning precision farming (Linsley and Bauer, 1929).

Technology used in PA is developing rapidly. This is evident by the number and diversity of publications in international journals presentations at international conferences (Khosla, 2010).

PA adoption is based on a systems approach, encompassing all aspects of farming to deliver low-input, high-efficiency, sustainable agriculture (Shibusawa, 1998). It also benefits from the development and coherent use of several technologies, including the Global Positioning System (GPS), Geographic Information System (GIS), miniaturised computer components, automatic control, variable rate, in-field and remote sensing, mobile computing, advanced information processing, and telecommunications (Gibbons, 2000).

It is, however, important to observe that after more than two decades of development, PA has reached a crossroads with much of the necessary technology available but with the environmental and economic benefits yet to be quantified. While there is no lack of technological innovations, the development of agronomic and ecological principles for optimised recommendations for inputs at the localised level is generally lacking. Many farmers in the UK are uncertain whether to adopt available PA technologies on their farms. However, the main driver for widespread uptake of PA technologies might well come from concerns over use of agrochemicals and ever-stricter environment legislations.

This review aims to provide an updated review of the application of PA specifically in cereals and oilseeds by exploring its current uses and limitations, including uses of sensors either remotely or proximal (e.g. in the soil), and data processing issues. In addition, advances in PA are discussed, highlighting key knowledge gaps. Although this article is limited to arable systems, the critical analysis of the information gathered is relevant to grazing and horticulture.

### **3. Precision agriculture: the components**

#### **3.1. Information**

##### **3.1.1. Machine to machine communication**

In PA there are some serious issues with compatibility between farm instruments and tractors. Vast majority of these instruments are often only compatible with other tractors of the same brand due to the proprietary file formats. This forces farmers to use different ISOBUS boxes in their tractors to standardise the communication between the tractor and the instruments.

In order to tackle these issues, the agricultural industry decided to bring in a standard operational language that all implements and machines must follow. Early PA systems underwent several format changes which resulted in the publication of ISO 11783, the Agricultural Data Interchange Standard (ADIS), but this system had flaws and failed to deliver (Speckmann and Jahns, 1999).

Further development resulted in ISO 11787, currently used by some (but not all) manufacturers. Despite nearly two decades of further progress, no fully adopted standard exists.

### **3.1.2. Information management**

Collection of information on variables, such as soil, and interpretation of soil analyses and yield maps can be expensive and time consuming (Sanchez, Ramalho *et al.*, 2015). It is crucial to know how this information can benefit crop production and overall decision-making, for instance some fields require little information to determine the cause of yield variability (rolling topography) while other fields require extensive data collection and, even then yield variation may still be unexplained.

In addition to this, a huge amount of PA data has been accumulated and there is a serious problem of 'data overflow'. For the spatial/temporal information that has been collected, there is an urgent need for tools specifically designed for data management and interpretation.

### **3.1.3. Data interpretation**

Advances in information and telecommunication technologies have allowed farmers to acquire vast amounts of site-specific data for their fields, with the ultimate potential being to reduce uncertainty in decision-making (Blackmore, 2000a). As PA is intrinsically information-intensive, farmers face many difficulties in efficiently managing the enormous amount of data they collect. They may also lack the skills and sufficient time needed to analyse the data and critically interpret the information. In order to reap the benefits from PA, there is a clear need to develop additional skills and knowledge concerning how to use the large, heterogeneous data sets and information gathered to assess the effects of weather and soil properties on crop production, and to develop management plans to increase efficiency and adjust inputs in following years (Cui, 2013).

## **3.2. Spatial data**

### **3.2.1. Satellite navigation system**

The best-known network of navigation satellites is the US-owned Global Positioning System (GPS). This network consists of three parts: the satellites, a control station on the ground and a receiving device. A GPS receiver/antenna can be placed on any piece of agricultural machinery and can provide accurate location information in terms of latitude and longitude (Stafford, 1996). The GPS or Differential GPS (GPS with improved location accuracy) is the "backbone" of most PA practices (Auernhammer *et al.*, 1995).

Since GPS was made available for non-military use, two further satellite navigation systems have been launched; GLONASS, the Russian equivalent of GPS through its military background, and Galileo, a civilian EU-owned satellite-based navigation system consisting of 30 satellites. By using

a combined Galileo-GPS-GLONASS system, higher positioning accuracy is possible (Luccio, 2014). By 2020, from most European locations, six to eight Galileo satellites will be visible which, in combination with GPS and GLONASS signals, will allow positions to be determined to within a few centimetres, depending on the service used (Li *et al.*, 2015).

High-precision navigation systems enable the use of Controlled Traffic Farming (CTF), which minimises compaction by ensuring machinery uses exactly the same tracks in the field, year in/year out. This helps to avoid environmental problems associated with soil compaction and considerably reduces energy for cultivation. As a result, yields can also be up to 5% higher (Hallett *et al.*, 2012).

It is essential for the success of any site-specific operation that any action is recorded and accurately referenced, so that the information could be used to inform future treatment decisions. The GPS/DGPS makes it possible to record the in-field variability as geographically encoded data (Nemenyi *et al.*, 2003). By using the geographical positioning system it is possible to locate the information for further analysis and make a visual presentation in a Geographic Information System (GIS).

