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Future Directions of Precision Agriculture★

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Abstract. Precision Agriculture is advancing but not as fast as predicted 5 years ago. The development of proper decision-support systems for implementing precision decisions remains a major stumbling block to adoption. Other critical research issues are discussed, namely, insufficient recognition of temporal variation, lack of whole-farm focus, crop quality assessment methods, product tracking and environmental auditing. A generic research programme for precision agriculture is presented. A typology of agriculture countries is introduced and the potential of each type for precision agriculture discussed.

Keywords: site-specific crop management, resource economics

Introduction

The brief of this paper is to discuss the possible developments in, and impediments to, precision agriculture (PA) in the world external to the United States of America, i.e., most of the world (95.4% of the world's population, 87.7% of the arable land, 81.3% of the tractors)—a tall order. Nevertheless there are some trends that will probably drive the direction of PA worldwide, and some that will be more influential in different regions. We shall focus on those trends here.

This paper is dedicated to the memory of Pierre Robert who did more than anyone to develop and popularise precision agriculture (Robert, 1993, 1999, 2002). The definition of precision agriculture is still evolving as technology changes and our understanding of what is achievable grows. Over the years the emphasis has changed from simply "farming by soil" (Robert, 1993), through variable-rate technologies, to vehicle guidance systems and will evolve to product quality and environmental management. At various places throughout the world the degree of development, and consequently the focus, varies. In new countries (or new crop commodities), yield mapping and the option of variable-rate application of inputs are generally what gets things started as a means to save costs while, in time, product quality comes more into focus. When governments learn about PA, environmental

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management also becomes a focus but this is a cumbersome process as it implies changes in the existing policy paradigms (e.g. Bouma *et al.*, 2002).

Definitions of PA abound. The diversity is well displayed on the website of the Laboratory for Agricultural Machinery and Processing, Katholieke University, Leuven (http://www.agr.kuleuven.ac.be/aee/amc/research/precag/introduction/PA definitions.htm—last accessed 12/04). One generic definition could be ''that kind of agriculture that increases the number of (correct) decisions per unit area of land per unit time with associated net benefits''. This moves the focus a little away from simply spatial resolution to one involving the fineness of decisions in both space and time. This more generic definition does not imply a particular technology or set of technologies, the decisions can be made by electronic sensors, GPS, GIS, VRT etc., but they can also be made by humans. Here we concentrate on crop production, i.e., site-specific crop production, but similar issues arise with respect to livestock, fisheries, forestry and other natural resources management.

What are those associated benefits mentioned in the definition above? In simple terms—a concomitant increase in quantity and/or quality of production and/or the environment along with the same or decreased inputs. A proper definition of this in quantitative terms has been elusive. This will indeed involve a triple-bottom line kind of definition focussing on sustainable development and taking into account traditional profitability along with environmental and social benefits. (Some have even argued for a fourth, a spiritual dimension). The last consideration suggests a rather broad question: Can precision agriculture make us feel better about the world? Our hypothesis may well be that this can be the case and the specific challenge, then, is to make this plausible.

There are very few data on the adoption of PA in various countries and worldwide. Zhang *et al.* (2002) gave a ''worldwide overview''. Griffin *et al.* (2004) provide the most recent and comprehensive assessment of uptake. Details of developments in South America can be found at the website www.agriculturadeprecision.org (last accessed 12/04). Dobermann *et al.* (2002) and Wang *et al.* (2001) present some developments in Asia and Gandah *et al.* (2000), Florax *et al.* (2002) and Voortman *et al.* (2004) present an African example. It would be fair to say that adoption has not been as rapid as was predicted 5 years ago. Why?

Generic issues

Political dimensions

When one considers precision agriculture from a world perspective, one cannot deny or ignore its political dimensions. There are several such dimensions, some appear negative, others positive and they cover a wide range of partly ideological perspectives of potential users. For example, some see the technological focus of PA as a way of enhancing the hegemony of multinational farming corporations, thus some see dangers in its adoption in the developing world. Others imagine that because of its technological demands, PA has little to no application in the developing world. Some see the potential public good benefits of PA, such as practical processes for environmental auditing and management, and product tracking for quality assurance for consumers. (The latter offers a solution to the GMO marketing issue).

