Final Report

Sugar Research and Development Corporation Project CSE018

Precision Agriculture:
An avenue for profitable innovation in the Australian sugar industry, or expensive technology we can do without ?

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Executive Summary

Precision Agriculture (PA) is an all-encompassing term given to a suite of technologies which promote improved management of agricultural production through recognition that the potential productivity of agricultural land can vary considerably, even over very short distances (a few m). The key technologies involved are yield monitors, remote and proximal sensing, the global positioning system (GPS) and geographical information systems.

This project was conducted in response to the recognition by the Sugar Research and Development Corporation (SRDC) that the Australian sugar industry needs an informed basis from which to make decisions as to appropriate investment in PA. The project took the form of a review of published literature on PA and two industry workshops: the first conducted mid-project to provide the Industry Reference Group with an opportunity to review project progress and to make input to the recommendations emerging from it; the second conducted at the completion of the project to inform industry of the conclusions drawn and to promote industry input into SRDC's priority setting with respect to future PA research.

The review briefly discusses the philosophy underpinning PA, looks at PA research and application in a range of cropping systems, including sugarcane production, from around the world and considers the key drivers of short range spatial variability in these production systems. Constraints to the adoption of PA and its likely economic benefits are also considered in light of experiences from around the world. The opportunities that PA offers to the Australian sugar industry are identified, along with recommendations of further research, development and extension to facilitate its productive and profitable adoption.

It is concluded that sugarcane production is ideally suited to the adoption of PA. However, a number of key tasks in Research, Development and Extension (RDE) are identified which will be required to enable its implementation in the Australian sugar industry. These are as follows:

1. Access to calibrated, and easily calibratable, yield monitoring systems and the associated development of a robust protocol for yield map production is required.
2. An assessment should be made of the utility for in-field management, the most appropriate and cost-effective spatial resolution and the optimal time of image acquisition, for remotely sensed imagery. Associated with this, an evaluation of the merits of airborne compared to satellite-based remote sensing platforms should be carried out.
3. Case studies highlighting the utility (and shortcomings) of the various tools of PA in delineating management zones within sugarcane blocks should be undertaken in each of the major canegrowing regions. These should include investigation of relationships between yield, indices of crop quality, soil properties and terrain attributes (pre- and post- laser levelling) as the basis for more targeted management, and evaluation of the merits of selective harvesting based on ccs variation and of the targeted application of ripeners. The opportunities for variable management of irrigation water should also be explored. In all cases, economic analysis should form a key part of the research, and should determine and demonstrate the potential profitability of PA approaches, as well as inform advice as to the relative merits of putting effort into removing variation as opposed to managing in response to it.
4. An evaluation of the utility of whole-of-block approaches for sugarcane agronomic experimentation and the development of site specific criteria for interpretation of soil test data and development site-specific management strategies should be undertaken.
5. Training and extension support in PA data acquisition, management and analysis should be developed and provided to leading growers and consultants. The emergence of local service

provicers in these aspects of PA, in addition and as opposed to equipment sales, should also be encouraged. As part of this activity, a possible role for groups like the Herbert Resource Information Centre (HRIC), regional Productivity Services and the Southern precision Agriculture Association (SPAA) should be considered and encouraged. However, it is suggested that implementation of this recommendation be witheld until the case studies (recommendation 3) begin to demonstrate that PA is likely to enhance industry profitability.

6. A sensor development program should be initiated. Of highest priority is development of an on-the-go sugar (ie ccs) sensor for use during harvesting. Development of companion sensors for other attributes of cane quality, including key sugar impurities, may also be warranted.

7. An evaluation should be made of the most appropriate ways of integrating existing Sugar Mill and Productivity Service data collection and harvest management systems with PA applications. As part of this, consideration should be given to software compatibility and ease of integration of 'standard PA methodologies' with software platforms currently being used in the sugar industry, and/or the need for a move to software platforms not currently being used.

In addition, there would be much value in initiating research aimed at demonstrating the contribution that PA can make to improved environmental stewardship. Whilst not an essential task in terms of facilitating access to the agronomic and economic benefits of PA, the importance of an ability to demonstrate that the sugar industry is playing its role in preserving the sensitive ecosystems which border it is something which can not be overstated.

Background

Land is variable. This is a truism, irrespective of the scale of inspection; no two soil particles are the same, no two fields are the same, no two farming regions are the same and neither, of course, are any two countries. Variability should be especially apparent in the Australian sugar industry given that it occupies the active floodplains of rivers draining a strip of around 2000 km of the Great Dividing Range - in regions as diverse as Tully, where mean annual rainfall is around 4000 mm, and the Burdekin (less than 300 km to the south and with mean annual rainfall of around 950 mm) where irrigation water is an essential input to production. Because of the strong influence on crop production of soil properties, rooting depth, nutrition, agronomic management, and the interaction of these factors with climate, the agricultural productivity of land is also highly variable. Yet the majority of agricultural activity, like sugarcane production, is carried out in square or rectangular paddocks using management strategies which assume uniformity within production units which may be as large as many hundreds of hectares. The application of Precision Agriculture to many crop production systems worldwide, and in particular, the use of yield mapping, shows that this assumption is flawed.

Indeed, the advent of Precision Agriculture (PA) is a response to the recognition that land is indeed variable, and also to the recent availability of some key enabling technologies, of which global positioning systems (GPS), geographical information systems (GIS), crop yield monitors and remote sensing are the most important. Some exploratory research and application of PA to sugarcane production took place in Australia during the latter part of the 1990s, but a collapse in world sugar prices to around 5c/lb, amongst other factors, resulted in almost no sustained adoption. Recently, and following similar interest in the Australian grains industries, there has been strong sugar industry interest in controlled traffic and the application of GPS-guidance systems to sugarcane production. Along with much improved sugar prices, acceptance of a general need for the

industry to modernise, and the on-going need for the industry to demonstrate the use of environmentally sustainable best-practice, this has led to renewed interest in PA.

This project is a response to this renewed sugar industry interest in PA, and in particular, a desire on the part of the Sugar Research and Development Corporation (SRDC) to ensure that any future investment in PA-related research, development and extension (RDE) is as well targeted as possible.

Objectives

Drawing on our expertise and 10 years experience in Precision Agriculture (PA) research and application for the sugar, grains and wine industries, our close links to key sugar industry practitioners and personnel, and input from SRDC's own nominees, this project will:
- Conduct a review to identify the opportunities, advantages, limitations, risks and costs of the range of technologies that would be applicable to implementation of PA in sugarcane;
- Identify where future RDE would benefit the industry in implementing PA for sugarcane;
- Provide a report and present discussion on the above as described in SRDC's terms of reference.

Each of these objectives has been met.

Methodology

Three main methodologies were employed in this project. First, a review of the scientific literature pertinent to PA was conducted. Second, and after all members had been provided with a draft copy of the review, a one-day workshop was held mid-project (February 22nd, Townsville) in which members of the project's Industry Reference Group were asked to describe their own experiences with PA (if any), and to make input into the development of recommendations arising from the review for future R, D and E which would benefit the industry in implementing PA. Finally, an open industry workshop was held (May 11th, Cairns) at which the project outputs were presented to industry and at which an evaluation of the project impact and effectiveness was conducted.

Outputs

The literature review is attached at Appendix 1.
A report on the mid-project workshop is attached at Appendix 2.
A report on the project evaluation carried out at the industry workshop held at the end of the project is attached at Appendix 3.

The detail contained in Appendix 3 is significant in that it offers strong endorsement for the recommendations derived from the review (see below and Appendix 1). Thirty six participants at the SRDC-facilitated workshop held in Cairns at the end of the project provided feedback as follows:

A high ranking was given to the potential for precision agriculture to contribute to the Australian sugarcane industry (8.25 out of 10). In terms of the relative importance of different aspects of PA, high rankings were given by the workshop participants to yield monitors (8.97/10), GPS/GIS systems (8.92/10), attribute mapping (8.28/10), remote sensing (7.94/10), soil sensing (7.89/10) and

variable rate application (7.74/10). Participants ranked requirements for further RDE as follows: skills development for industry personnel (9.00/10), economic benefits of PA (8.86/10), yield monitor (8.80/10), environmental benefits of PA (8.63/10), experimental methodology (8.17/10) and quality sensors (8.12/10) highly. Feedback also suggested a coordinated industry approach to researching and implementing PA as well as investigation into identification of causes and management of variability were important.

Intellectual Property

None.

Environmental and Social Impacts

There are no negative environmental impacts arising from this project. However, implementation of its recommendations and the adoption of PA by the Australian sugar industry has the potential to deliver significant environmental benefits.

Expected Outcomes

The project team believe that the review (Appendix 1), and especially its recommendations, provides SRDC with a sound basis on which to make investment decisions pertaining to R, D and E relating to PA; the industry workshop (Appendix 3) also made a useful contribution to this process. More generally, we believe that adoption of PA by the industry may lead to enhanced industry profitability through the more efficient use of the inputs to production, improved mechanisms for realising the outputs from production, together with a reduced environmental impact arising from canegrowing.

Overall, we anticipate an increased industry return from SRDC investments in PA, resulting from an improved understanding of the best process for introducing the technologies to the sugar industry.

Recommendations / Future Research Needs

This review (Appendix 1) identified a number of future research needs which would facilitate the appropriate adoption of PA in the Australian sugar industry and made a number of recommendations accordingly. These are detailed in Appendix 1, and in particular, sections 7 and 8, and are also reproduced in the Executive summary above. These relate to:

1. The need for calibrated, and easily calibratable, yield monitoring systems and a robust protocol for yield map production.
2. Assessment of the utility for in-field management, of remotely sensed imagery and the most appropriate and cost-effective spatial resolution, acquisition platform (satellite or aircraft) and optimal time of image acquisition.
3. The need for regional PA case studies.
4. Evaluation of the whole-of-block approaches for sugarcane agronomic experimentation.
5. Training and extension support in PA data acquisition, management and analysis.
6. Development of on-the-go sensors for ccs and, perhaps, key impurities, for use during harvesting.

7. Integration of existing Sugar Mill and Productivity Service data collection and harvest management systems with PA applications.
8. Evaluation of PA as a tool to assist in improved environmental management.

List of Publications

No publications have arisen from this project to date. However, the review attached at Appendix 1 is presently being revised (and shortened) prior to submission for publication in *Precision Agriculture*.

An article reporting on this project appeared in the *Australian Canegrower* **29** (9) – 7 May 2007.

Appendix 1.

Precision Agriculture – An avenue for profitable innovation in the Australian sugar industry, or expensive technology we can do without ?

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Summary

Precision Agriculture (PA) is an all-encompassing term given to a suite of technologies which promote improved management of agricultural production through recognition that the potential productivity of agricultural land can vary considerably, even over very short distances (a few m). The key technologies involved are yield monitors, remote and proximal sensing, the global positioning system (GPS) and geographical information systems.

This review is a response to the recognition by the Sugar Research and Development Corporation (SRDC) that the Australian sugar industry needs an informed basis from which to make decisions as to appropriate investment in PA – whether these be in terms of pragmatic application by Australian cane growers, or with respect to research to facilitate such adoption. The review briefly discusses the philosophy underpinning PA, looks at PA research and application in a range of cropping systems, including sugarcane production, from around the world and considers the key drivers of variability in these production systems. Constraints to the adoption of PA and its likely economic benefits are also considered in light of experiences from around the world. The opportunities that PA offers to the Australian sugar industry are identified, along with recommendations of further research, development and extension to facilitate its productive and profitable adoption.

It is concluded that sugarcane production is ideally suited to the adoption of PA, and a number of recommendations are made as to how this adoption might be supported. However, for adoption to be successful, significant changes to current (Australian) practices may be required, especially with respect to harvest management. It also seems likely that, for the benefits of PA to be maximised, the sugar industry will need to consider it as a tool for optimising the holistic management of sugar production, as opposed to solely an avenue for improving the agronomic management of sugarcane.

1.   Introduction

Land is variable. This is a truism, irrespective of the scale of inspection; no two soil particles are the same, no two fields are the same, no two farming regions are the same and neither, of course, are any two countries. Variability should be especially apparent in the Australian sugar industry given that it occupies the active floodplains of rivers draining a strip of around 2000 km of the Great Dividing Range - in regions as diverse as Tully, where mean annual rainfall is around 4000 mm, and the Burdekin (less than 300 km to the south and with mean annual rainfall of around 950 mm) where irrigation water is an essential input to production. Because of the strong influence on crop production of soil properties, rooting depth, nutrition, agronomic management, and the interaction of these factors with climate (Runge and Hons, 1999), the agricultural productivity of land is also highly variable. Yet the majority of agricultural activity, like sugarcane production, is carried out in square or rectangular paddocks, which may be as large as many hundreds of hectares, under the assumption that the optimal practice is to use a single uniform management strategy. As Figure 1 illustrates, this assumption is flawed.

