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KEYNOTE PAPER

Implementing Precision Agriculture in the 21st Century

John V. Stafford

Silsoe Solutions, Ampthill, UK; e-mail: John.stafford@silsoe-solutions.co.uk

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Precision agriculture has generated a very high profile in the agricultural industry over the last decade of the second millennium—but the fact of 'within-field spatial variability', has been known for centuries. With the advent of the satellite-based Global Positioning System, farmers gained the potential to take account of spatial variability. The topic has been 'technology-driven' and so many of the engineering developments are in place, with understanding of the biological processes on a localized scale lagging behind. Nonetheless, further technology development is required, particularly in the area of sensing and mapping systems to provide spatially related data on crop, soil and environmental factors. Precision agriculture is 'information-intense' and could not be realized without the enormous advances in networking and computer processing power.

Precision agriculture, as a crop management concept, can meet much of the increasing environmental, economic, market and public pressures on arable agriculture. By the end of the new decade, most arable enterprises will have taken on the concept on a whole-farm basis.

1. Introduction

Over the last 10 years, precision agriculture has gained an increasing profile in the agricultural community. Although considerable research effort has been expended, it is still only a minority of farmers who practice any part of this new concept. The advisors are keen to learn and agricultural and other engineering companies are producing equipment of increasing sophistication to enable the practice of precision agriculture. However, agricultural engineers did not invent it! The basis of precision agriculture—the spatial and temporal variability in soil and crop factors within a field—has been appreciated for centuries. The reader is referred, for instance, to the writings of the early Jewish Fathers (Midrash, Genesis Rabbah XIII, 13) and the parable of the sower in the Bible (Matthew 13 v 8).

In the past centuries, the very small size of fields and their delineation by natural boundaries, such as water courses and change of soil type, may have enabled farmers to vary treatments manually. However, with the enlargement of fields, intensive production and mechanization in the latter half of the last century, it was not possible to take account of within-field spatial variability without a significant development in technology.

The pivotal technology that drove the development of the precision agriculture concept was the establishment, in the late 1970s, of the Global Positioning System (GPS) based on a constellation of satellites placed in orbit by the US Department of Defense. This system provided the potential to determine position (latitude, longitude and altitude) anywhere on earth, 24 h a day, to an accuracy of a few centimetres. With such information available to field machines, the treatment applied during field operations could be related to very localized requirement within the field.

Although one could quote work earlier in the 20th century (*e.g.* Linsley & Bauer, 1929; Eden & Maskell, 1928) as setting the first seeds of precision agriculture, it was mainly due to Johnson *et al.* (1983), who developed the concept of 'custom prescribed tillage'. They were visionaries in terms of how automation, sensing systems, location systems and 'information technology' would transform agricultural crop production as the technology came on-stream. They stated, 'Future machinery used in production agriculture will be automatically controlled to prescribe cultural practices, based on soil, crop and climate. Some soil and crop information may be sensed on-the-go and stored in a computer on board the prime mover or field machine. This computer, in turn, could be programmed to make real-time decisions based on this information to control cultural practices such as fertilizer, herbicide and pesticide application. Important to this concept is a general spatial position-sensing system that can pinpoint the position of a machine in the field at any time'. Matthews (1983) also foresaw the need for greater precision in crop management and that would require, '… continuous variation of the quantity of inputs to match the needs of soil or crop in a localised region'.

Probably, the first real application of precision agriculture was the 'on-the-go' fertilizer blending and distribution system developed by Soil Teq in the USA (Fairchild, 1988) which used information from aerial photography and grid soil samples to generate a fertilizer application map. Positioning of the field vehicle, however, was by dead reckoning as GPS was not sufficiently developed for civilian use. Further applications and greater research effort were put in place in the early 1990s, as GPS became more reliable, the satellite constellation neared completion and civilian receivers became available (Stafford & Ambler, 1994). Amongst such developments were spatially variable herbicide application (Miller & Stafford, 1993), dynamic sensing of soil organic matter using spectral reflectance sensors (Price & Hummel, 1994) and yield mapping (Vansichen & de Baerdemaeker, 1991; Searcy *et al*., 1989; Stafford *et al*., 1991).