It is fair to say that PA will only succeed when it can be framed in a context that appeals to politicians, non-governmental organisations (NGO's) and potential users. The natural tendency of scientists to assume that what they consider to be a good product of research will be enthusiastically embraced by potential users has proved to be naive. Adoption of any given technique in practice requires much support, explanation and nurture. Therefore, defining an overarching context for PA that overcomes some of the stereotypical ideas mentioned above, is a clear priority for PA research in future. Without it, PA may always remain an idea for the future.

A way forward here is to keep a farmer's perspective as the central focus. PA may help any farmer, be it a manager of a "megafarm" in Europe or a small farmer in Africa, to do better than that which is being done already. This perspective, which starts with the tacit knowledge of a farmer, should be helpful as it appeals, in principle, to politicians, farmers and interested citizens alike. Let's consider nitrogen management as an example of building from this perspective. Tacit knowledge, while essential for any farmer will be unlikely to answer the question as to how much nitrate will leach into the groundwater during a cropping season. Still, farmers in many parts of the world are required by law to manage their land in such a manner that groundwater is not polluted. PA can help here to fine-tune existing management procedures (which have been based on years of experience) to reduce nitrogen leaching. So, rather than present PA as a cure-all, it can be positioned to fill specific (and crucial) gaps in the tacit knowledge of farmers.

Research issues

In PA research so far there has been a lot of work on yield monitoring (e.g. Colvin and Arslan, 2000) and some work on quantifying soil variation (e.g. Godwin and Miller, 2003; Adamchuck *et al.*, 2004) for variable-rate application (VRA) of inputs. Today most of the focus seems to be on some form of zone management (Whelan and McBratney, 2003), but there are not many formal Decision Support Systems (DSS) and no well-designed strategies that are flexible enough to incorporate these practices and concepts into the range of management processes that operate in the practical world. The true practical applicability of PA technology really remains linked to high-tech agriculture. Vehicle guidance (and auto-steer) systems are being adopted widely because, from a user's point of view, economic benefits are readily achievable without the need for much, or any, added decision support or system component integration.

The lack of development of appropriate DSS has hindered the full adoption of PA and maybe it is time to consider whether a DSS which encompasses all management aspects is an appropriate goal. Farmers are engaged in adaptive management in a highly variable and unpredictable environment and therefore no farm (or farmer) is the same. It may be more realistic to aim at delivering strategies for specific aspects that fit into an overall management plan that has a highly tacit character at its foundation. Decisions/strategies for site-specific crop management will therefore be best achieved through experiments performed economically on-farm by farmers using the tools of precision agriculture (e.g. van Alphen 2002; Whelan *et al.,* 2003).

Some critical research issues

Besides the crucial policy issues and the decision-support question, there are six other issues which require urgent and ongoing attention by researchers to develop the PA concept to its full potential. They are listed approximately in order of importance.

(a) Appropriate criteria for economic assessment of PA.
(b) Insufficient recognition of temporal variation.
(c) Lack of whole-farm focus.
(d) Crop quality assessment methods.
(e) Product tracking and traceability.
(f) Environmental auditing.

Appropriate criteria for economic assessment of PA. Perhaps the biggest generic impediment is a well-constructed quantitative formulation of optimisation criteria for cropping management that includes environmental impact. A complete criterion would encompass all aspects of the PA concept: spatial and temporally induced variability of yield, profitability of the agricultural enterprise, sustainability of the resource base (soil and water), environmental issues (Bongiovanni and Lowenberg-DeBoer, 2004) and the value of information. These criteria may be designed specifically for different management hypotheses (e.g. uniform, zone and continuous management) and assessed in a single loop of sequential testing.

The criteria should incorporate both private and social values regarding the agricultural production on any specific field (Ancev *et al*., 2004). Private values may be represented by a profit function:

$$\pi = p_y y - \mathbf{c}'\mathbf{x}, \tag{1}$$

where p_y is the exogenous price received per unit of a given crop y, $\mathbf{c}$ is a vector of input prices and $\mathbf{x}$ is a vector of controlled inputs used for producing crop y.