(a) (b)

(c) (d)
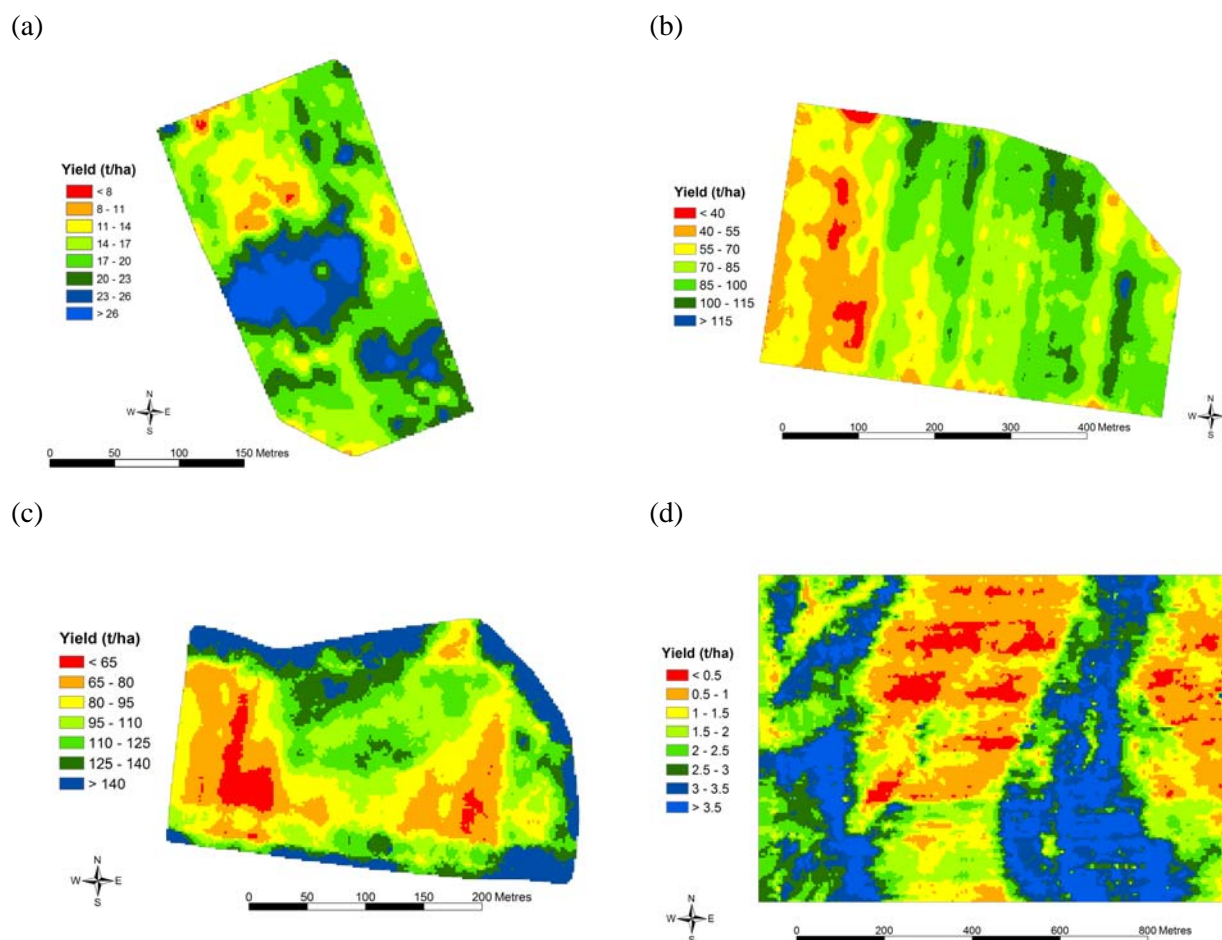
Figure 1. Yield variation in (a) a 4.3 ha Shiraz vineyard in Padthaway, SA (Bramley and Hamilton (2005); (b) a 22 ha tomato field near Jerilderie, NSW (data kindly provided by Brendan Williams, GPS-Ag); (c) a 12.5 ha block of sugarcane near Ingham, Qld (Bramley and Quabba, 2001, 2002); and (d) a 79 ha wheat paddock at Three Springs, WA (Wong and Asseng, 2006).

The advent of so-called 'Precision Agriculture' (PA; eg Cook and Bramley, 1998; Pierce and Nowak, 1999; Srinivasan, 2006) is a response to the recognition that land is indeed variable, and also to the recent availability of some key enabling technologies, of which global positioning systems (GPS), geographical information systems (GIS), crop yield monitors and remote sensing are the most important. Some exploratory research and application of PA to sugarcane production took place in Australia during the latter part of the 1990s (see section 4 below), but a collapse in world sugar prices, amongst other factors, resulted in almost no sustained adoption. Recently, and following similar interest in the Australian grains industries, there has been strong sugar industry interest in controlled traffic and the application of GPS-guidance systems to sugarcane production. Along with much improved sugar prices, acceptance of a general need for the industry to modernise, and the on-going need for the industry to demonstrate the use of environmentally sustainable best-practice, this has led to renewed interest in PA (Wrigley and Moore, 2006).

This review has been prepared in response to this renewed sugar industry interest in PA, and in particular, a desire on the part of the Australian Sugar Research and Development Corporation (SRDC) to ensure that any future investment in PA-related research, development and extension (RDE) is as well targeted as possible. It therefore has a similar set of objectives to a workshop held almost 10 years ago when the application of PA to sugarcane production was first canvassed
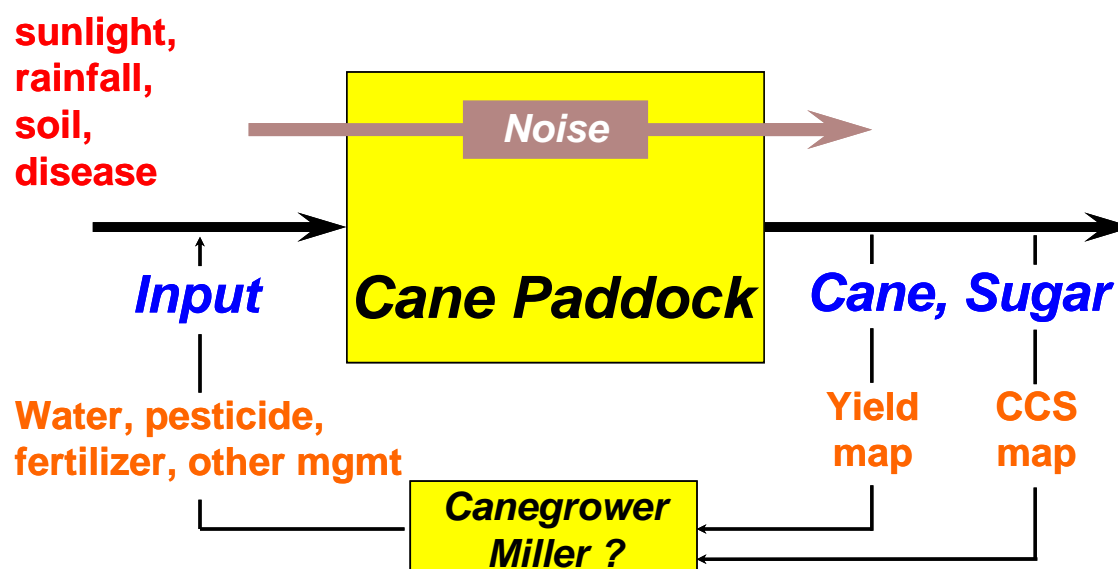
(Bramley *et al.*, 1997). In the interim, a significant body of grower and researcher experience has accumulated in other industries around the world (eg Srinivasan, 2006 and references therein), and in particular, in Australia (eg Cook *et al.*, 2006) where, in addition to the predominant PA focus in the grains industries, there has also been interest shown by the wine, cotton and other cropping industries. The biennial International Conference on Precision Agriculture hosted by the University of Minnesota has now been held on eight occasions, whilst the European Conference on Precision Agriculture will be held for the 6th time during 2007; the 10th Annual Australasian Symposium on Precision Agriculture (see www.usyd.edu.au/su/agric/acpa/pag.htm) was held in 2006 and is now jointly hosted by the University of Sydney and SPAA (www.spaa.com.au), an Australian farmer-based group active in the practical use of PA. The journal *Precision Agriculture* has published 7 volumes comprising 33 issues since its inception, whilst aspects of PA are regularly canvassed at more general agronomic conferences and technical meetings. Meanwhile, in Australia, publications providing advice and instruction on PA for growers and their advisors have been produced for both the grains (Leonard and Price, 2006) and wine (Proffitt *et al.*, 2006) industries; both of these publications have much to offer interested sugarcane growers and their advisors, and indeed to producers of other crops.

Against this background, and the extensive literature associated with it, this review makes no attempt to be comprehensive in referring to all published research on PA. Rather, it focuses on exemplary published work from around the world, and uses this, together with the research experience of the author and colleagues in the application of PA to the Australian wine, sugar and grains industries, to draw out the important issues that can be expected to require attention in considering the application of PA to sugarcane production in Australia. Since the idea of PA as 'information-intensive' agriculture (Fountas *et al.*, 2005) is a central theme, the use of controlled-traffic and GPS guidance systems are not canvassed in any detail in this review as their application neither generates nor requires detailed information about crops or soils at high spatial resolution. It is nevertheless recognised that controlled traffic and guidance systems may play an integral part in the adoption of PA by Australian canegrowers, since such technologies, which are already being adopted, can be useful in familiarising growers with the use of GPS in their production systems and may reduce the capital investment required for adoption of yield mapping and targeted management. These issues, amongst others, are canvassed by a companion review (Davis *et al.*, 2007).

2.   Background philosophy and enabling technologies

Ten years ago, Rawlins (1997) noted that PA was neither new nor complicated since, even by that time, it had already been practiced in the dairy industry for many years, with cows producing a full bucket of milk being given a full scoop of grain at milking, and those producing half a bucket only getting half a scoop. The focus is therefore on the animal rather than the herd (Cook and Bramley, 1998; Wathes, *et al.*, 2005). That is not to suggest that in cropping applications of PA, the focus is necessarily on individual plants. Indeed, in annual cropping systems, such an approach is unlikely to be either pragmatically or economically feasible. Rather, what have conventionally been managed as large homogenous fields are divided into smaller units of characteristic performance, or 'zones' (Cuppitt and Whelan, 2001; Whelan and McBratney, 2003), for which some form of differential or targeted management may be warranted. Of course, farmers have always known that their fields were variable, but without the tools to either quantify or manage this variability, they have had to treat it as 'noise' (Cook and Bramley, 1998) and so have had little choice but to manage on the basis of homogeneity.

The philosophy behind the move towards more targeted management and the tools on which it depends have been discussed widely elsewhere (eg Bramley *et al.*, 1997 and references therein; Pierce and Nowak, 1999; Cook and Bramley, 1998; Srinivasan, 2006 and references therein). In summary, it is recognised that the inherent variability of land (topography, soil properties; see

sunlight,
rainfall,
soil,
disease

Noise

Input

Cane Paddock

Cane, Sugar

Water, pesticide,
fertilizer, other mgmt

Yield
map

CCS
map

Canegrower
Miller ?

Figure 2. Sugarcane production as a partially controllable input-output process. Whilst some things cannot be controlled (eg the incidence of sunlight) resulting in some *noise* in the system, many of the inputs may be controlled, and with the feedback information provided by the yield map, these may be controlled differentially and with greater certainty of achieving desired outcomes than is possible at present under a uniform system of management.

section 5), leads to variation in its potential productivity. As a result, the input-output relationships driving the production system (Figure 2) can vary, often over distances of only a few metres (Cook and Bramley, 2000; McBratney and Pringle, 1999). By better understanding these relationships, management strategies may be implemented in which the inputs to the production system are closely matched to the desired and/or expected outputs (Figure 2). Thus, the adoption of PA aims to increase the likelihood of a beneficial outcome by either better targeting inputs (Cook and Bramley, 1998) or selective harvesting of outputs (Bramley *et al.*, 2005b; Proffitt *et al.*, 2006). Note that whilst 'inputs' are often taken to infer fertilisers, they also include irrigation water, pesticides, herbicides, labour and significantly, the timing of operations such as harvesting. In the case of sugarcane production, they could also include the use of chemical ripeners, or dual row or high density planting as opposed to single rows at 'standard' intervals. There may also be opportunities for selectively harvesting sugarcane (see sections 3.2 and 7 below).

The implementation of a PA approach to agricultural production is analogous to the idea of *process control* as employed in manufacturing industry. Cook (1997) noted that one of the fundamentals of business management is that continuous improvement is necessary to maintain competitiveness in an international market. Muchow *et al.* (2000) made a similar observation in a sugar production context. Similarly, Kaydos (1991) suggested that permanent product improvement only occurs when the production process is itself changed. Thus, PA provides a suite of tools that may assist in improving the production process and, as a consequence, the product. These tools promote the capacity for growers to acquire detailed geo-referenced information about crop performance and to start using this to tailor production according to their expectations and desired goals in terms of yield, quality and the environment.

It follows from the above that a number of key enabling technologies are critical to PA, of which global positioning systems (GPS), geographical information systems (GIS), crop yield monitors and remote sensing are the most important. It is beyond the scope of this review to provide detailed discussion of how these work, and since they have been in use for a variety of applications for many years, not necessarily just in agriculture, such discussion is unlikely to usefully add to what is already available; remote sensing, in particular, is supported by a vast literature. Suffice to say here that

several good general descriptions of the relevant technologies are readily available. Recent accounts are provided in Leonard and Price (2006), Proffitt *et al* (2006) and Stafford (2006), whilst more sugarcane-focussed, albeit older, discussions are presented in Bramley *et al.* (1997).

Arguably of greater importance to the sugar industry at this stage than the question of how do these technologies work, is the question of how they can best be used ? Whilst the answers to these questions are inextricably linked, if we accept that they do work and focus instead on how to take advantage of this, the benefits of using them may accrue more quickly. This point is illustrated here using remote sensing as an example. Remote sensing is a particularly pertinent example for sugar producers because the crop is too tall and too dense for much of the season for on-ground inspection to reveal anything other than the condition of the cane at the edge of a field; obtaining information about the cane in the centre of a field is extremely difficult.

A number of remote sensing instruments are already available to Australian farmers (eg Hall *et al.*, 2002) and the calculation of indices such as the normalised difference vegetation index (NDVI; Rouse *et al.*, 1973), using data collected from them, is well understood by researchers and commercial service providers alike, although Schmidt *et al.* (2004) note that selection of the most appropriate vegetation index for sugarcane is still a researchable issue. What is probably less well understood by potential users in the sugar industry, are issues surrounding the choice of spatial resolution (what is the smallest detectable object on the ground ?), radiometric resolution (how many 'bits' or levels, usually represented by colours, should the observed radiation be divided into ?), spectral resolution (how many wavebands can be simultaneously recorded ?), and the optimal timing and repeat frequency of image acquisition; Hall *et al.* (2002) provide a useful discussion of these issues. In practice however, and assuming that NDVI or a related index of photosynthetically active biomass is what is required, radiometric and spectral resolution are not factors which purchasers of remote sensing have much control over, since for all practical purposes, they are determined by the commercial availability of particular remote sensing platforms. Thus, in the first instance, and mindful that processing costs are directly proportional to spatial resolution, sugar producers would do better to put their effort into consideration of what spatial (ie on-ground) resolution is appropriate and when during the season such imagery provides the most useful information; subsequent research may indicate that specific applications such as disease identification or variety discrimination may warrant modification of spectral resolution or the acquisition of imagery at wavelengths other than the standard blue, green, red and infra-red used in multispectral applications (eg Apan *et al.*, 2004; Arkun *et al.*, 2000; Galvão *et al.*, 2005; Markley and Fitzpatrick, 2004). The need for such research will primarily be driven by the questions that industry wishes to ask of such technology in addition to the ubiquitous desire for mid-season information about canopy size and condition (eg Hall *et al.*, 2002), the consequent prediction of yield (eg Almeida *et al.*, 2006), or some index of crop quality (eg Lamb *et al.*, 2004). This then leads to another key question as to what other technologies, remote or proximal, might be needed that are not currently available ? In a sugar industry context, an 'on the go' commercial cane sugar (ccs) sensor is an obvious example. In the meantime, and given the predominance of a 'closed canopy' over most of the growing season, meaning that effort need not be put into removal of inter-row (ie non-cane) signals, the question of what spatial resolution is desired will be largely determined by the size of the minimum area for which growers would consider targeted management to be feasible. In turn, and along with other factors, such as the likelihood of cloud cover at the desired time of image acquisition, this will have a bearing on whether satellite or airborne platforms are most appropriate for sugar applications.