It has been suggested that precision agriculture is currently at a crossroads (Stafford, 1999a) with much of the necessary technology available commercially but with the environmental and economic benefits of implementing the concept as yet unproven, except in a few cases (*e.g*. for herbicide—see Miller & Paice, 1998), and much development of agronomy still required to determine optimum recommendation procedures for inputs at the localized level. Hence, many farmers are uncertain as to whether to practise precision agriculture on their farms. The purpose of this paper is to consider how precision agriculture may evolve in the new millennium, the drivers for its uptake and the necessary developments.

1.1. *Progress into a new millennium*

Precision agriculture is seen to be the correct way ahead for crop producers in the next millennium because crop production is more precise, because inputs are optimized leading to reduced costs and environmental impact and because the concept provides the audit trail that consumers and legislation increasingly require. However, there are three barriers to be overcome for it to be widely implemented.

(a) Precision agriculture is 'information-intense' as illustrated in the information flow diagram of *Fig. 1*. The mapping of many different soil, crop and environmental factors within a field produces large quantities of data for the crop manager to deal with. To the field data is added his own knowledge base derived from experience and external data sources such as weather and market information. This 'data overload' for the manager has to be overcome by development of data integration tools, expert systems and decision support systems (Sigrimis *et al*., 1999). Part of this development must include the standardization of data formats and transfer protocols.

(b) There is a lack of rational procedures and strategies for determining application requirements on a localized basis and a parallel lack of scientifically validated evidence for the benefits claimed for the concept. Both of these can only be addressed by soil and crop science and agronomic research and experimentation.

(c) Although data required on soil, crop and environmental factors can be obtained, most methods are labour-intensive and costly (such as soil sampling followed by laboratory analysis). The data required must be generated by automatic sensor systems sensing specific factors or suitable surrogates. Thus, development of rapid sensing systems must take place before precision agriculture is widely practised. With the development of systems that can provide data at fine spatial resolution, the development of more precise application technologies and precise and reliable position computation has become necessary.

Agricultural engineers must take a lead in overcoming the first and third barriers but, as the last decade of

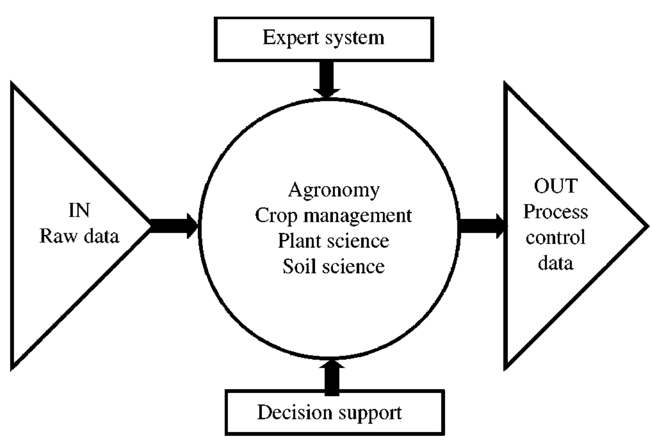

Fig. 1. Information flow

research in precision agriculture has shown, the topic is multidisciplinary and so inter-disciplinary teams are needed to develop solutions.

1.2. *Drivers*

Four drivers may be identified that will provide the motivation for widespread uptake of precision agriculture; environmental legislation, traceability and public concern over farming practices. A fourth, and negative, driver may be public aversion to genetic modification of crops; precision agriculture provides an alternative and realistic means to reduce and optimize the use of agrochemicals.

The threat of a pesticide tax in the UK has been present for some time, following strict environmental legislation in Denmark and Germany that taxes and seeks to control agro-chemicals and nitrogenous fertilizers. European Union directives may well be established that will force farmers in member countries to reduce significantly usage of agrochemicals. Much more efficient, optimized use of agrochemicals must be the corollary—a role that precision agriculture practices can fulfil.

Legislation and consumer/supermarket pressure is already enforcing increasing traceability throughout the food chain and the concept of an audit trail from soil to supermarket shelf is in common discussion (Zilberman & Millock, 1997). In the UK, a local environmental risk assessment for pesticides (LERAP) is now in force (Anon, 1999). Precision agriculture provides the means for precise, targeted application, recording of all field treatments at the metre scale, tracking from operation to operation and transfer of recorded information with the harvested product.