The yield of the crop may be represented by

$$y_{it} = f_{it}(\mathbf{x}_{it}|E(\varepsilon_t|\varepsilon_{t-1}, \ldots \varepsilon_{t-T}); \mathbf{z}_{it}(\mathbf{x}_{it-1}, \ldots \mathbf{x}_{it-T}); \varepsilon_t), \tag{2}$$

where subscript i denotes a spatial index, so that $i = 1$ denotes that the crop is managed uniformly, and subscript t denotes the time step. The time step here is defined in general terms and might conform to various situations, ranging from a daily time step where one can simulate the expected yield and make input decisions accordingly, to a season time step where the time variability only means that the optimal management is likely to change from one season to the next. The vector of controlled input quantities is denoted by $\mathbf{x}_{it}$.[1] Eq. (2) simply states that the quantities of inputs used are dependent on the farmers' expectations (E) about the random uncontrolled inputs ε_t, like rainfall and temperature. These expectations are in turn conditioned on the past realisations of those random inputs. The yield is further dependent on the vector of uncontrolled inputs $\mathbf{z}_{it}(\mathbf{x}_{it-1}, \ldots \mathbf{x}_{it-T})$ which are influenced by past agricultural practices.[2] Such inputs are certain soil physical and chemical properties, including pH, nutrient soil tests, salinity etc. It may be assumed that a social goal is to keep these uncontrolled inputs affected by the agricultural practices at some sustainable level. This may be represented by the "sustainability equation" whereby the level of these inputs is not allowed to drop below some desired value $\mathbf{Z}$:

$$\mathbf{z}_{it}(\mathbf{x}_{it-1}, \ldots \mathbf{x}_{it-T}) \geq \mathbf{Z}, \quad \forall t. \tag{3}$$

Negative (or positive) environmental effects that are associated with the farming practice have to be taken into account when conducting an analysis from a social perspective. Here, the focus is on the negative effects, although positive environmental effects from agriculture are undoubtedly present as highlighted by the multifunctional agriculture argument, which states that agriculture not only provides products but also provides landscaping, agri-biological diversity, conservation and other environmental amenities (MAFN, 2004). The negative environmental effects from farming could be summarised with an environmental damage cost function

$$EDC_t = DC_t(EM_{it}(\mathbf{x}_{it}, \mathbf{x}_{it-1} \ldots \mathbf{x}_{it-T}, \mathbf{z}_{it}, \varepsilon_t), EV_t), \tag{4}$$

where EDC_t denotes the environmental damage costs (not necessarily site-specific) in a given time period. They represent the social costs DC_t as a function of agricultural pollution emissions (almost always site specific) EM_{it} and the economic values EV_t associated with these pollution emissions. The emissions are a function of past and current use of controlled inputs, current state of uncontrolled inputs and current random inputs.

Based on the yield-response function and the environmental damage function, the criterion for representing the social values can be approximated by the solution to the following social optimisation problem:

$$\max_{\mathbf{x}_{it}} TB_0 = \sum_{i=0}^{n} \sum_{t=1}^{\infty} \frac{1}{(1+r)^t} \left[(p_{y_t} y_{it} - \mathbf{c}_t' \mathbf{x}_{it}) - EDC_t \right], \tag{5}$$

subject to Eqs. (2), (3) and (4).

Here, the total social benefits from the agricultural enterprise (TB_0) are the sum of all future discounted (using the social discount rate r) profits to the farmers net of environmental damage costs. The aim is to maximise TB_0 by the optimal choice of the vector of controlled inputs $\mathbf{x}$ (including precision agriculture inputs) in each time period.

Environmental damage costs

As specified in the above criterion, the costs of environmental damage from an agricultural activity are a function of the controlled and uncontrolled inputs to that activity, and their interactions thereof. Due to the site-specific nature of every agricultural field, the pollution emission functions are at present difficult to estimate and generalise. Some available computer simulation models can be used to approximate the pollutant emissions from agricultural processes (Ancev *et al.*, 2003). These models are utilised to numerically determine the relationship between the inputs and the pollution emissions from the agricultural activities (van Alphen, 2002).