### **3.2.2. Geographic Information Systems**

These are a set of computer tools that allow users to work with data that are tied to a particular location or spatially mapped area on a farm (Price, 2006). It also makes it possible to generate a complex view about fields and to make valid agro-technological decisions (Pecze, 2001). Most available GIS technology is reliable but also fairly expensive, depending on the features and capabilities of the program.

GIS allows for multiple detailed data to be graphically depicted on a map and utilised for decision making. Although farmers have long utilised maps for data collection and decision making, the difference with applying the advanced technology of GIS is that these interactive maps can exhibit “intelligence” where you can ask questions and get answers.

### **3.2.3. Proximal sensing**

Ground based proximal sensors are generally mounted on agricultural machinery and are able to collect valuable information on spatial variation within a field. Proximal sensors began to emerge in early 1990s and one of the most important components of proximal sensing was soil sensing. It envisaged a continuous real-time sensing of spatial variations in soil properties using sensors mounted on tractors. One of the first applications of proximal soil sensors was by Sudduth and Hummel (1993), this near infra-red (NIR) sensor was able to detect soil moisture levels as well as organic matter contents.

Adamchuck *et al.* (2004) reviewed then available proximal sensors and categorised these into six classes; electrical and electromagnetic, acoustic, optical and radiometric, mechanical, pneumatic and electromechanical (Adamchuck, et al., 2004).

One of the major benefits of proximal sensing is its ability to quantify the heterogeneity of soil within a field (Fystro, 2005). However, the integration of different sensing systems in multisensory platforms (both proximal and remote) may allow better prediction of agronomic soil attributes.

#### **3.2.4. Remote sensing**

Remote sensing is the process of acquiring information about the earth's surface without actually coming in contact with it. This is done by recording energy, which is either reflected or emitted from the earth's surface (Elarab, Ticlavilca et al. 2015). It allows detection and/or characterisation of an object, series of objects, or the landscape without having the sensor in physical contact with the soil. This technology can be used to obtain various layers of information about soil and crop conditions. It uses aerial or satellite imaging to sense crop vegetation and identify crop stresses and injuries, or pest infestations. Some of the tools used in remote sensing are described below:

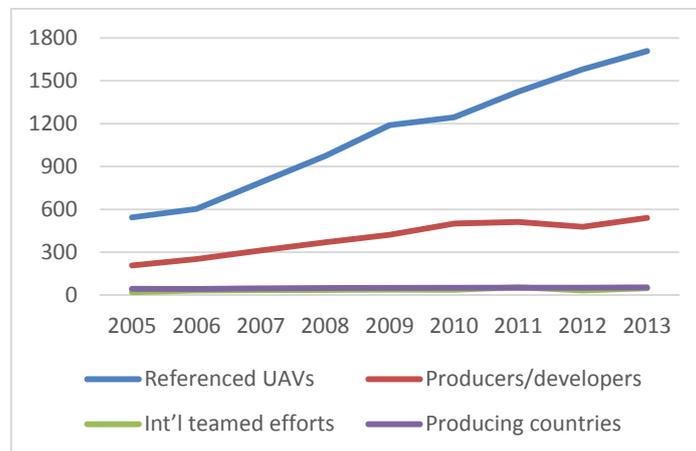
1. Conventional aeroplanes: images can be used to map the spatial variability of biotic and abiotic parameters on agricultural plots at spatial resolutions of 0.25–0.50 m (Stereocarto, 2010). Natural Environment Research Council (NERC) UK have also been involved in mapping soil heterogeneity in the UK with Cranfield University by using fixed wing aircraft.
2. Unmanned aerial vehicles (UAVs), which fly at low altitudes, have been developed by commercial companies (UAV, 2010) to provide high spatial resolution images, with the advantage of autonomous management and ability to work in cloudy days. In recent years there has been a huge increase in the production of UAVs (Figure 2).

Several researchers and/or companies have balanced the requirements of the payload and aerial platform to enable UAVs for agricultural purposes. For instance, a mini-UAV equipped with a suitable imaging device is required for successful Normalized Difference Vegetation Index (NDVI) computation. Similarly, Rufino and Moccia (2005) used a radio-controlled fixed-wing model UAV to fly a thermal imager and a hyperspectral sensor in visible-NIR bands for forest fire monitoring.

While the use of laser scanners or LiDAR (Light Detector and Ranging) is now common in traditional photogrammetry, their application to UAV for PaRS (photogrammetry and Remote Sensing) remains a challenge. This is either due to the trade-off between performance and the size or cost of LiDAR, or the effect of flight dynamics on the measurement process (Wallace *et al.*, 2012). Despite such difficulties, one of the first UAV-borne LiDAR and camera integrations was presented by Nagai *et al.*, 2004.

3. Satellites, such as Quick Bird, provide high spatial resolution images of around 2.0–2.4 m in multi-spectra, depending on the image and number of colours (Digital Globe Corp, 2010).