2.1. *Spatial vs temporal variation and the null hypothesis of PA*

A significant constraint to the adoption of PA in Australian broadacre cereal cropping has been a perception that, irrespective of any economic benefit which may accrue in a given year, investment in PA is not necessarily going to be cost-effective because the magnitude of inter-annual variation in crop yields (which is climate-driven, and primarily due to rainfall) may be greater than the range of intra-annual (ie within field) variation (eg. Robertson and Brennan, 2006). Indeed, Wong and Asseng

(2006) demonstrated that the degree of spatial variation in a WA wheat paddock in a given year was a function of seasonal rainfall. An additional complication in broadacre cropping is the use of rotations involving crops (eg wheat and lupins) which may have quite different fertilizer requirements. These sort of concerns led Whelan and McBratney (2000) to pose the 'null hypothesis of precision agriculture' which states that "given the large temporal variation evident in crop yield relative to the scale of a single field, then the optimal risk aversion strategy is uniform management."

Bramley and Hamilton (2004; 2006) analysed yield maps obtained from a number of vineyards over several vintages to demonstrate that the patterns of variation in winegrape yields were stable in time, even though annual mean yields varied markedly from year to year as a function of climatic variation. This lead Bramley and Hamilton (2004) to reject the null hypothesis of PA. The perennial nature of grapevines perhaps makes vineyards a simpler system than a broadacre field under rotation, as does the use of centre-pivot irrigation in some US corn-soybean systems (eg Diker *et al.*, 2004). Nevertheless, both Robertson *et al.* (2006) and Wong and Asseng (2006), have shown that provided seasonal climate variation is accounted for, systems of 'zonal management' may offer advantage over more conventional uniform approaches in the WA wheatbelt. So as McBratney *et al.* (2005b) point out, "we need to think of precision management as appropriate spatial AND temporal intervention". At the same time, it should also be recognised that PA is a continuous cyclical process (Figure 3; Cook and Bramley, 1998) rather than a one-off action and therefore has its own temporal dimension.

An additional important consequence of the cyclical nature of PA is that it lends itself to incremental, as opposed to immediate adoption (Cook and Bramley, 1998). Clearly, having at least *some* information about the production system is better than having none, but having access to every available technology is not a pre-requisite to starting down the PA path. Note also that conventional wisdom accumulated in the broadacre grains industries suggests that several years of yield data may be needed for the identification of *management zones* warranting differential treatment. In winegrape production (eg Proffitt *et al.*, 2006), the perennial nature of the crop and consequent demonstration
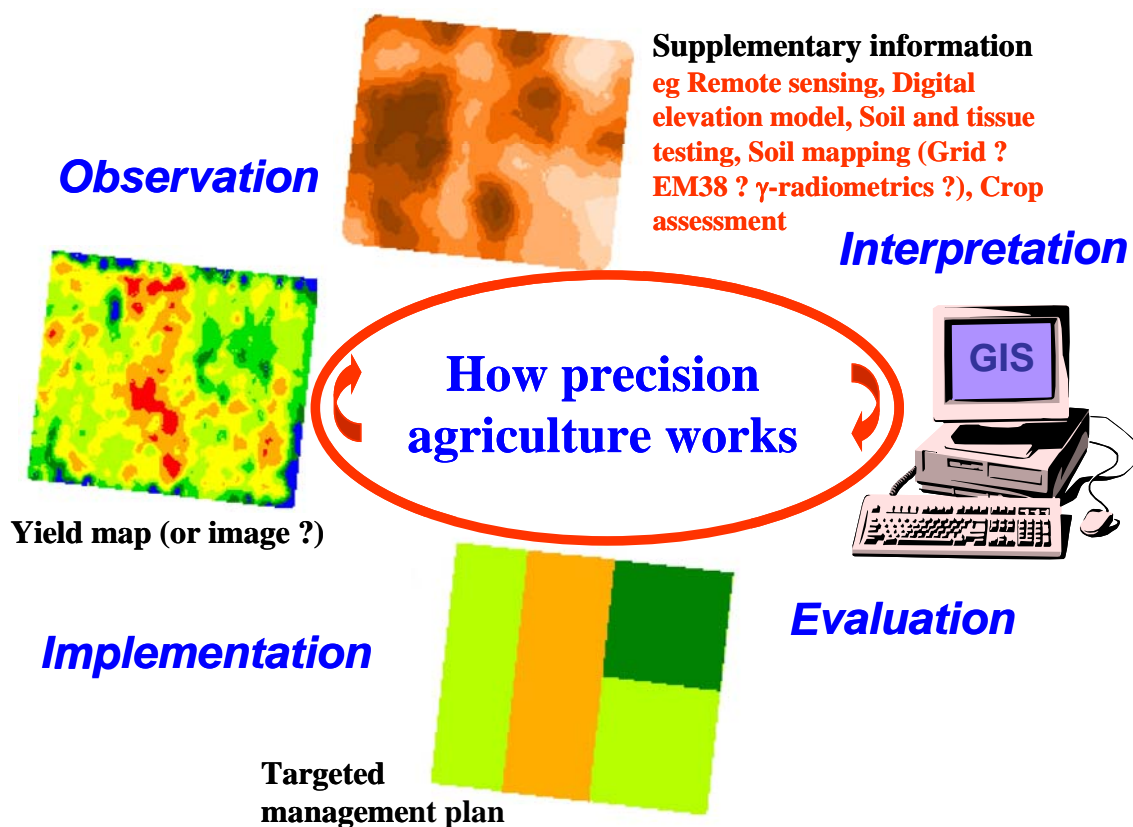
Figure 3. Precision agriculture is a continuous cyclical process.

that patterns of vineyard variability tend to be stable in time (Bramley and Hamilton, 2004) has enabled the 'waiting period' to be shortened somewhat, an advantage which, given the ratooning habit, may also accrue to sugarcane producers; research will be needed to confirm this.

3.   PA around the world

One of the most recent reviews of the state of broadacre PA around the world was conducted by Griffin and Lowenberg-DeBoer (2005). This lists the use of PA by growers of corn (maize), soybeans, potatoes, wheat, sugarbeet, barley, sorghum, cotton, oats and rice. In addition to these crops, significant advances have been made in the commercial application of PA to the production of winegrapes (eg Bramley *et al.*, 2005b; Proffitt *et al.*, 2006), citrus (Esquivel, 2005; Zaman and Schumann, 2005, 2006), bananas (Stoorvogel and Bouma, 2005), tea and date palms (Blackmore, 2003), and PA has even been used to assist in the management of sporting venues (Smith – cited by Blackmore, 2003) and railway lines (Antuniassi *et al.*, 2004); the latter could be an unexpected avenue of adoption in the Australian sugar industry ! Aside from along railway lines, site specific management of weeds has been employed in a range of crops (Gerhards and Christensen, 2006), whilst PA approaches to disease management are also being explored (eg. Heap and McKay, 2005). Research has also canvassed the application of PA to the management of tobacco and olives (Blackmore *et al.*, 2006), tomatoes (Lee *et al.*, 1999; Zhang *et al.*, 2005; Figure 1b), kiwifruit (Praat *et al.*, 2006) and sugarcane (eg Bramley and Quabba, 2001 – see section 4). Detailed reviews of the application of PA to corn and soybeans (Colvin, 2006), potatoes (McKenzie and Woods, 2006), rice (Roel *et al.*, 2006), sugarbeet (Franzen, 2006) and cotton (Johnson *et al.*, 2006) are collated in Srinivasan (2006), in which the status of PA around the world is also canvassed; Precision Viticulture (PV) is reviewed by Bramley and Hamilton (2006) and Tisseyre *et al.* (2006). Leonard and Price (2006) provide a summary of recent developments arising from a major Australian Grains Research and Development Corporation investment in grains-related PA research, along with advice for adopting farmers.

The first published yield map derived from a yield monitor and GPS was produced from a canola crop in Germany in 1990 (Haneklaus *et al.*, 1991; Schnug *et al.*, 1991). Since then, the corn-soybean growers of the mid-west of the US have dominated PA activity. It is estimated that about 90% of the world's yield monitors are in the US where around 35% of the planted corn acreage and 10 % of the wheat acreage was being yield monitored in the early 2000s (Griffin and Lowenberg-DeBoer, 2005). Interestingly, a significant number of US yield monitor users do not use them with GPS and so do not produce yield maps or use these for targeted or spatial management; possible reasons for this lack of adoption are discussed more fully in section 6. Nevertheless, the main drivers for adoption have been the cost efficiencies perceived as being readily achievable through the variable rate application of fertilizers and other soil amendments (eg Lowenberg-DeBoer, 2003; Godwin *et al.*, 2003; Doerge, 2005), in particular with respect to the maximisation of yield (Blackmore *et al.*, 2006). In Europe, one of the main reasons for interest in PA is its potential use as a tool for minimising any detrimental environmental impacts of agricultural production (Stoorvogel and Bouma, 2005; Blackmore *et al.*, 2006; Lowenberg-DeBoer, 2003), for demonstrating the sustainability of production systems and for product tracking (McBratney *et al.*, 2005b).

Given the availability of recent reviews of PA in different cropping systems and countries (Srinivasan, 2006 and references therein), the focus here is on three areas that may prove important in informing the on-going development of PA for sugarcane production.

3.1.   *Economic benefits from PA*

At the 2004 Sir Mark Oliphant Conference, a small but international 'think-tank' held in Melbourne, a Canadian academic argued that "as of 2004, precision agriculture is not a commercial reality and its generalised benefits – including financial and environmental – have not been clearly demonstrated".

The main basis for this argument appeared to be a lack of published data which lend economic weight to the push for adoption of PA technologies. Of course, farmers do not generally publish analysis of their own economic performance ! Nevertheless, early studies (eg. Swinton and Lowenberg-DeBoer, 1998) were circumspect, probably due to the observation (Pannell, 2006) that, in some cropping systems, even large deviations from the economically optimum agricultural decision can make little difference to the payoff. However, a review of more than 108 studies, predominantly relating to the use of variable rate application (VRA) of fertilizers in US broadacre cropping (Lambert and Lowenberg-DeBoer, 2000), found that 63% supported the view that PA was profitable. More recently, Godwin *et al.* (2003) have demonstrated that the benefits of adopting PA in UK cereal production depend on interactions between farm size, the costs of PA equipment and the yield increase required to offset these costs. Nevertheless, they estimated that in UK cereal farming, the average benefit of variable rate nitrogen application compared to uniform application was £22 ha^{-1}. In an update to the Lambert and Lowenberg-DeBoer (2000) survey, Griffin and Lowenberg-DeBoer (2005) reported that of 210 published studies in which economic losses or benefits were reported, 68% reported benefits from some sort of PA technology; again, this survey was predominantly reflective of US broadacre cropping. Importantly however, around half of the studies reporting benefits were written or co-authored by economists (Griffin and Lowenberg-DeBoer, 2005). The significance of this is that many of the earlier studies conducted by agronomists, soil scientists or agricultural engineers are susceptible to the criticism that some of the costs of PA were inadequately accounted for, including for example, costs associated with human capital or the costs of analysing spatial data (Bullock and Bullock, 2000; Lowenberg-DeBoer, 2003). More generally, Lowenberg-DeBoer (2003) concluded that in the US, the use of VRA is likely to be profitable on higher value crops (eg sugar beet), but will be break-even at best for bulk commodities (eg corn); one presumes that sugarcane fits into the same class as sugarbeet and in Australia, it is certainly "higher value" than dryland wheat, the major crop grown by the majority of Australian adopters of PA.

In the Australian wine industry, there is a perception in some quarters that because remote sensing has proved so effective as a vineyard management tool (Bramley *et al.*, 2005b), yield monitoring, which is perceived as more expensive, is not an essential component of PA. The normal response to this is that (a) since the crop has to be harvested, it may as well be yield mapped, especially since the cost of a yield monitor is a small fraction of the cost of a harvester; and (b) that in contrast to PA tools such as remote sensing and EM38 soil survey, yield maps do not need ground truthing since they represent actual rather than surrogate measures. It is therefore interesting that in broadacre cereal cropping, remote sensing of crops has a much lower level of acceptance than yield monitoring. Indeed, Griffin and Lowenberg-DeBoer (2005) identified remotely sensed imagery as the "least adopted" technology amongst those covered by their survey; Lowenberg-DeBoer (2003) described yield monitors as "the killer application of information technology for agriculture". Tenkorang and Lowenberg-DeBoer (2004) reviewed "hundreds of remote sensing studies" of which only 10 provided estimates of economic benefit. The highest return (US$14 acre^{-1}) in any study which provided details of how the benefit was estimated did not take the cost of image analysis into account. It should be noted that whilst the A$25-30 ha^{-1} that Australian grapegrowers pay for airborne remote sensing is a small fraction of both their total costs and value of production, it does not include the cost of ground-truthing the imagery which is an essential step in any application of remote sensing in agriculture. Griffin and Lowenberg-DeBoer (2005) ascribed the low uptake of remote sensing in broadacre agriculture to a lack of perceived usefulness of mapping growing crops given that most decisions are made at planting, to the fact that maps of bare soil do not change greatly over time. They also offered the view that there are "relatively few reliable remote sensing analysis or consulting firms". They were also critical of the frequent use of subscription-based marketing strategies in which several images per season had to be bought. The latter is generally not a problem in Australia currently and image purchase normally includes the processing cost. However, it does not include ground truthing which must be undertaken for the full value of the imagery to accrue.