The economic values of environmental damage from agriculture are even more difficult to assess, as testified by the lack of economic literature on valuing damages from agricultural pollution. The social costs of these environmental damages will be dependent on the type of environmental values involved. For some environmental values, such as the intrinsic value (the *per se* value) of environmental assets, there are not meaningful ways for economic valuation. For others, the more anthropocentric and utilitarian environmental values, economic methods exist that can be used for evaluation. These economic methods produce reliable and credible value estimates for the directly utilitarian, "active use" values. This is not the case with the less tangible, more elusive "passive use" values, for which there is a great amount of uncertainty associated with the economic value estimates.[3]

When dealing with "passive use" values it is perhaps better to take particular positions out-of-principle, rather than suggest that science can provide a fully quantitative analysis at the time of decision-making. For instance, there has been much discussion in the Netherlands about drilling for natural gas in the "Waddenzee", an ecosystem that is recognised as a world treasure by UNESCO. Scientists tried to model the possible lowering of the sea bottom following the extraction of the natural gas and the ensuing effects on ecology. In view of all the variables involved, the task is scientifically impossible at present, and it would be more realistic to base the debate and political decisions on a statement of principle by political parties which can be either in favour of drilling (an economic focus) or against (an ecological focus). Then, the voter is offered a clear choice. Science has little to offer here. This aspect is also clear when considering the *precautionary principle* in environmental legislation: lack of scientific certainty should not be a reason for inaction when dealing with environmental problems. An example is the ozone-hole: there was no scientific certainty that chlorofluorocarbon gasses were causing the holes in the ozone layer in the 1980s. Still, production of CFC's was terminated and it turns out now, after 20 years, that this was a good decision because the ozone layer re-established itself.

There is another economic aspect of course in relation to the environmental impact from agriculture, which has to do with the current environmental regulation applying to agriculture. These regulations clearly have a direct impact on the economic aspects being considered here, in terms of constraining the input choices and hence profitability (Eq. 5). Nitrogen fertiliser regulation and taxes in Europe are one good example. Threshold values for water and air quality provide solid limits that must be met. They are, in fact, proxy values that indicate a level of pollution that is still acceptable from an environmental or health point of view. The challenge is then to minimise the costs of achieving such limits by creative use of innovative management techniques, including PA.

Insufficient recognition of temporal variation. We have become very familiar with yield maps and analysing the spatial variation in them. We seem to have forgotten about 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 increased.

Some have recognised parts of fields which are temporally stable and others which vary from year to year—this allows better management of weather and climatic risk. A second issue is within-season management. Fine-tuning of within-field operations with split applications using feedback from crop monitoring is clearly a promising way of optimising inputs. Van Alphen and Stoorvogel (2000) saved 17–25% of fertiliser input this way as compared with the regular procedure used by the farmer which was based on up-to-date fertilisation advice by extension services. A second example of within-season management would be the control of soil moisture. Monitoring networks for soil water are still expensive and need to be further developed, as they provide the key to precision irrigation and the more efficient use of increasingly scarce and more-expensive irrigation water. We need to think of precision management as appropriate spatial AND temporal intervention.

Lack of whole-farm focus. Probably 90% or more of the precision agriculture studies reported in the seven International Precision Agriculture Conferences held in Minneapolis, USA and the four European Conferences on Precision Agriculture have been done on single fields on experimental farms or commercial farms. Many studies consider several fields but almost always on different farms. The challenge for precision agriculture is to become an integral part of the normal farming process. Therefore we should like to see all fields on a farm managed in a precision way. Taking the simple example of zone management, we should like to be able to recognise the management classes (groups of soil and agronomic properties) and zones (their spatio-temporal expression) across a whole farm. van Alphen (2002) distinguished four "management units" within a 110 ha farm, which combined several soil types that were pedologically, but not functionally, different. These management units occurred in different patterns within the ten fields of the farm. We need to be able to distinguish such management zones cost effectively at large scales. This is a research challenge. Once this is done, farmers can decide on those fields which are most suitable for precision management and the cropping regimes for the various parcels.