Satellite images are commercially available but require further processing into a GIS format because these images are not as detailed as aerial photos (Gomez-Candon *et al.*, 2011). Further, the size of the satellite images are typically large, implying that it is very costly for the individual medium-sized farm holding to utilise the images (Bakhtiari and Hematian, 2013).



**Figure 2.** Number of referenced UAVs and developmental initiatives between 2005 and 2013. Source: Colomina and Molina, 2014.

By linking GPS to yield monitoring devices, soil and pest sampling, remote sensing, and information, such as topography, soil type, water patterns, previous and current cultural practices, a farmer can create maps showing how these parameters vary within a field and make management decisions accordingly.

### 3.3. Yield monitoring and mapping

Yield mapping is a first step into precision agriculture for many farmers. A combine-mounted yield monitor measures and records such information as grain flow (typically via a sensor at the top of the clean grain elevator), grain moisture, area covered, and spatial location.

Systematic errors can occur in yield mapping; software associated with a yield monitor can normally clean up the data to some degree, such as removing extremely high or low yield data points, but errors can still remain. Whilst providing useful information, these maps can only offer an approximation of crop yield at a given location for several reasons, including differences in grain flow from the edges of the combine header and time lags caused by the threshing process. Therefore, a general smoothing effect is observed which tends to overestimate the low-yielding areas and underestimate the high-yielding areas (Blackmore, 2000b).

Yield maps are now commonplace, but interpreting these yield maps can be challenging as many factors interact to affect crop yield within a given field and year and may not be stable from year to

year. The high and low zones may change, depending on climate or other factors (McKinion *et al.*, 2010). For example, in a dry year, the sandy soils in a field will have low yields, yet in a wet year these same soils will probably have higher yields than the clays in the same field.

Points to remember when evaluating the yield maps:

1. A yield map only documents the spatial distribution of crop yield and does not explain what factors caused the variations.
2. A yield map reflects all the inputs, environmental variables and field variability of the previous crop. The usefulness of a yield map for the following season is uncertain, even for the same crop.
3. The key to yield map interpretation is to understand more about the causes of yield variation and which causes can be altered by crop management. This can be achieved through evaluation of multiple layered temporal data stacking.
4. If the ranges for yield are not selected properly, the appearance of the map can be misleading.

Yield mapping is valuable when farmers use the information to improve management decisions. It is relatively low-cost compared to intensive soil sampling and provides complete coverage of the field, which is impossible even when taking soil samples on an intensive grid.

### **3.4. Addressing variability**

A large part of PA research is devoted towards precision nutrient management. This can improve nutrient use efficiency and environmental protection. An objective of precision nutrient management is the analysis and interpretation of spatial variability of soils in order to establish management zones (Rovira *et al.*, 2015).

#### **3.4.1. Soil characteristics**

The standard method of soil sampling for each field is by a single composite soil sample which is a mix of several (5 to 10) sub-samples taken throughout the field (generally a single composite sample can represent a maximum size of 4 ha). These sub-samples attempt to provide "average" conditions in the field. An unrepresentative sub-sample will affect the nutrient levels of the single composite sample and, therefore, change the fertiliser recommendations for variable rates. Composite soil samples that represent entire individual fields are not geo-referenced (Sandmann and Lertzman, 2003).

Geo-referenced soil samples that are used for PA can be taken in one of the three ways:

1. Systematic soil sampling: the samples are taken on an intensive grid, for example 40 x 40 m, over the whole field.

2. Standard sampling: the sampling density is one composite sample per hectare, but not on a true grid.
3. Directed sampling: soil samples are taken in zones within the fields that are selected by using aerial photos, topography or yield maps.

In these three methods, the soil samples are geo-referenced (Lund *et al.*, 1999). This implies, for example, that the soil N/P/K levels have an exact latitude and longitude position in the field. Geo-referenced soil samples are required so that the maps of nutrient levels can be used together with yield maps to help explain variability in the yield. More recently, there has been increasing emphasis on real-time, on-the-go monitoring with ground based sensors (Peets *et al.*, 2012, Adamchuk *et al.*, 2004 and 2008).

Soil apparent electrical conductivity (ECa), which is related to different soil physical properties such as clay content, moisture content, bulk density and salinity, can be conveniently used to determine soil variability. Electromagnetic induction (EMI) can be conveniently employed to measure soil ECa (Kuang *et al.*, 2012), however, it might be influenced by soil edaphic factors (Krajco, 2007). In order to gain more information about soils spatial variability in the UK National Soil Map ([landis.org.uk](http://landis.org.uk)) can be used (for England and Wales currently), at the time of writing, this facility is being hosted by the Cranfield University.

#### **3.4.2. Water and nutrients**

The potential of PA to address water and nutrient availability challenges has improved as a result of the development of sensor technologies, combined with procedures to link mapped variables to farming operations, such as tillage, seeding, fertilisation, herbicide and pesticide application and harvesting.