2. Positioning systems

In the early days of precision agriculture, GPS was unreliable for dynamic positioning within the field. Typical position resolution with differential operation was 5 m ($2 \times$ r.m.s. value) with a skewed Gaussian error distribution extending out to tens of metres (Stafford & Ambler, 1994). The incomplete constellation of satellites accentuated the problem of signal obscuration by trees and buildings (Lachapelle & Henriksen, 1995; Brock & Karakurt, 1999) and multi-path reflections were a significant cause of poor positioning. GPS receivers were bulky and expensive. In 2000, the general perception is that GPS is a mature technology with considerable, sophisticated processing power built into commercial receivers that have reduced in price very significantly (handheld, 12 channel GPS receivers are now available at less than £100). The satellite constellation is complete and receivers typically receive signals from 8 to 12 satellites above the horizon. Most receivers used in precision agriculture are 12 channel and use phase smoothed pseudo-range positioning with claimed sub-metre accuracies. A typical example is the Trimble Ag132 receiver with integral differential receiver—http://www.trimble.com/precise/agri/index.htm (mention of commercial products is for illustrative purposes only and implies no endorsement). Thus, GPS is seen to be an available tool that needs little further development.

The new millennium will, however, see important developments in positioning to benefit precision agriculture. Some aspects of precision agriculture, such as avoidance of spray overlap and application control near sensitive areas such as field margins, will be practised at a smaller and smaller scale requiring higher resolution positioning. Targeting of field inputs to some crops will be at the plant scale and even down to leaf scale requiring much enhanced reliability and accuracy of dynamic positioning. Traceability will require recording precise application information tagged with very accurate position data.

Positioning resolution is seriously limited by the deliberate downgrading, known as selective availability (SA), of satellite signals by the US Department of Defense (Langley, 1997a). Although differential mode compensates for much of the downgrading, there will be significant gains when SA is turned off. A US Presidential Decision Directive (McNeff, 1999) indicated that this would happen in 2006. However, a Whitehouse press release issued on 1 May 2000 (http://www.whitehouse.gov/library/PressReleases.cgi?date = 0 and briefing = 0) stated that SA was turned off on that day. The Russian GLONASS positioning system (Langley, 1997b) is not downgraded but reliability of the system is in doubt because of maintenance issues. There are some combined GPS/GLONASS receivers available commercially which give enhanced positioning but they are expensive and are unlikely to be taken up for precision agriculture. A European global navigation satellite system (GNSS), 'Galileo', has been under discussion for some time (Spiller et al., 1998) and is now being subjected to a 'definition study' funded by the European Union and the European Space Agency which is due to report in December 2000. The plan is for the system to be developed by a public–private partnership and be operational by 2008 (Divis, 1999). Such a system should provide improved positioning accuracy and reliability compared to GPS.

Possible technical enhancements in GNSS in the new millennium must be set in the context of the advanced technology and processing power already incorporated into GPS receivers. The accuracy of the standard positioning service based on pseudo-range calculation of the clear acquisition signal from the satellites is limited by the repetition rate (1·023 MHz) of the pseudo-random binary code transmitted on one satellite carrier (the L1 signal). If civilian access were allowed to the Precise Positioning Service where the precise (P) code is transmitted on the L2 signal at 10 times the rate (10·23 MHz) then a significant improvement in positioning accuracy could be achieved.

Kinematic GPS, where position is determined by measuring the phase shift in the satellite carrier signal between transmission and reception, gives the potential for centimetre accuracy. The wavelength of the carrier is about 19 cm and so phase shift measurement to 1% would yield a range measurement of 2 mm (Goad, 1996). However, kinematic GPS has not been used in precision agriculture so far because of cycle ambiguity and cycle slip with momentary loss of satellite signal. Phase shift smoothing is, however, being used in current pseudo-range receivers to improve position resolution. By using a double-differencing technique (Spilker and Parkinson, 1996; Langley, 1998), real-time kinematic (RTK) GPS is possible to provide high resolution dynamic positioning. The robustness of RTK GPS will certainly be improved and come into regular use in precision agriculture.