Crop-quality assessment methods. Some of the competitive advantage of precision agriculture will come from the in-field separation of product into quality classes. Economic benefits will come especially if there are non-linearities in the payment of quality premiums. Quality criteria are particularly important for high-value crops such as cotton (fibre length, thickness, strength and colour) and grapes (principally titratable acidity, pH and sugar content plus several others). Some work on the on-the-go sensing of protein and oil content of grains and pulses has been successful but in-field separation (as far as we are aware) remains a concept rather than reality. There has been interesting work on quality assessment on grapes (Tisseyre *et al.*, 2001; Ortega *et al.*, 2003), kiwifruit and bananas (Stoorvogel *et al.*, 2000, 2004). A secondary benefit of this approach is the mapping of quality characteristics to improve agronomic management for optimising the quantity/quality. A lot of work is needed on developing quality criteria and sensor systems in a product-chain approach which will make it feasible to interact effectively with customers.

Product tracking and traceability. Consumers are increasingly demanding more information on the food products they purchase. This has been highlighted by the GMO issue especially in Europe. Precision agriculture offers the possibility of tracking product through a system. The ultimate aim would be a label capable of being read by a consumer's handheld computer/phone/organiser that describes the operations that have been undertaken to produce the product. Progress in electronic labelling is growing apace. So far there is a limited amount of product tracking (e.g. Opara and Mazaud, 2001; Nilsson *et al*., 2004; Tavernier, 2004) but not usually from the perspective of precision agriculture. New European Union regulations (Regulation (EC) no. 178/2002) will provide an added impetus to such developments.

Therefore product tracking and traceability should be a major new focus of precision agriculture research, particularly to provide the tools on-farm to initiate the process.

Environmental auditing. A simple corollary of the product-tracking techniques is the ability of farmers to demonstrate the operations and associated fertiliser/chemical rates that have been applied across a farm. This would allow environmental auditing compliance to be done effectively. However, there are large institutional hurdles which have to be cleared before this can be achieved. Environmental regulations within the European Union, for example, focus on the *means* to achieve environmental objectives rather than on the environmental *goals* to be achieved. Rather than check the groundwater quality directly, emphasis is on arbitrary allowable fertilisation rates that have an unclear relationship to groundwater quality. This approach is associated with massive bureaucratic control mechanisms that are essentially built on a lack of trust in farmers. The challenge is to change this fundamentally by building on farmers' expertise to achieve environmental goals that have been accepted by society. PA in the hands of modern, capable farmers is a powerful tool to achieve this different approach as it is based on trust rather than distrust.

It remains important that governments are made aware of the potential of PA for environmental auditing but it will be very difficult to change current habits. On the positive side, using PA for environmental auditing creates a foundation for restoring trust as a basis for the interaction between governments, farmers and consumers. Research is needed to develop protocols for using data gathered through precision agriculture technologies and this requires inclusion of lawyers and institutional experts in the research teams. Research should aim for specific, well-illustrated case studies that are essential to initiate the necessary paradigm shift.

Training issues

Just how much is the lack of education and knowledge a stumbling block to successful adoption of PA? There is no doubt that this is a problem. We perceive that the lack of functional decision-support tools is still the most rate-limiting step to adoption. Nevertheless there is a need to build human capacity in the field of PA globally. The preferred model for developed countries would be consultants highly trained in precision agriculture who interpret the data, make agronomic recommendations and design and analyse on-going experiments in conjunction with soil and weather monitoring networks to optimise production. At present, there is a lack of researchers and graduates in PA worldwide. Farmers need training principally in the concepts, possibilities and machinery interfaces.

Generic issues—a programme structure for future PA research & development

A programme structure that addresses the key research and implementation issues mentioned above that could be applied at varying intensities within individual countries and commodity groups would be as follows.

Hardware and sensors programme

Objectives
Such a programme would need to develop new equipment and technologies that can be

- extended to farmers as new techniques
- marketed by manufacturers as improved equipment.