Christensen *et al.* (2005) conducted a study on water and nutrient stress (nitrogen, phosphorus and potassium) through discrimination-based analysis of the visible and near infrared reflectance of maize leaves. The study revealed that prior knowledge of the water status of the plant can increase the ability to discriminate nutrient stress significantly. The study also proved that the knowledge of spatial location of leaves within a plant can be helpful to identify nutrient stress more accurately than whole plant behaviour (i.e. mean reflectance data from all leaves within a plant). In a recent AHDB Cereals & Oilseeds-funded project by Kindred *et al.* (2016), the mean N optimum for six experimental sites varied from near zero to 322 kg ha<sup>-1</sup> during the same year, 2011. Furthermore, mean grain yields for the six sites varied between 8 and 10 t ha<sup>-1</sup>. Within-field variation in N optimum exceeded 100 kg N ha<sup>-1</sup> at all but one site. The report concluded that caution is needed if selecting automated N management as the benefits could only be observed with large scale adoption.

### **3.4.3. Variable rate technology (VRT)**

The use of Variable Rate Technology allows precise seeding, optimisation on planting density and improved application rate efficiency of herbicides, pesticides and nutrients, resulting in cost reduction and reducing environmental impact (Grasso *et al.*, 2011). This is the approach used to achieve site-specific application rates of inputs. Yield maps show the potential for Site Specific Crop Management (SSCM) methods, both from an economic and environmental perspective.

In recent years, granular applicators equipped with VRT have gained popularity. Swisher *et al.*, (1999) designed an optical sensor to measure flow rates of granular fertiliser in air streams for feedback control of a variable-rate spreader. Uniform-rate tests were conducted to assess the accuracy of variable-rate application from four granular applicators: two spin-disc spreaders and two pneumatic applicators. The finding showed potential application errors with VRT and the need for proper calibration to maintain acceptable performance and demonstrated the need for a VRT equipment testing standard (Fulton *et al.*, 2005).

Similarly, research funded by AHDB Cereals & Oilseeds showed that residual N calculation for only topsoil is not effective and can be misleading (Knight, 2006) for some crops like maize due to high mobile nature of  $\text{NO}_3$ . For some soils, residual N and potentiality of N-mineralisation of that soil during crop growth should be taken into consideration for N application map preparation for VRT application. Plant-scale treatments using spatial resolution, internal guidance and precision spray nozzles have already been achieved (Hague *et al.*, 1997). Future research in VRT should be concentrated in the development of true precision patch sprayer equipment, more accurate granular fertiliser applicators and their standards (Mondal and Tewari, 2007).

## **4. The economic benefits of precision agriculture**

The scale of the benefits obtained from PA depends upon the magnitude of the response to the corrective/variable treatments and the proportion of the field that will respond. Typically, a farmed area of 250 ha of cereals, where 30% of the area will respond to corrective or variable treatment, requires an increase in yield on the responsive areas between  $0.25 \text{ t ha}^{-1}$  and  $1.0 \text{ t ha}^{-1}$  for the basic and the most expensive system, respectively (Godwin *et al.*, 2003). However, it is noteworthy that since the aforementioned review by Godwin *et al.* (2003), technology has improved significantly with a profound decrease in the associated cost of the technology.

The above-mentioned figures will change in inverse proportion to: (i) the size of the area managed with each PA system; (ii) the percentage of the field responsive to the treatment; (iii) the level of engagement (technology purchased, i.e. a full or partial); (iv) depreciation and interest rates; and (v) the area of crops managed.

The economic benefit of VRT methods depends upon the crop type, area, and geographic location, amongst other factors. It has been demonstrated that the economic margins of precision fertiliser applications increase with increasing fertiliser and crop prices (Pablo *et al.*, 2014). In high-value crops, the higher profitability can be achieved with quality-specific harvesting based on the sensing of the nutrient status of the crop canopy. However, there is still no clear picture for all crops under all growing conditions (Pablo *et al.*, 2014). In a report by Knight *et al.*, (2009) the cost/benefit of many of the components of PA was discussed, suggesting the requirements for each case.

The growth in the adoption of PA in the UK has shown that between 2009 and 2012, the proportion of farmers using PA increased. The increase for GPS-controlled steering was greatest, from 14% to 22%, for soil mapping from 14% to 20%, for variable rate application from 13% to 16% and for yield mapping from 7% to 11%. The two most common reasons for adopting precision farming techniques were to improve accuracy in farming operations (76% of farms in 2012) and 63% of the farmers believed that PA reduced the input costs (DEFRA, 2013). These figures for the UK suggest that farmers consider PA can provide viable solutions for them.

Furthermore, the study revealed that nearly 50% of the farmers in 2012 who do not use any technology claimed that PA was not cost-effective and/or the initial setup costs were too high, 28% said they were not suitable or appropriate for the type or size of farm, and a similar proportion, (27%) said that they were too complicated. This suggests that there is a long way to go before the majority is convinced.

In another study, Schieffer and Dillon (2013) used a whole-farm model based on a Kentucky grain farm to investigate the effects of PA adoption on production choices under various agro-environmental policy frameworks. The study concluded that as PA techniques are more widely used, the economics of farm management will change, effecting how farms respond to agro-environmental policies, particularly those that rely on financial incentives.