Similarly, integration of navigation systems (Gordon, 1998) will be enhanced to provide reliable and robust positioning—if one system fails to reach its positioning specification momentarily, then there is at least one other system to take over. Such systems have been developed using GPS and other field machinery navigation data such as velocity and heading (*e.g.* Stafford & Bolam, 1996). Future systems are likely to integrate visual (camera-based) navigation (such as that described by Southall *et al.*, 1998) with GPS for precision application at the individual plant level.

3. Sensing systems

Precision agriculture is information-intense; a lot of position tagged, sensed data, *i.e.* mapped data, are required to generate treatment maps. The ideal to attain is real-time, robust, low-cost mapping systems for soil, crop and environment variables. However, the only commercial systems available to date are yield mapping and soil conductivity mapping systems. Satellite remote sensed images are available but not processed into a form that is suitable for the crop manager to use as a quantified data source.

Soil and crop data, such as soil moisture and acidity, crop vigour and disease presence can be obtained—but only by laborious and costly manual sampling and analysis or by visual surveying. Cost-effective mapping systems will be developed in the next decade that will enable collection of essential data for implementation of precision agriculture practices.

3.1. *Crop*

If the 'crop is the best sensor of its own environment' (Legg & Stafford, 1998) then sensing systems that can tap into what the crop is 'saying' may provide information on crop condition necessary to direct spatially variable inputs. Such information would come primarily from the spectral reflectance characteristics of the crop and be monitored by radiometric and hyperspectral sensing devices mounted on platforms ranging from field vehicle to satellite. A scanning radiometer system, mounted on a tractor, has been described by Stafford and Bolam (1998) and a commercial, tractor-mounted radiometric system has been introduced by Hydro-Precise which can map spatial variability in the crop although it is currently marketed as a real-time variable nitrogenous fertilizer application system.

Satellite remote sensing has held out much promise for within-field monitoring but has, so far, failed to deliver. Problems include timeliness of images because of cloud cover, cost, poor spatial resolution and lack of processing to produce image data of use to the crop manager (Steven, 1993). Two commercial systems are due to go on line in the next few years that should address these problems. One of these, the X-Star project, led by Matra Marconi Space plans to launch a high spatial resolution satellite with a 10 spectral band scanner in 2004. The project uses crop models and algorithms developed at Institut National de la Recherche Agronomique (INRA) and Institut Technique des Cereales et des Fourrages (ITCF) (http://www.itcf.com/dossiers/dos1_ch4_3.html) in France to process images into usable spatial maps of biophysical data such as leaf area index, soil brightness, crop cover and nitrogen stress (Moulin *et al.*, 1998). A high-spatial resolution, frequent revisit time satellite, IKONOS, was launched in September 1999. Its imaging scanners have a ground resolution of 1 m panchromatic (450–900 nm) and 4 m multispectral (three visible and one near-infrared band). The revisit frequency is 1–3 days. The satellite therefore has the potential to provide the data required for precision agriculture. An early example image, illustrating its spatial resolution, is shown in *Fig. 2*. Another potentially useful source of remote-sensed data are the synthetic aperture radar (SAR) images from satellites such as ESR2 which have the advantage of penetrating clouds. The reflected image is sensitive to surface structure and moisture content but still requires interpretation as with the visible and near-infrared images. There is potential for combining SAR

Fig. 2. An image from the IKONOS satellite of the London 'Eye' by the River Thames

and optical data to improve information for crop management (Moran *et al*., 1997).

Processing and interpretation of the image data is essential and the problems of identifying causes for the observed effects on crop reflectance, observed by Steven (1993), remain. However, integrating image data with other ground-derived spatial data to determine underlying causes holds out promise for a solution in the next decade (Welsh *et al*., 1999).

Mapping of the spatial variability in plant stress may enable variable treatment for stress factors such as disease, nutrient deficiency or insufficient moisture. However, as mentioned above, discrimination between factors using spectral reflectance is difficult because all induce leaf chlorosis with little distinguishing spectral characteristics. Developments in gene manipulation of crop plants, which are the subject of current research, may enable differentiation of stress factors because gene expression depends on the stressing factor. The reader is referred, for example, to The Sunday Times, 17 May 1998, which reported early research at IACR-Rothamsted and The Institute of Cell and Molecular Biology, Edinburgh University. An optical sensor with high specificity may then be used to identify crop areas that are, for instance, suffering a specific disease attack. Leaf fluorescence may be one such mechanism that may be sensed. Although genetic manipulation to enable sensing of spatially variable crop factors may become technically feasible in the next decade, public antipathy towards the concept of genetic manipulation may inhibit its practical implementation.