Possible subprogrammes – Positioning and guidance, Crop sensing (stress, nutrient, yield potential), Environmental Sensing (soil—moisture, compaction, nutrient, disease), Seeding (seed bed preparation—seed zone versus rooting zone management, placement in the profile, moisture seeking, uniformity across machine), Fertilising (placement in profile), Spraying (incorporation into soil profile, spot spraying), Mechanical weed control (inter row and inter plant), Harvesting (quantity and quality assessment and separation).

Data analysis and decision support programme

Objectives
Such a programme would need to develop:

- protocols and standards for the production of yield maps and other key data layers;
- robust methods for data analysis and integration, and delineation of management zones;
- innovative designs for the implementation of whole-of-field experimentation based on the principles of process control and methods for the analysis of the results of such experiments; and
- easy-to use software and other packaged tools to facilitate the use and adoption of the above by farmers, their consultants and researchers.

Possible subprogrammes – Data management and processing, On-farm experimentation and process control, Software development.

Commodity & whole-farm focus programme

Objectives
Such a programme would try to:

- Apply developed technologies and DSS strategies commercially on-farm. Cost-benefit analysis of commercial site-specific management including environmental cost and evaluating the triple-bottom line.
- Integrate technologies to achieve a whole-farm focus to site-specific crop management rather than the current unit (field) by unit (field) approach.
- Establishment of protocols for site-specific management for different commodities e.g. cotton, grape and wine, grains, horticulture, livestock, sugarcane, coffee.

Possible subprogrammes – Evaluation (including economic appraisal) of site-specific on-farm operations (sowing, chemical application, harvesting), Precision commodity production, Whole enterprise optimisation.

Environmental auditing & product tracking programme

Objectives
Such a programme would attempt to improve the quality and decrease the environmental impact of an agricultural product through promoting greater vertical integration and would,

- Provide the consumer of a product with information on the environmental impact and quality assurance of a production system.
- Provide a grower with consumer and supply-chain feedback on the product and where possible spatially apply the information within the production system.
- Attempt to understand the economics of environmental information in Precision Agriculture and apply this knowledge to benefit on-farm profitability.

Possible subprogrammes – Supply chain information systems (tracking), Environmental auditing, Quality auditing, Economics of site-specific environmental information.

Community empowerment and capacity building programme

Objectives
Such a programme would need to:

- Improve adoption of PA technologies at the farm level. Specific activities within this sub-programme would include: Raising awareness of PA technologies through presentations to schools, community groups, field days and local media outlets. The idea would be to compare the current situation with the one to be made possible by PA and place matters in a context of sustainable development. Provision of short PA training programmes for farmers. Exposure of commodity specific PA demonstration sites. Facilitation of local PA interest groups.

- To develop the next generation of PA professionals through: Training of masters and doctoral research students in PA. The development of new PA curriculum materials at undergraduate and postgraduate levels. The development of graduate courses in PA particularly aimed at the education of agronomic consultants.
- Develop linkages between researchers, farmers, farm machinery manufacturers, sensing, positioning and instrument manufacturers and consultants within the PA sector to: Enhance adoption of existing PA technology by facilitating information exchange between these sectors. Promote the adoption of new technologies developed by researchers as well as consultants and other firms within the small and medium enterprise (SME) sector. Encourage the adoption of data standards to enhance the exchange of data between sensor technologies and farm-machinery delivery platforms.

Possible subprogrammes – On-farm adoption of PA management practices, Professional training in PA, Commercialisation of PA technologies.

Typology of precision agriculture regions

To gain an understanding of the possibilities worldwide, it seems worthwhile to recognise four different types of agricultural region. This typology is based on the level of general economic development, the level of government support for agriculture, and the nature of the production unit.

Type A. Developed economies with government-supported agriculture

The European Union dominates this class, but it also includes Japan and the USA. It is within these countries that precision agriculture developed. Subsidisation of agriculture has led to increased inputs to maximise production leading to severe environmental impacts. These problems are being increasingly recognised. The most recent EU policy calls for reductions in import duties and export subsidies. Also the WTO recently condemned the price support for cotton in the USA. And, particularly in Europe, recognition of the social need for sustainably-managed landscapes should shift the focus from maximum production to environmentally optimal production following some of the features of Eq. (5). The aim for farmers will be to maximise income both from value of the product (quantity and quality) and through payments from good environmental practices. Equation (5) will come more into play if and when agriculture moves to applying environmental penalties as well as payments to the true cost of production. The relatively limited adoption of PA in the EU suggests that the environmental management possibilities have not yet taken hold.