An earlier comprehensive study conducted by Robertson *et al.*, (2007) on the cost benefit analysis of PA demonstrated that Australian farmers have adopted systems that are profitable and are recovering the initial capital outlay within a few years, and they also see a number of intangible benefits e.g. more innovation, improved satisfaction through saving valuable time etc. While the results from this study will go some way towards informing the debate about the profitability of PA, it also illustrates that the use of, and benefits from, PA technology varies farm to farm, in line with farmer preferences and circumstances.

## **5. Future research and development in PA**

### **5.1. Inclusion of historical data for image/map analysis**

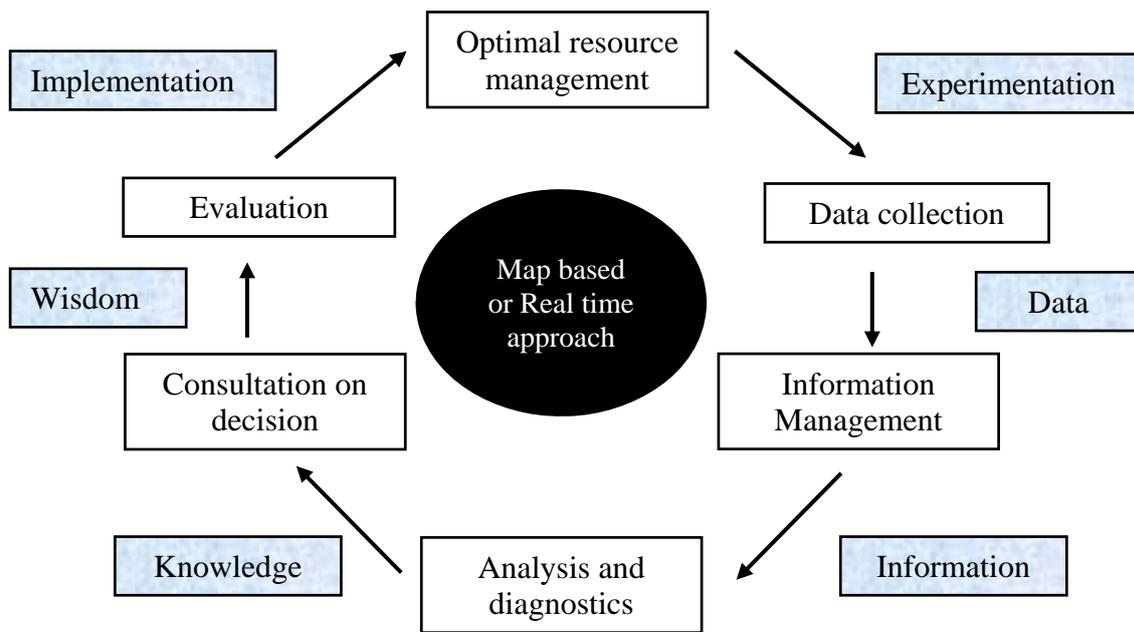
There is a significant potential in PA for combining archived remote sensing data with real-time data (Thenkabail, 2003). Historical archives of satellite remote sensing data are available for Landsat, SPOT, IRS, IKONOS, QuickBird and more recently, Sentinel II with red, blue, green and NIR spectral reflectance bands at spatial resolutions of from 0.6 to 30 m (Zhang and Hong, 2005).

Similarly, images at a fixed location could be analysed across multiple crop growth stages, seasons and years in order to identify relatively homogeneous sub-regions of fields that differ from one another in leaf area index, NDVI, and potential yield. Auxiliary data at the same sites, including crop yield maps, digital elevation models and soil series maps could be combined with historical remote sensing data to identify potential management zones where precision agricultural input operations can be implemented.

The rapidly increasing frequency and quality of remotely-sensed images, with satellites such as EO-1 Hyperion, Sentinel II and the upcoming (2016) NASA Hyperspectral Infrared Imager (HyspIRI) satellite means that real time agricultural decision making can be supported by current satellite imagery (i.e. at most a few days old).

Another crucial factor in improving farm economy and increase resource use efficiency in agriculture is improvement in long term weather forecast. Although there has been significant improvement in forecasting accuracy, it is still a challenge to predict weather accurately and anomalies are much higher even for a few days in advance. There is a dire need to use crop growth and weather forecasting models which could improve the reliability and users confidence.

To gain the full potential of PA, farmers should be engaged in shaping research and development of new technologies and practices, enabling adaptation to market requirements. While PA, as at present, can be promoted in a top-down manner, participatory development is preferable so as to build up human capabilities for decision-making and management (Figure 3).



**Figure 3.** Decision management in precision agriculture.

## 6. Key challenges and knowledge gaps

Although there has been an enormous increase in the technology available to farmers, the adoption of PA has been less than expected, in part because it has been difficult to quantify benefits, such as better allocation of inputs and increase in yield compared to the costs of investment (Kindred *et al.*, 2016). There is still a need to simplify the technology, to improve decision models, variable rate applications, and to develop new, less costly and reliable sources of data for making better PA decisions.