Another application for 'smart plants' may be in weed/crop discrimination. The very similar spectral characteristics of crop and weed species makes discrimination technically difficult as shown by the relatively small success of research over the last ten years to develop weed detection techniques (Stafford & Benlloch, 1997; Vrindts *et al*., 1999). With appropriate gene manipulation of crop plants, spectral reflectance characteristics may be changed sufficiently to enable robust discrimination from weeds. Variable herbicide application strategies (Christensen *et al*., 1999) will, however, require species as well as presence/absence information on weed distributions in crops. Robust weed mapping approaches will be developed based on sensing multiple weed attributes such as spectral characteristics, morphological information, crop/weed geometries and distribution patterns within crops (Robbins, 1998).

Cereal quality is becoming more important than yield especially as the price of cereals reduces on world markets. There is well-substantiated evidence that quality as well as yields are spatially variable within fields (Stafford, 1999b) and systems will be developed to exploit such variation to add value to the harvested crop. Long *et al*. (1998) have shown that nitrogen fertilizer can be targeted according to a previous season grain quality (protein content) map to improve the efficiency of uptake and reduce spatial variation in quality in the current season. Thylen *et al*. (1999) and Stafford (1999b) have shown that sorting grain from a field into different quality bands may be economically worthwhile. The technical developments required in the next decade are of on-combine sorting systems and online quality sensors. The latter will probably be based on near-infrared absorption techniques (Engel *et al*., 1997).

3.2. *Soil*

The complex interaction between soil and crop growth means that it is difficult to infer spatially variable treatment from mapped soil factors. However, sensing and mapping of soil factors provide decision support information to the crop manager in identifying factors limiting to growth and yield in various parts of the field. For instance, a map of soil nutrient availability may alert the manager to areas of deficiency but cannot be used directly for variable application of fertilizer. On the other hand, a compaction map or soil pH map provides direct information for varying subsoiling or liming treatment.

Research studies (*e.g*. Lund *et al*., 1999; Suddeth *et al*., 1995) have shown how mapping soil electrical conductivity can be a good surrogate measurement for spatially variable factors that are not easy to sense and map such as soil type and moisture content. The technique is now available as a commercial service using direct conductivity measurement via two soil cutting discs (the Veris System from Veris Technologies, 601 N. Broadway, Salina, KS, USA) and indirectly using a non-contact electromagnetic induction probe such as the Geonics EM38 (Geonics Ltd, Mississauga, Ont, Canada). The concept of surrogate sensing and mapping is one that is likely to be taken up more in the next decade where factors, such as specific soil-borne pests (*e.g*. Potato Cyst

Nematode), are difficult or impossible to sense directly. Another example is the use of a sequence of yield maps in an analysis procedure described by Lark and Stafford (1997) to divide a field into a limited number of sub-regions which, in many cases, delineate soil boundaries.

The precision agriculture concept will be increasingly applied to soil manipulation operations such as seedbed preparation to optimize seedbed structure and sub-soiling to only those areas of a field requiring it. Sensors need to be developed to characterize and map structure and to map soil strength. There have been some research studies (scarlett *et al*., 1997; Stafford & hendrick, 1988) but commercial equipment is not yet available.

3.3. *Topography*

There is increasing appreciation of how subtle changes in field topography (slope, aspect, depressions) can affect crop development (Bishop & McBratney, 1999). The spatial variability in topography is captured in a digital elevation model (DEM) which can be laboriously generated by conventional survey methods. With the wider availability and lower cost of high-resolution GPS (such as kinematic GPS), it is becoming increasingly possible to generate DEMs at reasonable cost. Russell *et al.* (1999) have shown that phase smoothed differential GPS can generate DEMs to a height resolution of 50–100 mm. With DEM information generated from GPS and aerial photogrammetry, it should be possible to determine variation in crop height across a field to provide another information layer in decision support.