Type B. Developed economies with minimally government-supported agriculture

Countries include Australia, New Zealand, Argentina and Brazil. Precision agriculture technology came later to these countries than to the US and Europe. Because of the reliance in these economies on agricultural exports, emphasis is on competitive advantage and production quantity and quality, rather than the environment. Some believe this type, because of its relatively large field sizes, has the greatest potential for precision agriculture, at least initially.

Type C. Developing economies with plantation and/or centrally-planned agriculture

This applies to most third-world countries. Precision agriculture is being applied to sugar-cane in Brazil and Mauritius, oil palm in Malaysia, bananas in Costa Rica and research is beginning in coffee. Yield monitoring systems have been, or are being, developed but these are generally for high-value food crops so the emphasis will be on quality. Medium technology is appropriate here. The Costa Rica banana work is an excellent example (Stoorvogel *et al.,* 2000, 2004).

Type D. Developing economies with small-scale or subsistence agriculture

Most third world countries have some of this kind of farming. As this depends on small-holders on small tracts of land, it has been thought that precision agriculture has little application. To the degree that PA is technology dependent, this is true. However the 1970s saw the initial development of "appropriate technology" for such circumstances. There remains a big challenge for "appropriate PA technology" for this class and Cook *et al.* (2003) succinctly discuss a number of options for the application of the PA philosophy in these countries. Notwithstanding the technology issue, precision agriculture can be implemented through improved agronomic decision-making at the same spatial scale by increasing the number of decisions per unit time. This can be achieved by improving the monitoring of crops through farmer training along with appropriate DSS tools. The NUTMON (Smaling and Fresco, 1993) set of decision-support systems, (www.nutmon.org—last accessed 12/04), has been applied successfully in Africa (Faerge and Magid, 2004; De Jaeger *et al.,* 2004).

Indices of potential for precision agriculture. While site-specific indices of opportunity for PA at the within-field and within-farm scales are under development (e.g. Pringle *et al.,* 2003), a broader, simpler approach is taken here to assess the situation at the country level. Using and combining published statistics[4] (www.nationmaster.com—last accessed 12/04) as first suggested by Swinton and Lowenberg-DeBoer (2001), some indices can be derived which may act as indicators of a country's overall suitability for precision agriculture.

A very simple spatial index may be the area of land each person must manage (Table 1). Based on the simple notion that, on average, the environmental variation

Table 1. Country indices of "potential" for precision agriculture

	Spatial index		Environmental index	
Rank	Country	Ha of cropland/ worker	Country	Fertiliser use (kg per ha of cropland)
1	Canada	154.2	Ireland	594.5
2	Australia	142.5	Netherlands	450.2
3	United States	77.1	Egypt	385.8
4	Denmark	29.5	Costa Rica	385.0
5	France	25.4	Slovenia	369.4
6	Sweden	25.4	Japan	301.0
7	New Zealand	23.3	United Kingdom	285.8
8	Bulgaria	23.3	Vietnam	285.3
9	Russia	21.5	Israel	256.0
10	Finland	19.9	China	255.6
11	Kazakhstan	18.7	New Zealand	255.5
12	Argentina	18.5	Switzerland	233.4
13	Estonia	18.3	Germany	228.2
14	Lithuania	17.6	Norway	222.0
15	Libya	17.5	Chile	212.9
16	Latvia	17.0	France	211.7
17	Spain	16.2	Lebanon	199.6
18	Germany	15.2	Malaysia	187.8
19	Slovenia	14.6	Korea North	175.5
20	United Kingdom	13.7	Denmark	159.9
21	Ukraine	12.4	Italy	159.4
22	Belarus	12.0	Bangladesh	156.3
23	Hungary	11.6	Austria	151.7
24	Croatia	11.3	Uzbekistan	149.9
25	Norway	11.0	Colombia	144.8
26	Czech Republic	10.2	United Arab Emirates	142.1
27	Guyana	10.2	Finland	140.6
28	South Africa	9.9	Croatia	139.8
29	Austria	9.2	Pakistan	135.1
30	Italy	9.1	Sri Lanka	128.9
31	Bosnia and Herzegovina	8.5	Belarus	128.7
32	Slovakia	8.2	Honduras	126.5
33	Uruguay	7.9	Greece	118.7
34	Romania	7.7	Spain	118.0
35	Cuba	7.2	Brazil	114.0
36	Nicaragua	6.9	Guatemala	111.1
37	Ireland	6.8	Poland	106.0
38	Israel	6.6	Saudi Arabia	104.6
39	Lebanon	6.4	Sweden	103.5
40	Macedonia	6.0	United States	103.4