There are several needs for future research in PA and some of these have been described below:

1. Sensors are needed for direct estimation of nutrient deficiencies without the use of reference strips in both tillage and grassland farming systems. Further, these sensors and associated software should be ubiquitous and interoperable.
2. More emphasis is required on the development of chemometric or spectral decomposition methods of analysis, since spatial and spectral resolution of hyperspectral sensing systems are now adequate for many PA applications.
3. Historical archives of satellite remote sensing data at moderate to high spatial resolution and traditional spectral resolution should be integrated with real-time remote sensing data at high spatial and spectral resolution for improved decision making in PA.

4. Temporal variation: Over the years we have learnt a good deal about the yield maps and analysing the spatial variation within them, but we seem to have underestimated the importance of temporal variation. A rule of thumb might say that, if we look at the variation of yield across a field and across years, half of the variation comes from year-to-year variation. Knowledge of this temporal aspect needs to be greatly improved.
5. Crop quality assessment: In the past a lot of emphasis has been on the variable rates of agro-chemicals and factors associated with the crop yield, but the crop quality has never been given sufficient consideration. An associated benefit of this approach is the mapping of quality characteristics to improve agronomic management for optimising quantity and or quality (McBratney *et al.*, 2005).
6. Perceived ease of use (PEU): The presence of experts in PA initiates a learning process, enabling potential users to become more aware and confident about PA tools, and thus promoting the perception of an “easy to use” technology (Rezaei-Moghaddam and Salehi, 2010). PEU has been thoroughly investigated over the time and it seems to be most influenced by factors represented by the “objective usability” of a technology and the “computer self-efficacy” or “personal skills”, both a function of previous experience, education, external influence and support availability. All the aforementioned factors must be carefully addressed before a significant improvement in the uptake could be observed.
7. AHDB Cereals & Oilseeds has conducted a review on cost benefit analysis of PA techniques (Knight *et al.*, 2009), however, due to significant cost reduction in the technology used in PA, it might be timely to conduct another cost benefit analysis of the technology to provide a robust evidence to convince farmers of the economic advantage of PA.

## 7. References

- Adamchuk, V. I., Hummel, J. W., Morgan, M. T. and Upadhyaya, S. K. 2004. On-the-go soil sensors for precision agriculture. *Computers and Electronics in Agriculture* 44, 71–91.
- Adamchuk, V. I., Ingram, T. J., Sudduth, K. A. and Chung, S. 2008. On-the-go mapping of soil mechanical resistance using a linear depth effect model. *Transactions of the ASABE*, vol. 51, no. 6, pp. 1885-1894.
- Auernhammer, H., Muhr, T. and Demmel, M. (1995). GPS and DGPS as a challenge for environmentally-friendly agriculture. *Journal of Navigation* 48 (2): 268-278
- Bakhtiari, A.A. & Hematian A., (2013) “Precision Farming Technology, Opportunities and Difficulty”, *International Journal for Science and Emerging Technologies with Latest Trends*, Vol. 5, No. 1, pp1-14
- Batte, M.T. & Van Buren, F.N. 1999. Precision farming – Factor influencing productivity. Paper presented at the Northern Ohio Crops Day meeting, Wood County, Ohio.

- Blackmore, B. S. & Moore, M. R. (1999). Remedial Correction of Yield Map Data. *Precision Agriculture Journal* 1:53-66
- Blackmore, S., 2000 (a). Developing the principles of Precision Farming. In ICETS 2000: Proceedings of the ICETS 2000 (China Agricultural University, Beijing, China), p. 11-13.
- Blackmore, S., 2000 (b). The interpretation of trends from multiple yield maps. *Comput. Electron. Agric.* 26, 37/51.
- Christensen, L. K., S.K. Upadhyaya, B. Jahn, D.C. Slaughter, E. Tan and D. Hills, 2005: Determining the Influence of Water Deficiency on NPK Stress Discrimination in Maize using Spectral and Spatial Information. *Precision Agriculture* 6(6), 539-550
- Colomina, I., Molina, P., 2014. Unmanned aerial systems for photogrammetry and remote sensing: A review. *ISPRS J. Photogramm. Remote Sens.* 92, 79–97
- Cui, Y., 2013. "A systematic approach to evaluate and validate the spatial accuracy of farmers market locations using multi-geocoding services." *Applied Geography* 41: 87-95.
- Department for Environment Food and Rural Affairs (DEFRA), (2013), Farm Practices Survey Autumn 2012 – England, [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/181719/defra-stats-foodfarm-enviro-fps-statsrelease-autumn2012edition-130328.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/181719/defra-stats-foodfarm-enviro-fps-statsrelease-autumn2012edition-130328.pdf)
- Digital Globe Corp. 2010. A worldwide satellite provider company. Longmont, CO: DIGITAL GLOBE Corp. Accessed 4 July 2012, from <http://www.digitalglobe.com/>.
- Elarab M, Ticlavilca AM, Torres-Rua AF, Maslova I, McKee M. 2015. Estimating chlorophyll with thermal and broadband multispectral high resolution imagery from an unmanned aerial system using relevance vector machines for precision agriculture. *International Journal of Applied Earth Observation and Geoinformation.* 43:32-42.
- Fulton, J.P., S.A. Shearer, S.F. Higgins, D.W. Hancock and T.S. Stombaugh, 2005. Distribution pattern variability of granular VRT applicators. *Trans. Am. Soc. Agric. Eng.*, 48: 2053-2064.
- Fystro, G. 2002). The prediction of C and N content and their potential mineralisation in heterogeneous soil samples using Vis-NIR spectroscopy and comparative methods. *Plant Soil*, 246, 139e149
- Grisso, R., Alley, M., Thomason, W., Holshouser, D., & Roberson, G.T. (2011). Precision Farming Tools: Variable-Rate Application. In Virginia Cooperative Extension, 442-505, Arlington, US
- Gibbons, G., 2000. Turning a farm art into science - an overview of precision farming. URL: <http://www.precisionfarming.com>.
- Godwin, R. J., Richards, T. E., Wood, G. A., Welsh, J. P., & Knight, S. M., 2003. An economic analysis of the potential for precision farming in UK cereal production. *Biosystems Engineering*, 84, 533–545
- Gomez-Candon, D., Lopez-Granados F., Caballero-Novella, J.J., Gomez-Casero, M., Jurado-Exposito, M. & Garcia-Torres, L. 2011. Geo-referencing remote images for precision agriculture using artificial terrestrial targets. *Precision Agriculture*, 12(6): 876-891