4. Precise application

Implementation of precision agriculture to date has utilized existing field machinery and added controllers and GPS to enable spatially variable application. Thus, conventional spray booms have been used for patch spraying (Miller & Paice, 1998) and spinning disc applicators for variable fertilizer application (*e.g.* Amazone ZA-M spreader). The potential of precision agriculture will lead, however, to demands for the development of novel, precise application techniques to achieve the precision and reliability in material placement that follow from the precision and accuracy achievable by positioning and sensing systems. The conventional spinning disc fertilizer spreader, for instance, can hardly be described as 'precise'! Conventional spray nozzles typically deposit liquid over a half-metre diameter circle. The variability in the physical characteristics of granular and powder materials may mean that development of novel techniques are concentrated on liquid delivery systems.

As precision agriculture develops into the next century, there will be increasing demands for greater spatial precision for some applications and mechanisms and control systems will have to be developed that can apply precisely defined quantities to precisely defined targets. Such requirements are likely to be appropriate to high-value vegetable and specialist crops whilst arable crops such as cereals will continue to be treated on a 'management unit' basis.

The concept of 'plant-scale husbandry' where treatment is targeted according to the specific requirements of each plant, has already been developed (Hague *et al*., 1997). Their system achieved a spatial resolution of 50 mm using image-based and inertial guidance and was equipped with precision spray nozzles that could target individual plants. Dijksterhuis *et al.* (1998) have shown that a ten-fold increase in field vehicle guidance resolution (5 mm) is possible using real-time kinematic GPS. The coming decade may therefore see not only commercial take up of plant-scale precision agriculture but also development of 'leaf-scale' where differential treatments are applied to different parts of the plant.

Further developments in sensor resolution and specificity are, of course, required for this scenario and the approach may not be viable in economic terms. However, increasing consumer and supermarket demands for record keeping and traceability and environmental legislation will follow the greater precision made possible by technological development. There will then be the requirement for very precise application of inputs, which provides a challenge to agricultural engineers in innovative design and development.

5. Information management

It has already been emphasized that precision agriculture is 'information-intense'. As the amount of data generated on-farm from both mobile and static sources has increased, the need for standardized file and data formats has been recognized. On mobile equipment, the need for rationalizing the means for data flow and exchange has led to proposals for standardized data buses (Stafford & Ambler, 1988, 1993; Auernhammer, 1993). File and data formats have been standardized in ISO 11787 (referred to as 'ADIS'—agricultural data interchange standard) and are in use by some manufacturers. However, data bus standardization for tractors and attached implements, based on the Controller Area Network (CAN) protocol, is still under development by an ISO Technical Sub-committee (TC23/SC19/WG1). The resulting standard (ISO 11783) will be in 11 parts and is expected to be published within two years.

Both of these standards are of considerable importance in the development of precision agriculture so that information can be exchanged smoothly and efficiently between sensors, processors, controllers and software packages from different manufacturers. There has been considerable development of geographic information system (GIS) packages specifically for precision agriculture with a number of commercial systems available (such as LORIS from Kemira, AMAIS from Farmade and Agromap from Claas). Most of these can be described as GIS shells which enable import/export of data in various formats together with manipulation and display of data layers. There is an urgent need to develop and incorporate models/expert systems to interpret and integrate multi-source data into useful information.

6. Conclusion: a precision agriculture farm

Precision agriculture is a crop management concept. It should be implemented as such on a farm-wide basis and practised for all field operations concerned with the growing of crops. Environmental legislation with regard to the minimization and optimal use of inputs and market pressures for traceability and audit trails in the new decade will force producers to seriously consider precision agriculture as a solution. Alongside these pressures will be that of optimizing the use of technologically sophisticated equipment. Thus, machinery and equipment replacement policies will be on the basis of utilizing equipment as widely as possible in all field operations. Procedures for the integration and interpretation of the masses of spatially related data must be established both for generating rational treatment maps and as decision support to the manager.

The economic and environmental benefits of taking account of within-field spatial variability appear obvious although they have yet to be generally proved in field trials and experiments. Much of the technology is in place but there will be further important developments in the new decade, particularly in the area of sensing and mapping variability. It is essential that complementary research and development in agronomy, crop and soil science are successful in defining, explaining and making recommendations for variable application of inputs at the very localized level.

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