increases with area, the larger the area, the greater the spatial potential for PA. We note that national statistics will obscure, to some extent, regional differences within countries, e.g. the national average area of cropland per worker in Argentina is much smaller than in the Pampas region. This does not take account of the intrinsic environmental variability within a given area. Using this index, Canada, Australia (Type B) and the US are very suitable for PA.

Table 2. Key focus, barriers to adoption and research issues by typology

	Type A	Type B	Type C	Type D
Industry focus	Environment,	Profitability, quality	Quality,	Sustainability
Training focus	Graduates, consultants	Graduates, consultants	Researchers, managers	Researchers, farmers
Barrier to adoption	DSS	DSS	DSS	DSS, research support
Research issues	Environmental economics, Quality assurance and product tracking, Crop monitoring	Crop quality assessment Whole-farm optimisation	Crop quality asessment	Monitoring

A second indicator is based on an environmental index. In this case we simply use fertiliser usage because it might be seen to have an environmental impact. Those countries with high fertiliser usage have the potential to use precision agriculture to manage this more optimally. Many of the northern European countries and Japan (Type A) are listed here but it is interesting to note countries such as Egypt and Costa Rica are high on the list.

Other indices that would be useful would include crops produced (as PA is more likely to be profitable for higher-value crops), prices (higher prices leading to greater investment in optimising management), capital per worker and human capital (related to the skills and education of workers).

Issues by typology

When one fits together the generic research and training issues and the typology of precision agriculture regions, a matrix emerges (Table 2) indicating the key focuses, barriers to adoption and issues to be researched.

Conclusions

We have to be careful that we do not get stuck in a limited paradigm, such as zone management. Precision agriculture offers many countries a range of possibilities for all kinds of goals aimed at both the private and public good. The challenges are great, but they are also clear. Concerted and co-ordinated research effort is needed in the following six areas.

(1) Appropriate criteria for the economic assessment of PA.
(2) Recognition and quantification of temporal variation.
(3) Whole-farm focus.
(4) Crop quality assessment methods.

(5) Product tracking and quality assurance.
(6) Environmental auditing.

Notes

1. Controlled inputs refer to inputs that are under control of the farmer, like seed, fertilisation, irrigation, pesticides, labour, but also precision agriculture technology and management including own time commitment.
2. Indeed these uncontrolled inputs are likely to be dependent on the past random uncontrolled inputs ε_{t-i} as well. However, we are not explicitly making that assumption here in order to keep relative notational simplicity. We are grateful to a referee for pointing this out.
3. For a good introduction on the active and passive use values and the methods for their economic evaluation (see Bateman *et al.,* 2003).
4. We use the word statistics here with its original meaning, i.e., "state numbers" or numbers that describe attributes of a whole country.

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Merci sans excision
Nous vous remercions sans exception
Pierre de précision
Farming by soil
Farming without toil
Farming for oil
Farming minus spoil
GPS
VRT
DSS
Where are we?
Semi-automatons
Wrestling with variation
And the buck
Trying it up
Tying it down
Zoning it around
Gross and grainy
But with crystalvision
Somewhen precision
Will move a molecule here
Take two or three from there
Can do it everywhichwhere
Everywherever
Notre souvenir
de Pierre

David Van der Linden

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