- Hague, T., J.A. Marchant and N.D. Tillett, 1997. A system for plant scale husbandry. Stafford, J.V. (Ed.). Proceedings of the 1st European Conference on Precision Agriculture, September 7-10, Oxford, UK. pp: 635-642
- Hallett, P., A. Moxey, and T. Chamen, 2012. Studies to inform policy development with regard to soil degradation: Cost curve for mitigation of soil compaction, Defra  
<http://www.computer.org/web/nealnotes/content?g=7989281&type=article&urlTitle=farmers-embracing-technology-to-improve-agriculture>. Accessed on 19/04/2016  
<http://www.landis.org.uk/data/natmap.cfm>
- Ji, S., Chen, W., Ding, X., Chen, Y., Zhao, C. and HU, C. (2010). Potential Benefits of GPS/GLONASS/GALILEO Integration in an Urban Canyon – Hong Kong. *The Journal of Navigation*, 63, 681–693.
- Khosla, R. 2010. Precision agriculture: challenges and opportunities in a flat world. *19th World Congress of Soil Science, Soil Solutions for a Changing World*. Brisbane, Australia.
- Kindred, D.R., Storer, K., Hatley, D, Ginsburg, D, White, C, Catalayud, A, Milne, A., Marchant, B, Miller, P, Sylvester-Bradley, R. 2016. *Unpublished*, Automating N fertiliser management in cereals. AHDB funded project.
- Knight, S. M. 2006. Soil mineral nitrogen testing: practice and interpretation. Research Review. No 58. London: *HGCA* ss. 32
- Knight, S.; Miller, P.; Orson, J., 2009. An up-to-date cost/benefit analysis of precision farming techniques to guide growers of cereals and oilseeds. *HGCA Research Review* No. 71, pp. 115
- Kuang, B.; Mahmood, H. S.; Quraishi, Z.; Hoogmoed, W. B.; Mouazen, A. M.; van Henten, E. J., 2012. Sensing soil properties in the laboratory, in situ, and on-line: a review. In Donald Sparks, editors: *Advances in Agronomy*, 114, AGRON, UK: Academic Press, 155-224.
- Li, X., M. Ge, X. Dai, X. Ren, M. Fritsche, J. Wickert, and H. Schuh (2015b), Accuracy and reliability of multi-GNSS real-time precise positioning: GPS, GLONASS, BeiDou, and Galileo, *J. Geod.*, doi:10.1007/s00190-015-0802-8
- Linsley, C. M. a. F. C. Bauer., 1929. Test your soil for acidity. University of Illinois, USA, College of Agriculture. *Agriculture Expt. Sta. Circ.*346.
- Luccio, M, 2014. Satellite imagery for precision agriculture. A web article published at;  
<http://www.xyht.com/enviroag/satellite-imagery-precision-agriculture>.
- Lund, E.D., Christy, C.D., Drummond, P.E., 1999. Practical applications of soil electrical conductivity mapping. In: Stafford, J.V. (Ed.), *Precision Agriculture'99*, Proceedings of the Second European Conference on Precision Agriculture. Odense, Denmark, July 11–15. Sheffield Academic Press Ltd., Sheffield, UK, pp. 771–779
- McBratney A, Whelan B, Ancev T, Bouma J., 2005. Future directions of precision agriculture. *Precis Agric* 6:7–23