If the application of PA to sugarcane production is confined to agronomic, as opposed to environmental issues, it seems likely, based on the Griffin and Lowenberg-DeBoer (2005) survey, that benefits will accrue to some producers but not others. Which category a particular grower falls into is

likely to depend on both the ease with which the drivers of variation are identified, and the ease with which these can be beneficially managed on his/her farm. Key factors affecting both of these aspects will be the availability of appropriate diagnostic expertise and either the amount of 'management time' (Lowenberg-DeBoer, 2003) that the grower can afford to spend in addressing them, or the $ investment that the grower is willing to make in getting someone else to do this for him/her (see Section 6). Perceptions as to the likely size of the benefit relative to the cost of addressing it will also be crucial and will be treated differently by each individual. In this connection, it is important for researchers to appreciate that farmers do not generally make decisions regarding changes in management practice on the basis of the level of statistical significance seen in agronomic experiments. More typically, the decision as to whether a new practice should be adopted is made on the basis of considerations such as the magnitude of the response (eg additional yield), the benefit:cost trade-off, or whether the benefit is large enough to justify the additional effort required in doing something new (ie. "Can I be bothered ?"), amongst a whole raft of other possible considerations (eg Pannell *et al.*, 2006). For this reason, a participative farming systems approach (eg Carberry *et al.*, 2002; Everingham *et al.*, 2006) to future sugar PA research is strongly advocated here, as opposed to one in which industry is left to interpret research by itself. The same could be said about the evaluation of new technologies placed on the market by equipment manufacturers.

3.2.   *The yield vs quality imperative*

As indicated above, the early adopters of PA in broadacre cereal systems have overwhelmingly used yield mapping and other tools, such as high resolution soil survey (eg EM38) and elevation modelling, to promote the variable rate application of inputs to the production system; the most common use of VRA has been for nitrogen (N) fertilizer application (eg. Lowenberg-DeBoer, 2003; Godwin *et al.*, 2003). In contrast, the early adopters of Precision Viticulture have placed much greater focus on the use of remotely sensed imagery, with or without yield mapping, as a basis for 'selective harvesting' (Bramley *et al.*, 2005). Here, selective harvesting is defined as the split picking of grapes at harvest according to different yield / quality criteria, in order to exploit the observed variation (Bramley and Hamilton, 2005). Thus, rather than focussing on differential management of the inputs to production (ie VRA), selective harvesting involves the differential collection of outputs and is driven by the strong quality imperative which exists in the wine industry.

In contrast to growers of winegrapes, broadacre cereal producers do not generally have a strong 'ownership' of their crop once it leaves the farm gate; flour is flour, stockfeed is stockfeed and a loaf of sliced white bread is just that ! Exceptions may apply in the case of producers of high grade durum wheat or malting barley who may have specific relationships with particular producers of pasta or beer, but in the case of the grower delivering grain to a bulk silo for subsequent export overseas, supply chain management effectively comes to an end at the farm gate. Together with the predominance of bulk-handling of harvested crop, this is probably a major reason for a relatively small emphasis being placed on crop quality issues in PA application to grain production. Another has been the absence, until very recently, of a reliable protein sensor (Taylor *et al.*, 2005), or of on-line technologies for analysis of other aspects of grain chemistry or grain size (Reyns *et al.*, 2006). It has also been suggested that site-specific fertilization on the basis of grain yield and quality sensors "will not be possible" due to the highly variable nature of grain quality response curves (Reyns *et al.*, 2006), although one would have thought that this was precisely the type of problem that PA can help to address if the required measurement technology is available ! However, grain protein mapping coupled with yield mapping can assist greatly in optimising the efficiency of N fertilizer use (eg Long *et al.*, 1998; Taylor *et al.*, 2005). Recent research attempts have also been made to manipulate crop quality in the case of maize (Miao *et al.*, 2005), cotton (Gemtos *et al.*, 2005) and potatoes (Wijkmark *et al.*, 2005).

As for most grain growers, the involvement of Australian sugarcane growers in supply chain management effectively comes to an end as soon as the harvested cane leaves the farm. However, as

discussed below, similarities between the sugar and wine industries suggest that PA provides an opportunity for that to change.

Like the wine industry, but in marked contrast to the wheat industry, and especially the export-orientated Australian variant, the sugarcane-based sugar industry is highly vertically integrated. Both sugarcane and winegrapes undergo significant, and essential, value-added processing in a mill or winery which is generally located close to the point of crop production. Because of this, and in the case of winegrapes, the strong quality imperative associated with winemaking, harvesting of both crops is controlled to a greater extent by the crop processor than the grower. Under these circumstances, Bramley *et al.* (2005b) report a number of case studies from the Australian wine industry in which very significant financial benefits were realised by both growers and especially winemakers through the selective harvesting of winegrapes and allocation of fruit to product streams of differing value based on the quality of the fruit. In several cases, selective harvesting resulted in consignment of a greater proportion of a grape crop to higher value wine product streams. In one example, the financial benefit from selective harvesting was worth over A\$40,000 ha^{-1} in terms of the retail value of production. The same strategy could equally well be used to maximise delivery of lower quality fruit to lower value product streams depending on market demand and opportunity. Whatever, that opportunities arise for product segregation based on factors such as fruit quality and market demand is clear. Given that refined sugar is a pure product, demand-based product differentiation, if it even exists at all, is unlikely to be affected by the availability of PA. But knowledge of spatially variable sugar (ccs) yield, as opposed to cane yield, may enable more sugar to be produced at the mill and thus from the farm as a whole. Muchow *et al.* (1998; 2000), Higgins (1998) and Wood *et al.* (2005) have canvassed this issue at the regional scale and demonstrated the potential for significant increases in profitability over a system which assumes no spatial structure in regional ccs variation. Similarly, PA may promote an ability for cane from areas of fields that are prone to producing sugar containing impurities to be milled separately to cane from areas which are not, possibly leading to price premiums from refiners seeking an absence of impurities. The opportunity also exists for chemical ripeners to be applied differentially.

For advantage to be taken of such opportunities, growers and millers will need to know something about both the patterns of quality variation and also its temporal stability – in addition to those for yield. In the case of winegrapes, it has been shown that whilst the patterns of spatial variation in fruit quality indices tend to follow those for yield, the ranking of 'zones' with respect to crop quality can be temporally variable (Bramley, 2005; Bramley and Hamilton, 2005). Thus, for example, whilst the high, medium and low yielding zones will always be so, the low yielding zone might be the high quality zone one year, and the medium or low quality zone the next. In-season, and in particular, pre-harvest zone-based monitoring of crop quality therefore becomes critical if selective harvesting is to deliver the desired outcome. If the sugar industry decides that using PA to chase the benefits of selective harvesting is potentially worthwhile, sorting out the spatial and temporal interactions between yield and ccs will be a critical research issue. Lawes *et al.* (2003) had a preliminary look at this issue at regional scale in the Tully district. They found no spatial relationship between yield and ccs, although spatial variation in both was temporally stable.

3.3.   PA as an environmental management tool

In Europe, one of the main reasons for interest in PA is its potential use as a tool for minimising any detrimental environmental impacts of agricultural production, and for demonstrating the sustainability of production systems. PA lends itself to these objectives given the large amounts of data that are collected in the course of implementing it, and the opportunity to use these data in biophysical models describing processes such as nitrate leaching (eg Stoorvogel and Bouma, 2005). Intuitively, a management approach such as VRA, which seeks to maximise the efficiency with which inputs to production are used, should have the additional benefit of minimising the opportunity for off-site losses of these inputs. Khanna and Zilberman (1997) give a useful discussion of this issue and its implications for agro-environmental policy, whilst Stoorvogel and Bouma (2005) note that PA offers

European farmers an avenue through which they might more easily conform to legal restrictions on the use of agrochemicals such as fertilizers. In the US, Berry *et al.* (2003) have coined the term *Precision Conservation* in which spatial information is used in support of establishment of conservation buffers (Dosskey *et al.*, 2005) and management of soil erosion (Schumacher *et al.*, 2005), amongst other conservation objectives (Delgado *et al.*, 2005).

A comprehensive review of the role that PA may play in enhancing sustainability with respect to nutrient and pest management is provided by Bongiovanni and Lowenberg-DeBoer (2004) who also provide an analysis from Argentina which suggests that site-specific information and VRA could be used to maintain profitability while reducing N fertilizer applications. They present an analysis based on maize production which shows that PA is "a modestly more profitable alternative than whole field management for a wide range of restrictions on N application levels". Such restrictions include government legislation and the "farmers understanding of environmental stewardship". These results were considered conservative since they focussed only on N (Bongiovanni and Lowenberg-DeBoer, 2004). However, McBratney *et al.* (2005b) have argued that for "appropriate" economic assessment of PA (or of conventional agriculture, for that matter), all costs (or benefits) of negative (or positive) environmental effects need to be considered, although they acknowledged the difficulty of assessing these, and noted the distinct lack of economic literature on valuing damage from agricultural pollution.

In general, the low input systems which dominate Australian broadacre agriculture have meant that environmental applications of PA have tended to be of secondary importance to management of production. However, Wong *et al.* (2005) have explored the use of PA to minimise the detrimental effects of N fertilizer use in the WA wheatbelt, whilst Bramley (2003a; 2006) has described the use of PA for improved natural resource management in a salt-affected viticultural landscape in the Clare Valley. Given the proximity of the sugar industry to the Great Barrier reef, its apparent environmental footprint (eg Bramley and Roth, 2002; Thorburn et al., 2002), the need to use sustainable best practice, and the relatively high rates of fertilizer use compared to some other crop production systems, PA may represent an important tool in the quest for improved environmental management in the Australian sugar industry (Wrigley and Moore, 2006). In particular, it may assist in demonstrating that best management practice, including record keeping, and compliance is being employed. It may also make a valuable contribution to improved farm management planning. Thus, adoption of a Precision conservation philosophy (Berry *et al.*, 2003) should assist in managing the interactions between cane farming and environmental protection in the sensitive coastal floodplain ecosystems in which Australian sugarcane is predominantly grown. These are all issues to which research can make an important contribution.

4.   The state of play in the International sugar industry

Much of the early work in applying PA to sugarcane production was undertaken in Australia in the mid-late 1990s (Bramley and Quabba 2001, 2002 and references therein); other early work was initiated in Mauritius (Jhoty and Autrey, 2001). However, a collapse in the world sugar price towards the end of the decade, along with the perceived high cost of PA, mitigated against the Australian industry taking advantage of the early learnings. Indeed, were it not for this collapse in prices and the simultaneous occurrence of some very wet, low yielding years, it is possible that the Australian sugar industry might, by now, be seeing widespread use of yield mapping (Cox *et al.*, 1996, 1997; Harris and Cox, 1997) and other PA technologies (see Bramley *et al.*, 1997; 1998 and the references therein for a review).

4.1.   *Australia*

The first study of variability in cane production systems was the work of Kingston and Hyde (1995) who used hand sampling to demonstrate that within a single 8.8 ha sugarcane block in the Maryborough district, variation in ccs was considerable (up to 6.5 units). Whilst this work was neither

conducted with a view to developing understanding from a PA perspective, nor included spatial analysis, it was nevertheless prescient in identifying the magnitude and potential importance of intra-block variation in ccs. It therefore highlights the potential for canegrowers to use PA, like their winegrape growing counterparts, in terms of a crop quality imperative (eg Bramley *et al.*, 2005b) in addition to a focus on yield optimization.

A key driver of the early Australian interest in PA in sugarcane was the development of a yield monitoring system at the University of Southern Queensland (USQ; Cox *et al.*, 1996, 1997; Harris and Cox, 1997) and the use of the data collected during early testing to inform the differential application of gypsum to a 100 ha sugarcane paddock in the Burdekin that was variably affected by soil sodicity (Cox, 1997; Cox *et al.*, 1997, 1999). Controlled traffic systems, principally to counter the risk of stool tipping at harvest, along with targeted weed management were other early objectives (Cox, 1997). There was also a strong desire in some parts of the industry to address the short-comings of the 'one-size-fits-all' fertilizer recommendations which prevailed at that time (Wood *et al.*, 1997a,b); these have since been markedly improved with due recognition given to regional and soil type differences (Schroeder *et al.*, 2005).

Against this background, and the promise of the imminent commercialisation of the USQ system, the Australian industry began to get acquainted with PA via a symposium which aimed to evaluate the potential offered to canegrowers by PA (Bramley *et al.*, 1997; 1998). Bramley and Quabba (2001, 2002) subsequently completed two seasons of yield mapping in the Herbert River District using a prototype USQ system and implementing some of the early learnings from Australian PA research in grains (Cook, 1997; Cook and Bramley, 1998) with respect to data analysis. The main objective in this work was to evaluate the opportunity to identify zones of characteristic performance within cane blocks as a basis for targeting management of inputs and modifying harvesting practice. A somewhat similar effort was expended by the former fertilizer company, 'Pivot', at a range of locations throughout Queensland (N. Boddinar and D. Pollock – pers. comm.). Ultimately, the collapse in the sugar price, low yields and the failure to commercialise the USQ yield monitor (amongst other factors) left the Australian industry without the firm platform of research and technical support, which experience in other industries suggests is key to adoption beyond the most innovative of growers.

For all practical purposes, there was no further coordinated development of PA in the Australian industry beyond the 1999 season, other than the exploratory work on the use of controlled traffic in cane production (Smith, 2001; David Cox – pers. comm.). It is therefore somewhat ironic, and indicative of the opportunity that was missed, both by those involved in the commercialisation of the USQ yield monitoring system and industry more generally, that during a discussion of the potential application of PA to sugarcane production at an international meeting held in 2000, "the unavailability of a continuous yield monitoring system for chopper harvesters" was identified as a "particular concern" (Richard *et al.*, 2001). The recent advances in yield monitor development made in Cuba (see section 4.5 below) are therefore significant, as is the development of a new Australian yield monitor (see www.jaisaben.com/) - although it is a matter of some disappointment that no information on its design has been made available. Similarly, the attempts by CSR Sugar, Mackay Sugar and Burdekin Productivity Services (BPS) to use pressure sensors fitted to the hydraulic system controlling the choppers in cane harvesters, as a surrogate means of yield monitoring (L. McDonald, J. Markley, D. Pollock and T. Crowley – pers. comm.) are an important development. Relationships between the variation seen in chopper pressure, remotely sensed imagery, and soil resistivity are currently being investigated.

Despite the hiatus in funded Australian sugar PA research between 1999 and 2006, the early work did nevertheless provide some useful information about variability in cane production systems. In particular, the yield mapping undertaken by both Bramley and Quabba (2001, 2002) and Pivot (N. Boddinar and D. Pollock – pers. comm.) demonstrated that, as has been commonly seen in other crops (eg Pringle *et al.*, 2003), yield variation showed marked spatial structure. This strongly suggests that both zone-based and continuous variable rate management may have potential in sugarcane
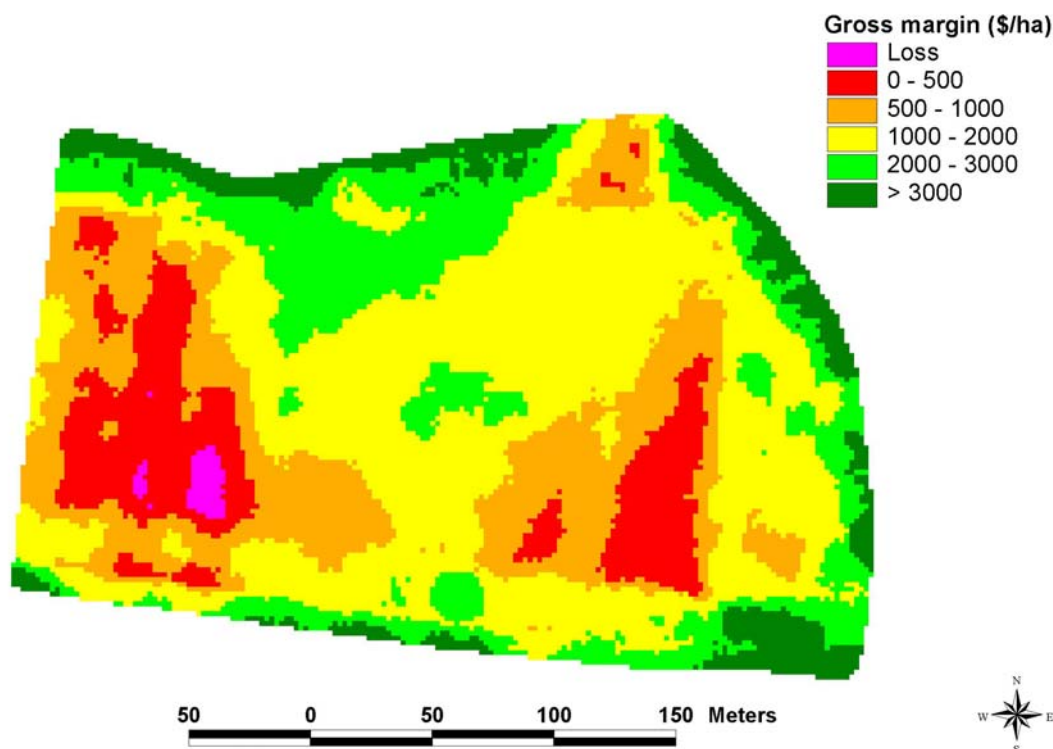
Figure 4.   Variation in yield and gross margin in a 12 ha block of sugarcane (1st ratoon) in the Herbert River District, 1998 (Data of Bramley and Quabba, 2001, 2002).

production. Significantly, Bramley and Quabba (2001, 2002) were also able to demonstrate that the range of variation in cane yield, as measured by the coefficient of variation (CV), was of the order of 30-45 % which is similar to that for a range of other crops for which yield monitoring equipment is available (Pringle *et al.*, 2003). As Bramley and Quabba (2001, 2002) have pointed out, if sugarcane yields are assumed to be normally distributed, a block of sugarcane with a mean yield of 100 t ha^{-1} and CV of 35%, can be expected to show yield variation in the range of 30 to 170 ha^{-1}. With such a range of variation, uniform management strategies are unlikely to be even close to optimal over significant proportions of sugarcane blocks. Thus, it was no surprise that Bramley and Quabba (2001, 2002) were able to demonstrate that a significant proportion of a 12 ha cane block in the Herbert River District (Figure 1c) was either operating at a loss or returning gross margins substantially below the goals of its owner (Figure 4).

One issue that needs attention is the question of robust and open calibration of chopper pressure sensor-based yield monitors, so that adjustment can be made of logged yields to match tonnages delivered to the mill. For gravimetric based sensors, calibration is straightforward and involves a simple linear transformation of the logged yield so that the total harvested amount recorded by the yield monitor matches the tonnage weighed at the mill (see for example, Bramley and Williams, 2001). The software that comes with the new Cuban system (see section 4.5 below) outputs yield in t ha^{-1}, although it is not clear on what basis chopper pressure, and the other indices measured, are converted to yield. A key question for users of both systems, and especially the kind of chopper pressure sensors being tested in Mackay and the Burdekin, relates to the form of the relationship between pressure and yield. Assumption of linearity based on data collected for whole rows, blocks or even days of harvesting, may distort the real spatial structure in the data *within* the row or block if the true relationship between pressure and yield is curvilinear. Clarification of this issue is especially important given that over 100 'MT Data' units are currently being used in the Australian industry (J. Markley, Mackay Sugar – pers. comm.), mainly for harvester tracking purposes, and that all of these could be readily converted to yield monitors through addition of off-the-shelf pressure sensors at a

cost of around $800. Nevertheless, exploratory use of both the Cuban and Australian systems in the Burdekin during 2006 has shown marked spatial structure to exist in the data collected, which does suggest that what is being measured is indeed some index of crop yield. To give confidence in these systems, together with an understanding of their level of accuracy, operators need clear instructions on their calibration, along with development of an appropriate protocol for converting the data to yield maps; in the latter regard, modification of the protocol developed for winegrapes (Bramley and Williams, 2001; Bramley, 2005) would be a useful starting point. Of course, it is presumably open to the industry to also re-visit the USQ yield monitoring system or that recently developed by Magalhães and Cerri (2007 – see section 4.5) which have the advantage of being gravimetric based systems and are therefore arguably quite easy to calibrate compared to the chopper pressure-based systems.

In addition to yield mapping, considerable effort has also gone into the application of remote sensing to Australian sugarcane production. The initial focus was on crop estimation and evaluation of the area under production (eg. McDonald and Routley, 1999). Markley *et al.* (2003) and Markley and Fitzpatrick (2004) further developed this work, one possible shortcoming of which was the reliance on the SPOT and LANDSAT systems which have on-ground resolutions of 20-25 m and therefore lead to considerable spatial inaccuracies, especially at the edges of blocks. Nevertheless, with accumulated operator experience, yield estimation accuracies of the order of 10% have been achieved using imagery obtained from these systems (J. Markley, Mackay Sugar – pers. comm.).

Whether the on-ground resolution of such satellite imagery is sufficient for its application to sugar PA is questionable, given that a single 25 m pixel will reflect composite information about approximately 16 rows. Indeed, the question of what the desirable on-ground resolution of remotely sensed imagery should be for application to PA in sugarcane, and thus what platform should be used to acquire it are matters worthy of further investigation. Certainly, the Australian wine industry has chosen to make use of airborne digital multispectral video (DMSV) remote sensing which offers higher spatial resolution than commercially available satellite imagery, with the most common commercial application being the use of 50 cm imagery (Hall *et al.*, 2002; Lamb, 2000; Bramley *et al.*, 2005b) which growers can purchase for approximately A$25 ha^{-1}. It is therefore of interest that Schmidt *et al.* (2001) evaluated the use of DMSV mounted in a micro-lite as a sugarcane crop monitoring tool. This work suggested that DMSV had potential in distinguishing varieties, crop age and identifying areas that were either subject to water stress or drainage problems. Based on experience in other industries (eg Lamb, 2000) these latter potential uses seem feasible, although the use of DMSV to distinguish varieties is an area that may require considerable further work since this is an application that might be expected to depend on hyperspectral methods (eg Arkun, 2001; Galvão *et al.*, 2005; Almeida *et al.*, 2006). Whether 50 cm, or coarser resolution (which would be cheaper) is appropriate for sugarcane sensing is something worthy of further investigation; 50 cm resolution is used for viticulture to allow removal of non-vine (ie inter-row) signals, something which is unlikely to be an issue for sugarcane sensing assuming that this is done after, or close to, canopy closure. Therein lies another key research issue for sugarcane remote sensing - evaluation of the most appropriate time during the season for the acquisition of remote sensing data (cf Lamb *et al.*, 2004). Further, given the length of the harvesting season and the consequent effect this has on crop age, resulting in cane of varying ages appearing in single images, this issue presents a potentially complex research issue.

Whilst much of the work done in Australia on remote sensing applications in sugarcane production have been much more targeted at issues associated with harvest management than PA (Markley *et al.*, 2003; Markley and Fitzpatrick, 2004), such technology along with GPS harvester tracking, logging of harvester performance, electronic consignment and GIS-based data management (Markley *et al.*, 2006) has left the industry well placed to integrate PA into existing systems; the recent adoption of controlled traffic and guidance is consistent with this view. Thus, whilst GPS-based harvest management as currently used should *not* be regarded as PA, there would be merit in examining how value could be added to these existing systems through integration with technologies such as yield monitors, especially as most Australian harvesters have tracking devices fitted and electronic consignment is being increasingly used (J. Powell, Caneharvesters – pers. comm).

4.2.   Mauritius

Following the early Australian research, the Mauritius Sugar Industry Research Institute embarked on a program of evaluating the potential application of PA to their cane production system (Jhoty and Autrey, 2001; Jhoty, 2003). This was a logical extension of the application of GIS and the use of so-called *permanent sampling units* to the monitoring of crop performance and leaf nutrient status (Chung Tze Cheong *et al.*, 2001) and also reflected the increasing move to mechanised production methods in Mauritius.

The approach taken was similar to that employed by the Australian Wine Industry (eg Bramley and Hamilton, 2004; 2005) and centred on evaluation of yield variation in both space and time, the application of remotely sensed imagery and the use of electromagnetic induction soil survey (EM38) to explore similarity in patterns of yield and soil property variation. As with the Australian work, yield monitoring was done using a prototype USQ system. The initial focus was on assessing the merits of the USQ yield monitor, which Jhoty (2001) and Jhoty *et al.* (2003) reported as having an accuracy of 97%. More significant, given the Australian progress in that area, was the reported range of yield variation (Jhoty, 2001; 2003) which was similar to that seen in Australia (eg. Figure 1c), with higher yields thought to be associated with higher soil water holding capacity (Jhoty *et al.*, 2003). As for most applications of PA in broadacre systems, the primary driver of this work appeared to be a desire to be able to better target inputs such as fertilizers, and also irrigation water in blocks under centre pivot irrigation; the optimal location of centre pivots was also seen as a useful potential application of GPS technology (I. Jhoty, formerly Mauritius Sugar Industry Research Institute – pers. comm.).

The present focus of the Mauritian research effort is an assessment of the feasibility of establishing a system of zonal management (Siram Ramasamy, Mauritius Sugar Industry Research Institute – pers. comm.). However, the rate of progress is being slowed by the perceived high cost of the various tools of PA. In addition, the commercial non-availability of a "reliable yield mapping package is hampering promotion of yield variability mapping to the farming community", as is the requirement for a higher level of training for workers using mechanized "high technology" equipment compared to those employed to use more traditional practices (Siram Ramasamy, Mauritius Sugar Industry Research Institute – pers. comm.).

4.3.   South Africa

Given the relative lack of mechanisation in the South African sugar industry, mainly as a consequence of an abundance of cheap labour, yield mapping received scant attention in that country until the recent attempts at developing a sensing system on a grab loader (Holmes *et al.*, 2005); unfortunately, these have not yet resulted in a system of acceptable accuracy, unlike the equivalent system used in Brazil (Saraiva *et al.*, 2000). In contrast, the major focus has been on the use of satellite-based remotely sensed imagery (Ferreira and Scheeppers, 1999; Schmidt *et al.*, 2001), and the appropriate sampling and analysis of both soil and plant tissue (Meyer *et al.*, 2004) – as in Mauritius, the targeted management of inputs such as fertilizer and water appears to be the main area of interest. Much of this work has been done in conjunction with assessments of remote sensing as a tool for crop estimation and evaluation of the area under sugarcane at the mill and district scale – similar to the exploratory Australian work of McDonald and Routley (1999).

4.4.   USA

In contrast to the approach taken in Australia, Mauritius and Cuba, and in spite of the development of a yield monitor (Benjamin *et al.*, 2001) that bears very strong similarities to the USQ system, the published accounts of sugarcane yield mapping in the USA employed a system which uses load cells on the 'field transport wagon' (Johnson and Richard, 2002, 2005a, b); this work is also distinguished by its focus on sugar production in addition to cane yield. Johnson and Richard (2002) reported a

range of yield variation within a single block (36-134 t ha^{-1}) of similar order of magnitude to that seen in Australia (Bramley and Quabba, 2001, 2002; eg Figure 1c), and also reported variation in 'theoretically recoverable sugar' (TRS) levels (51-104 kg/t) which together, led to variation in the yield of sugar from 2.64-14.57 t ha^{-1}.

Johnson and Richard (2005a) examined relationships between soil and yield variability and noted a large number of significant, albeit generally weak, correlations between a range of soil chemical properties (contents of P, K, Ca, Mg, S and organic matter, soil pH, buffer pH and CEC) and the components of yield. At one site, the strongest correlation (Pearson's correlation coefficient of -0.44) was between soil sulphur status and brix %, whilst at another, the strongest correlation (-0.54) was between organic matter % and pol %. No analysis of the spatial associations between these properties were presented although the potential for zonal management was identified. Building on this work, Johnson and Richard (2005b) noted that "all sugar parameters investigated were spatially correlated" (ie showed spatial structure in their variation), and given variation in soil pH (4.9-6.4) in the same cane blocks, conducted an experiment to evaluate the potential for variable rate application of lime. The results showed promise in terms of reducing the cost of liming, given the potential to apply it only to those areas where it was needed. Similarities between this work and the Australian work of Cox (1997) and Cox *et al.* (1997, 1999) were evident, notwithstanding the different objectives of ameliorating soil pH in the USA and sodicity in Australia.

The other significant piece of American work is that of Anderson *et al.* (1999). They examined the effects of soil variability on sugarcane yields in a 38 ha block in Florida in which there was considerable soil variation. Yield variation was also substantial (43-101 t ha^{-1}) and was shown to be related to soil Ca and Mg status, P buffering and the depth to water table. Whilst not specifically a PA study, this work nevertheless lends weight to the idea that the identification of soil-based zones and subsequent application of differential management strategies may have merit in some cane producing regions. It also re-enforces the desirability of access to soil property data in addition to surrogate measures of soil variability such as EM38 or VERIS. Viator and Downer (2005) found that variation in EC$_a$ was a poor predictor of yield variation in a Louisiana cane block, and that information on clay content, in addition to much improved weather forecasting, were required if variable rate N fertilizer management was to be successful.

4.5. *Brazil and Cuba*

Given the size of the Brazilian sugar industry as a whole, and of its various sugar estates, it is no surprise that the Brazilians have been active in exploring the application of PA approaches to sugarcane production. Much of the more recent on-ground work has been done in partnership with researchers from Cuba (M. Esquivel, TechAgro – pers. comm.), and these two countries are therefore considered together here.