- McKinion, J.M., J.L. Willers, and J.N. Jenkins. 2010. Spatial analyses to evaluate multi-crop yield stability for a field. *Comput. Electron. Agric.* 70:187–198.doi:10.1016/j.compag.2009.10.005
- Mondal P., Tewair V. K., 2007. Present status of precision farming, a review. *Int. J. Agric. Res.* 2, 1–10.
- Nagai, M., Shibasaki, R., Manandhar, D., Zhao, H., 2004. Development of digital surface and feature extraction by integrating laser scanner and CCD sensor with IMU. *IAPRSSIS*, Vol. 35(B5), Istanbul, Turkey
- Nemenyi, M., Mesterhazi, P.A., Pecze, Zs. & Stepan, Zs. 2003. The role of GIS and GPS in precision farming. *Computers and Electronics in Agriculture*, 40(1-3): 45-55
- Pablo J. Zarco-Tejada, N. Hubbard and P Loudjani 2014. Precision agriculture: An opportunity for EU farmers' potential support with the cap 2014-2020. (<http://www.europarl.europa.eu/studies>)
- Pecze, Zs. 2001. Case maps of the precision (site-specific) farming. A Ph.D. Dissertation. *University of West-Hungary, Mosonmagyaróvár.*
- Peets S, Mouazen AM, Blackburn K, Kuang B & Wiebensohn J., 2012. Methods and procedures for automatic collection and management of data acquired from on-the-go sensors with application to on-the-go soil sensors. *Computers and Electronics in Agriculture*, 81 104-112.
- Price, M. 2006. *Mastering ArcGIS*. Second Ed. New York, NY 10020: McGraw-Hill.
- Rezaei-Moghaddam K, Salehi S., 2010. Agricultural specialists' intention toward precision agriculture technologies: Integrating innovation characteristics to technology acceptance model. *Afr J Agric Res.* 5:1191–9
- Robertson, M., Carberry, P., & Brennan, L. 2007. The economic benefits of precision agriculture: case studies from Australia grain farms. Retrieved March 12, 2012
- Rovira-Más, F., Chatterjee, I. and Sáiz-Rubio, V. (2015). The Role of GNSS in the Navigation Strategies of CostEffective Agricultural Robots. *Computers and Electronics in Agriculture*, 112, 172-183
- Rufino, G., Moccia, A., 2005. Integrated VIS-NIR Hyperspectral/thermal-IR Electrooptical Payload System for a Mini-UAV. *American Institute of Aeronautics and Astronautics*, Arlington, VA, USA, pp. 647–664
- Sandmann, H., and K.P. Lertzman, 2003. Combining high-resolution aerial photography with gradient-directed transects to guide field sampling and forest mapping in mountainous terrain, *Forest Science*, 49(3):429–443.
- Sanchez S, Ramalho R, Sousa L, Plaza A. 2015. Real-time implementation of remotely sensed hyperspectral image unmixing on GPUs. *Journal of Real-Time Image Processing.* 10(3):469-83
- Schieffer, T., Dillon, T., (2013), Precision agriculture and agro-environmental policy, in: Precision agriculture '13, Ed Stafford J., Wageningen Academic Publishers, ISBN: 978- 90-8686-224-5.

- Shibusawa, S., 1998. Precision Farming and Terra-mechanics. *Fifth ISTVS Asia-Pacific Regional Conference in Korea*, October 20-22.
- Speckmann, H. and Jahns, G., 1999. Development and application of an agricultural BUS for data transfer. *Comput. Electron. Agric.*, 23, 219-237.
- Stafford, J.V., Evans, K., 2000. Spatial distribution of potato cyst nematode and the potential for varying nematicide application. *Proceedings of Fifth International Conference on Precision Agriculture (CD)*. July 16-19, 2000. Bloomington, MN, USA.
- Stereocarto. 2010. Airplane fleet company for remote sensing. Madrid: STEREOCARTO.  
Accessed 4 July 2012, from <http://www.stereocarto.com/en/productos/producto.php?id=43>
- Sudduth, K.A., J.W. Hummel. Soil organic matter, CEC, and moisture sensing with a portable NIR spectrophotometer. *Transactions of the ASAE*, 36 (1993), pp. 1571–1582
- Swisher, D.W., K.A. Sudduth and S.C. Borgelt, 1999. Optical measurement of granular fertiliser flow rates for precision agriculture. ASAE Paper No. 99-3111, American Society of Agricultural Engineers, St. Joseph, MI, USA
- Thenkabail, P.S., Lyon, G.J., and Huete, A., 2011. Book entitled: Hyperspectral Remote Sensing of Vegetation. *CRC Press- Taylor and Francis group, Boca Raton, London, New York*. Pp. 781
- UAV. 2010. Development of unmanned aerial vehicles. Accessed 4 July 2012, from <http://www.micropilot.com/>; <http://www.uavnavigation.com/>; <http://www.theuav.com/>.
- Wagner, P., 2000. Problems and Potential Economic Impact of Precision Farming. *In: 7th ICCTA: Computer Technology in Agricultural Management and Risk Prevention: Proceedings of the 7th International Congress for Computer Technology in Agriculture*. Edited by C. Conese and A. M. Falci (Supplemento agli Atti dell'Accademia dei Georgofili, Florence, Italy), pp. 241–249
- Wallace L, Lucieer A, Watson C, 2012. Development of a UAV–LiDAR system with application to forest inventory. *Remote Sens* 4: 1519–43.
- Whelan, B., Taylor, J., 2013. Precision Agriculture for Grain Production Systems. *Csiro Publishing*, Collingwood, VIC, Australia
- Zhang, Y.; Hong, G. 2005. An HIS and wavelet integrated approach to improve pan-sharpening visual quality of natural colour IKONOS and QuickBird image. *Inf. Fusion*. 6, 225–234.