Grid-based sampling of soils accompanied by measurement of cane yield over a 105 ha area (Cora and Marques, 2000; Cora *et al.*, 2001) demonstrated that both were variable, with the variation exhibiting marked spatial structure; yield varied from 74-120 t ha^{-1} (Cora *et al.*, 2001). Whilst this work did not include analysis of co-variation of yield and soil properties, it is evident that there were similarities in the patterns of variation. Thus, PA gained interest in the Brazilian sugar industry. Similarly, Cabrera *et al.* (2002) examined yield variability in a Cuban sugarcane field by splitting the field into a number of grid cells and weighing the cane that was manually harvested from each. The range of yield variation observed was very similar to that seen in Figure 1c, and was used to argue in favour of variable rate N fertilization.

Sparovek and Schnug (2001) conducted a theoretical evaluation of the differential application of P fertilizer and optimization of mechanical operations such as planting and harvesting in a 77 ha area in south-eastern Brazil; the optimization of mechanical operations was focussed mainly on the opportunity to minimize the risk of soil erosion. It was concluded that whilst "measurable advantages"

were not apparent in the case of P fertilization, possibly because P was yield limiting throughout the study area, they were "observed" in the case of targeted mechanical operations. Thus, whilst using straight rows rather than following contours might increase the risk of soil erosion, the increased efficiency of machinery use under the PA system was estimated to reduce the erosion risk. This example is, in essence, an argument in favour of machine guidance and controlled traffic. However, it is also a reflection of the relatively high cost of mechanized systems in Brazil couple with the fairly low cost of fertilizing sugarcane in Brazil (Roloff and Focht, 2006).

In terms of the measurement and monitoring of crop performance, the early Brazilian work was divided between development of a harvester-mounted yield monitor (Pagnano and Magalhães, 2001; Cerri and Magalhães, 2005) – which is essentially the same as the USQ system (Cox *et al.*, 1996, 1997; Harris and Cox, 1997); development of a weighing system for grab loaders used following hand harvesting (Saraiva *et al.*, 2000); and an approach similar to that used in the USA (Johnson and Richard, 2002), based on the use of load cells on haulout bins (Molin *et al.*, 2004). These differing Brazilian approaches largely reflected the use of either mechanical or hand harvesting. Despite this early work on yield monitoring, Roloff and Focht (2006) stated that "sugarcane yield monitoring is not a commercial reality yet", either for mechanically or hand harvested cane, and suggest that remote sensing provides a useful surrogate – although no details of the remote sensing systems used are provided. However, the recent publication (Magalhães and Cerri, 2007) of details of a new Brazilian yield monitoring system for sugarcane suggest that a commercially available system may be close at hand. This system is a modification of that of Cerri and Magalhães (2005) and includes a number of sensors to reduce *noise* and to otherwise monitor harvester performance in addition to logging yield; it nevertheless remains very similar to the USQ system. The recent development and commercial availability of a cane yield monitor by Cuban company 'TechAgro' (Hernandez *et al.*, 2005) is also significant. This system, much of the development of which was done in Brazil (M. Esquivel, TechAgro – pers. comm.), is now commercially available – both in Brazil and Australia. This system measures chopper pressure, base cutter pressure, cane flow in the feeding roller, and main extractor pressure and the data are processed by a proprietary algorithm to produce a yield estimate that is matched to GPS coordinates. The Cuban system is also distinguished by the fact that in addition to a yield monitor, it also includes automated control of forward speed and base cutter height, a guidance system that better synchronizes the position of the haulout bin relative to the harvester, and mapping software. Further development and testing of this system is on-going in Brazil, Cuba and Australia (M. Esquivel and F. Fernandez, TechAgro – pers. comm.).

In addition to these studies, there has also been an active research effort in sugarcane remote sensing in Brazil using satellite-based platforms (eg. Almeida *et al.*, 2006; Galvão *et al.*, 2005). The main focus of this work has been variety discrimination, assessment of the area in production and yield estimation. Given the on-ground resolution of the instruments used (eg 30 m in the case of Hyperion (Galvão *et al.*, 2005); 60 m for Landsat ETM (Almeida *et al.*, 2006)), it is difficult to see what these instruments might offer in a PA sense. However, the fact that Almeida *et al.* (2006) were able to predict yield with errors of around 5% - considerably less than the local mill – suggests that higher resolution instruments, if available and affordable, may have much to offer adopters of PA.

4.6. Other countries

There do not appear to be any published details of PA research or implementation in sugarcane production outside of the countries discussed above. However, the Indian industry has been exploring the use of satellite-based remote sensing and GIS in sugarcane production (Kumar, 2001), no doubt drawing on the abundant IT expertise in India. Repeat image acquisition matched to key growth stages enabled variety discrimination in addition to assessment of planted acreages. It is unclear whether or how the data collected were used to promote improved management of the crop. Similarly, work has been done in Thailand to assess spatial relationships between soil property variation and variation in sugarcane yield (Wongmaneeroj and Hongprayoon, 2004), although as in India, translation of this into implementation of PA is yet to occur.

There has been no real adoption of PA in Colombia, principally due to the non-availability of a yield monitor (Erikson, 2006), although the Colombian industry has "excelled" in its use of GIS for recordkeeping and datamining and so is well placed to adopt PA if and when it chooses. Indeed, between-field differential management, as opposed to within-field, is commonly practiced (James Cock, CIAT – pers. comm.) and the Colombian sugar industry therefore provides a good example of non-mechanised PA in the sense that its agronomic management is nevertheless site-specific and quite sophisticatedly so (Cook *et al.*, 2003).

5.   Soil and topography as a driver of variable crop performance and the need for new approaches to soil sampling and analysis

As indicated in the Introduction to this review, land is variable. It is therefore no surprise that the PA literature is full of studies relating variation in crop performance to soil and topographic variation.

The early work of Runge and Hons (1999), Moore and Tyndale-Biscoe (1999) and Machado *et al.* (2002) identified plant available stored water and seasonal rainfall as having the greatest effect on the yield of rainfed crops, and certainly a greater effect than variable N supply (Moore and Tyndale-Biscoe, 1999). At about the same time, a study in which 5 US cornbelt fields were intensively sampled on 15m grid such that 112-258 samples per field were analysed, showed that correlation coefficients between yield and a range of indices of soil *fertility* ranged from 0 to 0.77 (Mallarino *et al.*, 1999) with these coefficients being highly skewed towards the low end of the range. Somewhat similar results were obtained in a French study (Bourennane *et al.*, 2004). Thus, Machado *et al.* (2002) advocated that 'seasonally stable' factors such as soil texture should provide the basis for identification of management zones in which targeted management of 'seasonally unstable factors' such as N availability and the incidence of pests and disease should be practiced. In addition to variable supply of soil water, topographic variation has also been shown to be a critical driver of yield variation - for example, in maize grown in USA (Kaspar *et al.,* 2003; Grove *et al.*, 2005), barley and winter rye grown in Germany (Reuter *et al.*, 2005), potatoes grown in Sweden (Persson *et al.*, 2005) and Australian winegrapes (Bramley, 2006; Bramley and Williams, 2007). Undoubtedly, the variable supply of soil water will very often be linked to topographic variation, even in apparently 'flat' landscapes (eg Bramley, 2003b).

In spite of these results, the overwhelming focus in the predominantly US-based PA literature has been on the role and management of variable nutrient availability – especially N. Indeed, the man who most would credit with having been the 'father of PA', described PA as "a challenge for crop nutrition management" (Robert, 2002). This focus has arguably created a problem for US adopters of PA, who have seen the 'PA industry' built on the back of an explosion in soil sampling and analysis services which, early on, and apparently without robust scientific justification, chose grid-based soil sampling as the basis from which successful adoption of PA, and in particular, implementation of VRA fertilizer application, would flow. Thus, the focus was, and predominantly remains, on analysis of soil fertility, rather than soil water availability. In Australia, where yields are critically dependent on in-season rainfall, differential management has tended to be driven by an understanding of variable soil moisture availability (eg Wong and Asseng, 2006; Bramley, 2006) – an approach that is consistent with Runge and Hons' (1998) hierarchy of variables influencing crop yields, and the recommendations of Machado *et al.* (2002). Variable soil moisture availability affects potential yield. It therefore interacts with soil fertility to drive variation in fertilizer requirement, since areas with high moisture-dependent yield potential may need more fertilizer for that potential to be achieved than areas of lower moisture availability. This has been the basis for the Australian approach to VRA, irrespective of the crop of interest - zone delineation using yield and high resolution (eg EM38) soil maps, followed by appropriate targeted soil sampling and analysis for the purposes of making fertilizer decisions. It is an approach which contrasts markedly with that used in the US which, as stated, is almost solely driven by analysis of soil fertility in the absence of consideration of other factors.

5.1.   Soil sampling and analysis

The key role that variation in soil properties has in driving variation in crop performance raises questions as to the appropriate spatial intensity with which soils should be sampled – whether as a basis for diagnosis of problems or prediction of response to nutrient addition (ie fertilizer recommendations). As indicated, the approach adopted in the US is grid-based sampling (eg Robert, 2002), typically at an intensity of around 1 sample for every 1.5 ha (Mallarino and Wittry, 2004). Some authors (eg Magri *et al.*, 2005) have even suggested that grid sampling at an intensity as low as one sample per 2.5-5.5 ha is appropriate for the delineation fertility management zones ! However, an analysis of available published data on spatial variation of soil properties led McBratney and Pringle (1999) to conclude that, in order to obtain soil information at a resolution that was consistent with broadacre PA, sampling grids no larger than 20-30 m would be required. Similarly, Bramley (2003b) and Bramley and Janik (2005) have demonstrated the folly of the standard approach to vineyard soil survey in Australia which employs 75 m grids (approximately equivalent to 2 samples per ha); this grid spacing was shown to be much too large for characterising vineyard variability. Mallarino and Wittry (2004) compared grid based sampling at intensities ranging from one sample per 0.2 ha (ie 5 ha^{-1}) to one per 1.6 ha (ie 0.6 ha^{-1}) with zone based sampling and sampling based on local (1:12,0000) soil maps. Whilst they found that the best information was obtained when the highest sampling intensity was used, this was dismissed as not feasible for economic reasons and they concluded that for most analytes, either zone-based sampling or grid cells of 1.2-1.6 ha were adequate. Of course, one might suggest that detailed soil sampling and analysis should be an essential step in the identification of zones in the first place ! Furthermore, this result is clearly at odds with those of McBratney and Pringle (1999) and Bramley and Janik (2005). It is also at odds with the results of van Miervenne (2003) which suggest that PA may be useful even in small fields (< 1.7 ha), and therefore raises questions as to what "adequate" (Mallarino and Wittry, 2004) actually means ? As Cook and Bramley (2000) demonstrate, information such as soil test data only has value when it can be translated into knowledge for the purposes of making a better decision than would have been possible in the absence of that knowledge. A key question then, is: how might useful soil information be obtained in a cost effective manner at spatial resolutions that are consistent with PA ?

This question was considered by Bramley and Janik (2005) with respect to both soil sampling and analysis. In terms of soil sampling, the merits of a directed sampling approach based on electromagnetic (EM) soil survey at high spatial resolution (see section 5.2 – below) was demonstrated by Bramley (2003b) and Bramley and Janik (2005) for a vineyard situation; in this particular example, the same number of soil samples were taken in the directed approach as in the grid approach and so the only additional cost was that of the initial EM survey. Corwin *et al.* (2006) highlight the merits of EM survey and directed sampling for monitoring of soil quality. Selige *et al*. (2006) suggest hyperspectral remote sensing as an alternative source of high resolution soil data, whilst Pracilio *et al.* (2006) have found gamma ray spectrometry to be useful in the WA wheatbelt.

Aside from the issue of how many samples to take and where they should be taken from, PA also raises the key issue of how soils should be analysed. The reason for this is that a requirement to use traditional wet-chemistry approaches to soil analysis in a PA scenario would put an enormous strain on most laboratory resources given the numbers of samples required. As consequence, and consistent with the objectives of VRA, much effort has gone into the development of alternative or surrogate approaches to soil analysis based on both high speed laboratory methods, such as mid- and near infrared spectroscopy (eg Janik *et al*., 1998; Bramley and Janik, 2005; van Vuuren *et al.*, 2006; Viscarra Rossel *et al*., 2006), perhaps combined with soil inference systems (eg McBratney *et al*., 2006), or through the development of new sensors that can be used either *in situ* (eg Skogley, 1992; Qian and Schoenau, 2002) or on-the-go (eg Shibusawa *et al.*, 2005; Viscarra Rossel *et al.*, 2005; Adamchuk *et al.*, 2006). Which of these approaches is deemed preferable is open to debate and is clouded by the fact that the merits of a new soil test are nearly always assessed by comparison with the existing test which, may itself, be far from optimal. As McKenzie *et al.* (2003) conclude, the aim of characterising spatial variation in soil properties is best satisfied by "measuring more less well". With

Table 1.   Technologies for rapid soil sensing (derived from McKenzie *et al.*, 2003)[A].

Method	Lab / field / on-the-go	Comments
Mid-infrared reflectance	Lab / field?	Correlative technique. Good characterisation of mineral and organic surface properties and some bulk physical properties; less effective for measurement of plant nutrient availability.
Near-infrared reflectance	Lab / field / on-the-go?	As above. A tyne-mounted sensor has been developed by Japanese researchers. Unclear how wide a range of soils this would work in.
Visible / near-visible reflectance	On-the-go via remote or proximal sensing	Remote sensing is unlikely to yield information from deeper than 2 mm into the soil profile.
Ion-exchange resins	Lab or field (*in situ*)	*In situ* method. Has advantage of accounting for both surface chemistry and diffusive limitations to nutrient availability.
ISFET	Field / on-the-go	Potentially highly effective for real-time sensing.
Electromagnetic induction	Field / on-the-go	Widely used as an indicator of soil variability. Ground-truthing to soil properties of interest is essential.
Resistivity	On-the-go	As above. Two commercially available systems.
Ground-penetrating radar	Field / on-the-go / airborne	Highly material dependent. Potentially useful for identifying variation in soil moisture content.
γ-radiometrics	Field / on-the-go / airborne	Detects natural decay of isotopes of K, U and Th. Most useful for sensing variation in clay mineralogy.
Draught resistance	On-the-go	Load sensor easily mounted on a standard tractor 3-point linkage.

[A]Capacitance probe and other similar technologies for *in situ* assessment of soil moisture have deliberately been excluded from this list; a number of such technologies are readily commercially available.

respect to real-time on-the-go sensing of soil properties, it is also worth pointing out that a farmer very rarely makes a fertilizer decision the instant he/she obtains some soil test data, and very often, soil analysis is carried out many weeks in advance of the time at which the fertilizer decision has to be made. So the benefits of avoiding sampling costs through the use of on-the-go sensors need to be considered against the analytical accuracy of such methods compared to lab-based alternatives. In the opinion of this author, until such time as a range of on-the-go sensors are available with a capability of measuring a wider range of analytes than soil pH and lime requirement (eg. Viscarra Rossel *et al.*, 2005; Adamchuk *et al.*, 2006), some of the lab-based spectroscopy methods will probably offer the best way forward for agricultural industries such as sugar. McKenzie *et al.* (2003) provide a review of the potential benefits and opportunities of rapid soil measurement; a summary of the currently available technologies is given in Table 1.

5.2.   On-the-go assessment of soil variation using electromagnetic sensing (EM38 and VERIS)

As indicated above, the predominant means of acquiring information about soil variation at high spatial resolution involves electromagnetic measurement (EM) of either conductivity (eg EM38) or resistivity (eg VERIS). It is not the intention here to provide a detailed review of these methods since their mode of operation is well understood (McNeill, 1980; Lück *et al.*, 2005), they have been in use in soil science for a long time (eg Rhoades, 1992; Williams and Baker, 1982; Williams and Hoey, 1987), and have also been used to assist with practical agronomic decision making for several years (eg Evans, 1998). Indeed, VERIS is currently being used in the sugar industry (Tony Crowley, Independent Agricultural Resources – pers. comm.). Excellent reviews pertinent to both EM38 and VERIS, albeit with a north-American focus, are provided in a recent issue of *Computers and Electronics in Agriculture* (Anon, 2005 and references therein), whilst Gebbers and Lück (2005) provide a useful comparison of the various EM sensing technologies currently being used in Europe.

Whilst the sugar industry should feel confident on moving ahead in using these tools to better understand spatial variation in soil properties, it should be aware of two common mistakes which are often made by newcomers to EM sensing. First, it is not possible to make *a priori* assumptions about the nature of the information that an EM survey will provide. All EM survey does is measure the bulk electrical conductivity (EM38) or resistivity (VERIS) over a defined range of soil depth. In saline soils, the effects of salinity and its variability will dominate the EM signal. Where the soil is not saline, the amount and type of clay, and soil moisture will dominate the signal and therefore allow features such as texture contrasts to be identified (eg Bramley, 2003b). An excellent explanation of what soil properties EM instruments reflect and their hierarchy of importance is given by McBratney *et al.* (2005a), along with an attempt, using some first principals of soil science, to make use of numbers recorded by EM instruments. Whatever, it is essential that users understand that in order to get maximum value from EM soil survey, the survey data need to be ground-truthed against actual measurements of soil properties in much the same way as remotely sensed imagery needs to be ground-truthed against crop characteristics. Without ground truthing, EM survey simply provides an indication of soil variability, but says nothing about its cause.

The second commonly made mistake is to ignore the above and think that detailed investigation of what EM does and whether it correlates with soil properties in a particular cropping system is a pre-requisite to adoption by an industry that has not previously used it. The recent work of Kingston *et al.* (2006) is a good example of this sort of wasted research effort; what EM survey does is well understood and, as stated, ground-truthing (ie correlation) of EM data with measured soil properties is an essential step in maximising the value of the survey, whether it was carried out on soils under sugarcane (Kingston *et al.*, 2005) or one of the many other crops for which EM survey has been used to understand soil variability. In short, EM survey is a mature science and the sugar industry should feel able to use it with confidence.

As indicated above, elevation is commonly found to be a valuable data layer in understanding variability in crop production. There is no reason why this might not be expected to be the case in the sugar industry where production is rain-fed and where laser-levelling has not be used. In the irrigated areas such as the Burdekin, and in others where laser-levelling has been used, it is expected that access to elevation data pre-laser levelling may be invaluable in understanding post-levelling variability, given the likely effects of cut and fill on the distribution of the properties of present-day top- and subsoils. Such management-induced changes to the distribution of soil properties will likely be reflected by EM survey (Corwin *et al.*, 2006) and access to elevation data may also assist in distinguishing between management induced and inherent soil variation. Such elevation data are presumably potentially available from the levelling engineers and efforts should be made to retain them. Whilst elevation survey requires access to real-time kinematic GPS (RTKGPS; accurate to ± 2 cm in the *x*, *y* and *z* planes[1]) which is generally more costly to access than differential GPS (dGPS), the use of RTKGPS rather than dGPS for EM soil survey is recommended since it allows simultaneous survey of soil and topographic variation. The recent establishment of local base stations in some cane growing regions should greatly assist with access to accurate topographic data. Examination of these issues are certainly worthy of investigation by the Australian sugar industry.

6.   Constraints to adoption

Several authors have noted that the adoption of PA has been much less than was predicted 5 or 10 years ago (eg Cook *et al.*, 2000; Lowenberg-DeBoer, 2003; Fountas *et al.*, 2005; McBratney *et al.*, 2005b). Since the reason for this is not poor access to PA technology (eg. Wong *et al.*, 2005), the obvious question is: why is it so ?

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[1]Note that in Australia, standard GPS is accurate to about ± 6 m 95% of the time; differential GPS (with a commercially subscribed satellite differential correction) is accurate to ± 0.5-1 m in the *x* and *y* planes, but is only accurate to several m in the vertical (*z*) plane.

Whilst there is now plenty of evidence in the scientific literature of an economic benefit accruing from PA (see section 3.1 above), especially for higher value crops, a key issue amongst many farmers, and broadacre cereal growers in particular, is a perceived lack of benefit. Given the evidence to the contrary presented in section 3.1, this perception amongst farmers is probably a reflection of the need for an enhanced extension effort from researchers, service providers and equipment manufacturers. At least a part of this should include the admission that just as PA implies management that is site-specific, so too will the benefits that accrue be site-specific. Thus, they will be large for some farmers, and modest for others.

Pierce and Nowak (1999) cited the lack of compatibility between many PA components, a lack of well established agronomic relationships, the perceived complexity of PA compared to other emerging technologies (eg new disease-resistant varieties), the commodity-specific nature of some technologies, capital requirements and inadequate understanding of the space-time continuum. The latter has more recently been highlighted as an issue by McBratney *et al.* (2005b). Whilst the capital investment that PA requires is significant, especially in terms of yield monitoring and VRA, the fact is that this issue is nearly always considered without much consideration of the value of the information that it may provide (Cook and Bramley, 2000). It is also normally considered on the basis that the farmer, rather than his/her contractor, who may have many clients, is the person making the capital investment. Furthermore, anecdotal evidence from the Australian grains and wine industries suggests that when the costs of PA equipment are spread over several years, rather than being viewed as a single expense, they are perceived as much less expensive. Cox (1997) provided a compelling argument along these lines with respect to sugarcane yield mapping which, in the mid 1990s, was estimated to cost around A\$0.04 t^{-1}. Further, it is often forgotten that the cost of a yield monitor is a small fraction of the cost of a harvester (which is presumably why many grains headers now come with a yield monitor as a standard feature), and an even smaller fraction of the value of the crop it is being used to measure. However, the annual subscription fee payable for satellite differential GPS correction (approx. A\$2500 yr^{-1}) is viewed by many Australian farmers, even in high value crops like winegrapes, as expensive and a disincentive to its use. More generally, the high costs of soil and plant analysis are a bigger impediment in Australia (see section 5 above). The commodity-specific nature of some technologies (ie you can not use a cotton yield monitor for harvesting potatoes) is a real, but probably over-stated problem, and in the case of the sugar industry is unlikely to be an issue given that sugarcane harvesters are themselves commodity-specific. One consequence of this for sugarcane producers is that issues of equipment compatibility are much less likely to arise. This then leaves the closely-related issues of agronomic relationships and perceptions of complexity as arguably the most problematic.

Figure 3 presents a simple schematic of PA. Yet careful consideration of the various technologies identified in Figure 3 suggests that successful adoption requires access to skills in agronomy, soil science, information technology, spatial statistics and GIS. On the face of it, it would be surprising if all these skills resided in a single individual outside of the research community; they are by no means ubiquitous within it (see below) ! So how might a farmer access these skills ? The obvious solution is the employment of consultants and other service providers, but herein lies a significant problem. Cook *et al.* (2000) noted that adoption is slowest amongst independent agronomic advisors, partly due to their skill base, and in particular, conservatism amongst consultants, who generally have less incentive to change than the farmer clients whom they serve. Indeed for many agronomic consultants to take on PA, especially in the area of fertilizer recommendations, they may first need to acknowledge that their previous advice may not always have resulted in any benefit accruing to their clients. The K fertilizer experiment discussed by Cook and Bramley (2000) and Bramley and Janik (2005) provides strong evidence in support of this view. Cook and Bramley (2001) expanded this theme to include inertia amongst agronomic researchers. Indeed, it is striking that, in spite of a growing understanding of the sort of spatial variability shown in Figure 1, and the implications that it has for agronomic experimentation (Adams and Cook, 1997; 2000; Cook and Bramley, 2000; Bramley *et al.*, 2005a; see also section 7.1), very few agronomic researchers other than those directly involved in PA, give consideration to the possible effects that spatial variability may have on their research. The same comment can be made about those funding the research. Bramley and Janik (2005) and Cook and Bramley (2000) have highlighted the folly of such ignorance using examples from the Australian wine

and grains industries, whilst Doerge (2005) has outlined one of its consequences for maize production in Ontario, Colorado, Illinois, Iowa, Michigan, Minnesota, Missouri and Wisconsin. Across more than 480 field studies conducted in these states, variation in the recommended N rate explained less than 10% of the variation in the actual economically optimum N rate (EONR); EONR in sub-regions of a single paddock ranged from <30 to >200 kg N ha^{-1}, whilst the best predictor of EONR was the yield of control plots which received no N (Doerge, 2005). Of course, this information is not available to guide pre- or in-season N management because it is only available after the event. A further difficulty, which is much more a problem for US adopters of PA than those in Australia, has been the quasi-requirement to support adoption through a program of grid-based soil sampling (see section 5 above) which, given the focus on VRA fertilizer application has, in turn, focussed on analysis of soil fertility, rather than soil physical properties and rainfall which are the principal determinants of potential yield. Failure to account for these was the reason why soil test K data was of little use in the WA wheatbelt example of Cook and Bramley (2000). Thus, agronomy is indeed being left behind by PA (Cook and Bramley, 2001), and it is therefore of little surprise that lack of agronomic relationships should be a reason contributing to poor rates of PA adoption.

Given the relative lack of support amongst agronomists and consultants, together with the complexities highlighted above, it is little surprise that PA represents a huge task for many farmers who may not want to spend much time sitting at a computer producing yield maps and analysing data. In this connection, Lowenberg-DeBoer (2003) notes that whilst the unwillingness of farmers to commit 'management time' to PA may present an opportunity for consultants and other service providers, this same unwillingness of farmers to undertake their own computer analysis and decision making may be a key impediment to adoption. Robert (2002) makes a similar suggestion which is strongly supported by the results of a farmer survey conducted by Fountas *et al.* (2005) in the US and Denmark. Wong *et al.* (2005) have also suggested that a perception that PA-derived knowledge should replace existing farmer knowledge has also been a disincentive to adoption in Western Australia, noting that the development of methods which complement existing knowledge and decision making will be required if the full benefits from PA are to be realised. Clearly, adoption of such methods, along with those relating to the collection, processing, analysis and management/storage of data will be dependent on appropriate industry effort being put into PA capacity building amongst growers, consultants and researchers.

7.   Opportunities and research requirements for PA in the Australian sugar industry

In spite of the evidence from grains and winegrapes (see section 2.1 above) in support of the view that the 'null hypothesis of precision agriculture' (Whelan and McBratney, 2000) can be rejected, it does force consideration of some key questions which potential adopters of PA need to consider before investing in the capital or contracted services that this approach to agricultural production implies. First, growers need to know whether the patterns of within-field variation are constant from year to year. If they are not, then clearly the idea that PA increases the certainty that a given management decision will deliver a desired or expected outcome (Cook and Bramley 1998) may not be correct. Second, in crops with a quality imperative – the significance of ccs makes sugarcane one of these - growers need to know whether patterns of variation in yield are matched by patterns of variation in quality. If they are, then targeted management becomes a much simpler problem than if they are not, given for example, that it may be undesirable to focus on yield at the expense of quality, and possibly vice versa. Third, they want to know what the key drivers of variation are and whether these may be managed. Clearly, if these are either unknown or unmanageable, then the opportunities for targeting inputs are probably limited, even if the opportunity remains to segregate outputs. Finally, they want to know whether targeting management delivers an economic benefit over conventional uniform management. (Increasingly, the answer to this question is sought before answers to the others, a problem which presents immediate difficulties for researchers, equipment manufacturers and service providers alike).

The first and last of these questions are specifically addressed by the 'null hypothesis' of precision agriculture (Whelan and McBratney 2000), although answers to the others also critically impact on it. It is suggested that addressing these questions should form the basis of any research effort which might be set up by the Australian sugar industry. Desirably, the first 3 should be tackled together, albeit in chronological sequence, with economic evaluations of the answers obtained conducted as and when results become available. In the meantime, Figure 4 provides strong evidence that under uniform management, some parts of sugarcane fields may operate at a loss. Note that the map shown in Figure 4 was produced at a time when the world sugar price was about US12c/lb; it subsequently fell to around US5c/lb before recovering to its present level. Clearly, as the sugar price goes down, the probability of uniform management resulting in areas of negative gross margin within sugarcane blocks goes up. Conversely, when prices are high, targeted management of the inputs to production could result in growers achieving some very significant net returns. In this regard, evaluation of the merits of the targeted use of sugarcane ripeners is an obvious area worthy of investigation in addition to targeted application of other inputs to production. Sensibly, research into the merits of targeting application of ripeners would be coupled to investigation of the potential for selectively harvesting sugarcane.

Overall, one might suggest that the relatively late interest being shown in precision agriculture by the sugar industry amounts to a missed opportunity. Having said that, experience in industries in which adoption of PA has commenced suggests that, in the first instance, yield mapping leads to more questions than answers. It does, however, provide a powerful tool for assisting in understanding the factors limiting profitability and can act as a stimulus for growers to try to better understand the production system they are managing.

7.1. On-farm experimentation

Bramley and Janik (2005) have highlighted the fact that one consequence of the site-specific nature of PA is that, in addition to management being site specific, the derivation of management recommendations, for example via soil testing, may also need to be site-specific. This then raises the question of how site-specific recommendations might be developed. Adams and Cook (1997; 2000), Cook (1997) and Cook and Bramley (1998; 2000) have proposed the use of *whole-of-block* or, *on-farm experimentation* as a means of both fine tuning fertiliser recommendations and generating a site-specific basis for soil test interpretation.

As discussed in some detail by Bramley *et al.* (2005b), traditional forms of experimentation based on classical 'Fisherian' statistics (ie analysis of variance or ANOVA) explicitly ignore the kind of spatial variability shown in Figure 1. Generally, such experiments involve treatments imposed in small plots. The effects of spatial variation are assumed to be removed by randomising the allocation of treatments to plots, yet it is not hard to imagine that the success of such a process may be significantly impacted by the underlying spatial variation – which is not random ! Figure 5 illustrates the problems posed for traditional plot-based experiments by underlying variability and also demonstrates how random distribution of experimental treatments within a site may mitigate against any ability to measure treatment effects. Bramley *et al.* (2005a) provide an illustration from the Australian wine industry in which the effects of inherent variation in vine vigour severely compromised the utility of an experiment conducted by a wine company seeking to improve management of fruit quality. Had this variation been accounted for, the nature of the management strategies trialled in this experiment might have been quite different.

Of course, like a vineyard manager, a sugarcane farmer has to manage the whole field and farm, not just a few plots. The effects of the sort of spatial variation shown in Figures 1 and 5 therefore raise questions about how experiments should best be done – whether as part of a scientific research project, or by a grower who wants to evaluate a new management strategy. In the latter case, pragmatism is likely to lead the grower to apply a treatment over a whole row or group of rows, yet yield maps show that it is quite possible for the full range of yield variation to be encountered in a single row. Thus,
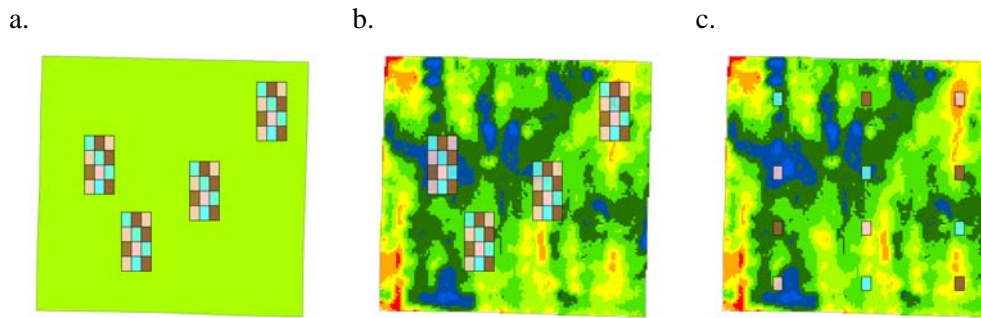
Figure 5. Possible locations for a classical agronomic experiment (a) in the absence of knowledge of underlying variation, (b) using one of the same designs but where information about underlying variation is available (in this case, a yield map), and (c) in an attempt to accommodate the effects of the underlying variation. (Bramley *et al.*, 2005a)

even if a grower deemed a new strategy to deliver a benefit when evaluated over whole rows, he/she would not necessarily know whether the benefit was accrued in some parts of it more than others.

Clearly, if the benefit was derived primarily towards one end of a row, adoption of the new strategy over the whole block would be sub-optimal, even if it were better than the previously used practice. This uncertainty leads to the idea that applying experimental treatments over the whole block and looking at their effects spatially might maximise the utility of the results. Adams and Cook (1997, 2000) used this idea in experiments conducted in broadacre cereal production, whilst Bramley *et al.* (2005a) have demonstrated the successful implementation of this approach to vineyard management. Current work in the Australian wine industry (Panten and Bramley, 2006) is evaluating appropriate designs for such experiments. Given that cane is grown as a row crop, this viticultural research may usefully inform exploring the opportunities of the whole of block approach in sugarcane production. Site-specific fine tuning of fertiliser management, variety evaluation, or assessment of the suitability of dual or high density planting are potential applications of such an approach. Doerge and Gardner (1999) showed how the use of a split planter, followed by yield mapping was useful in maize variety trials. This approach is readily transferable to sugarcane production and could also be used for planting density trials. There will doubtless be other aspects of sugarcane agronomy which could be advanced through the whole-of-block approach.

8.   Conclusions and recommendations

Precision Agriculture can be considered just as potentially applicable to sugarcane production as has been seen to be the case in other crop production systems. However, and based on the foregoing discussion, a number of key tasks in RDE will be required to enable its implementation in the Australian sugar industry. These are as follows:

1. Access to calibrated, and easily calibratable, yield monitoring systems and the associated development of a robust protocol for yield map production is required. Note that the latter could be readily and quickly delivered through appropriate modification of the winegrape protocol (Bramley and Williams, 2001).
2. An assessment should be made of the utility for in-field management, the most appropriate and cost-effective spatial resolution and the optimal time of image acquisition, for remotely sensed imagery. Associated with this, an evaluation of the merits of airborne compared to satellite-based remote sensing platforms should be carried out.
3. Case studies highlighting the utility (and shortcomings) of the various tools of PA in delineating management zones within sugarcane blocks should be undertaken in each of the major canegrowing regions. These should include investigation of relationships between yield,

indices of crop quality, soil properties and terrain attributes (pre- and post- laser levelling) as the basis for more targeted management, and evaluation of the merits of selective harvesting based on ccs variation and of the targeted application of ripeners. The opportunities for variable management of irrigation water should also be explored. Initiation of these studies is arguably the most important of the various tasks identified here. In all cases, economic analysis should form a key part of the research, and should determine and demonstrate the potential profitability of PA approaches, as well as inform advice as to the relative merits of putting effort into removing variation as opposed to managing in response to it.

4. An evaluation of the utility of whole-of-block approaches for sugarcane agronomic experimentation and the development of site specific criteria for interpretation of soil test data and development site-specific management strategies should be undertaken.

5. Training and extension support in PA data acquisition, management and analysis should be developed and provided to leading growers and consultants. The emergence of local service providers in these aspects of PA, in addition and as opposed to equipment sales, should also be encouraged. (Note that during an industry workshop held during preparation of this review, the point was forcibly made that whilst the Australian sugar industry has a strong culture of advice being made freely available, "people do not value things that they get for free". Thus, independent specialist service providers should be encouraged to fill commercial gaps and the industry should be encouraged to make use of them on a fee for service basis.). As part of this activity, a possible role for groups like the Herbert Resource Information Centre (HRIC), regional Productivity Services and SPAA should be considered and encouraged. The capacity building implicit in this recommendation will be key to the successful adoption of PA by the Australian sugar industry. However, it is suggested that implementation of this recommendation be witheld until the case studies (recommendation 3) begin to demonstrate that PA is likely to enhance industry profitability.

6. A sensor development program should be initiated. Of highest priority is development of an on-the-go sugar (ie ccs) sensor for use during harvesting. Development of companion sensors for other attributes of cane quality, including key sugar impurities, may also be warranted. The case for development of a css sensor seems clear; appropriate economic modelling, along with input from millers and sugar refiners, may be warranted prior to the development of other sensors.

7. An evaluation should be made of the most appropriate ways of integrating existing Sugar Mill and Productivity Service data collection and harvest management systems (eg Markley et al., 2006) with PA applications. As part of this, consideration should be given to software compatibility and ease of integration of 'standard PA methodologies' with software platforms currently being used in the sugar industry, and/or the need for a move to software platforms not currently being used.

Simultaneous to all of these activities, will be the need to keep abreast of developments in PA in other industries both in Australia and overseas. Support for grower, consultant and researcher visits to technical meetings, centres of expertise and cropping industries in which PA has been successfully implemented would therefore be highly valuable. In addition, there would be much value in initiating research aimed at demonstrating the contribution that PA can make to improved environmental stewardship. Whilst not an essential task in terms of facilitating access to the agronomic and economic benefits of PA, the importance of an ability to demonstrate that the sugar industry is playing its role in preserving the sensitive ecosystems which border it is something which can not be overstated.

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References

Adamchuk, V.I., Morgan, M.T., Brouder, S.M. 2006. Development of an on-the-go soil pH mapping method: Analysis of measurement variability. *Applied Engineering in Agriculture* **22**, 35-344.

Adams, M.L. and Cook, S.E. 1997. Methods of on-farm experimentation using precision agriculture technology. Paper No. 97-3020, ASAE, St Joseph, MI, USA.

Adams, M.L. and Cook, S.E. 2000. On-farm experimentation: Application of different analytical techniques for interpretation. *In: Proceedings of the Fifth International Conference on Precision Agriculture* Robert, P.C., Rust, R.H. and Larsen, W.E. (*Eds*). ASA-CSA-SSSA, Madison, WI, USA. CD-ROM

Almeida, T.I.R., De Souza Filho, C.R. and Rossetto, R. 2006. ASTER and Landsat ETM+ images applied to sugarcane yield forecast. *International Journal of Remote Sensing* **27**, 4057-4069.

Anderson, D.L., Portier, K.M. Obreza, T.A., Collins, M.E. and Pitts, D.J. 1999. Tree regression analysis to determine effects of soil variability on sugarcane yields. *Soil Science Society of America, Journal* **63**, 592-600.

Anon. 2005. Applications of apparent soil electrical conductivity in precision agriculture. *Computers and Electronics in Agriculture* **46**, 1-10.

Antuniassi, U.R., Velini, E.D. and Nogueira, H.C. 2004. Soil and weed survey for spatially variable herbicide application on railways. *Precision Agriculture* **5**, 27-39.

Apan, A., Held, A., Phinn, S. and Markley, J. 2004. Detecting sugarcane 'orange rust' disease using EI-1 Hyperion hyperspectral imagery. *International Journal of Remote Sensing* **25**, 489-498.

Arkun, S., Honey, F., Johnson, L., Lamb, D. Lieff, W. and Morgan, G. 2000. Airborne remote sensing of the vine canopy. *In:* Lamb, D.W (Ed) Vineyard monitoring and management beyond 2000 – A workshop investigating the latest technologies for monitoring and managing variability in vineyard productivity. CRC Viticulture, National Grape and Wine Industry Centre, Charles Sturt University, Wagga Wagga, NSW, 7-8-00.

Benjamin, C.E., Mailander, M.P and Rice, R.R. 2001. Sugar cane yield monitoring system. ASAE meeting paper No. 011189. St Joseph, Mich.

Berry, J.R., Delgado, J.A., Khosla, R. and Pierce, F.J. 2003. Precision conservation for environmental sustainability. *Journal of Soil and Water Conservation* **58**, 332-339.

Blackmore, S. 2003. Precision farming: A dynamic process. *In:* Robert, P.C., Rust, R.H and Larson, W.E. (Eds). Proceedings of the 6th International Conference on Precision Agriculture and Other Precision Resources Management, Minneapolis, Minnesota, USA, 14-17 July 2002. ASA-CSA-SSSA, Madison, WI. pp 84-104.

Blackmore, S., Griepentrog, H., Pedersen, S. and Fountas, S. 2006. Europe. *In:* Srinivasan, A. (*Ed*). *Handbook of Precision Agriculture: Principles and Applications.* The Haworth Press Inc., Binghamton, New York. pp. 567-613.

Bongiovanni, R. and Lowenberg-DeBoer, J. 2004. Precision Agriculture and sustainability. *Precision Agriculture* **5**, 359-387.

Bournennane, H., Nicoullaud, B., Couturier, A. and King, D. 2004. Exploring the spatial relationships between some soil properties and wheat yields in two soil types. *Precision Agriculture* **5**, 521-536.

Bramley, R.G.V. 2003a. Precision viticulture – Tools to optimize winegrape production in a difficult landscape. *In:* Robert, P. (*Ed*) Proceedings of the 6th International Conference on Precision Agriculture and Other Precision Resources Management, Minneapolis, Minnesota, USA, 14-17 July 2002. ASA-CSA-SSSA, Madison, WI. pp 648-657.

Bramley, R. 2003b. Smarter thinking on soil survey. *Australian and New Zealand Wine Industry Journal* **18** (3), 88-94.

Bramley, R.G.V. 2005. Understanding variability in winegrape production systems. 2. Within vineyard variation in quality over several vintages. *Australian Journal of Grape and Wine Research* **11** 33-42.

Bramley, R.G.V. 2006. Acquiring an informed sense of place – Practical applications of Precision Viticulture. *Australian and New Zealand Wine Industry Journal* **21** (1) 26-33.

Bramley, R.G.V. and Hamilton, R.P. 2004. Understanding variability in winegrape production systems. 1. Within vineyard variation in yield over several vintages. *Australian Journal of Grape and Wine Research* **10** 32-45.

Bramley, R.G.V. and Hamilton, R.P. 2005. Hitting the zone – Making viticulture more precise. *In:* Blair, R.J, Williams, P.J. and Pretorius, I.S. (*Eds*) Proceedings of the 12th Australian Wine Industry Technical Conference. Winetitles, Adelaide. pp. 57-61.

Bramley, R.G.V. and Hamilton, R.P. 2006. *Terroir* and Precision Viticulture: Are they compatible ? *In:* Van Leeuwen, C., Roby, J-P., Marguerit, E. and Fanet, J. (Eds). 2006. *Terroirs Viticoles 2006* 1, 3-5 Juillet, Bordeaux. ENITA de Bordeaux. pp.218-225.

Bramley, R.G.V. and Janik, L.J. 2005. Precision agriculture demands a new approach to soil and plant sampling and analysis – Examples from Australia. *Communications in Soil Science and Plant Analysis* **36** 9-22.

Bramley, R.G.V. and Quabba, R.P. 2001. Opportunities for improving the management of sugarcane production through the adoption of precision agriculture – An Australian perspective. *Proceedings of the 24th Congress of the International Society of Sugar Cane Technologists*, 17-21 September, Brisbane. ASSCT, Mackay, Australia. pp 38-46. Also available at www.clw.csiro.au/staff/RBramley/publications.html

Bramley, R.G.V. and the late Quabba, R.P. 2002. Opportunities for improving the management of sugarcane production through the adoption of precision agriculture – An Australian perspective. *International Sugar Journal* **104**, 152-161.

Bramley, R.G.V and Williams, S.K. 2001. A protocol for the construction of yield maps from data collected using commercially available grape yield monitors. www.crcv.com.au/CRCVProtocolBkfinal.pdf Cooperative Research Centre for Viticulture, Adelaide.

Bramley, R.G.V. and Williams, S.K. 2007. Topographic variation – A key driver of variable vineyard productivity and wine quality. *In:* Stafford, J.V. (*Ed*) Proceedings of the 6th European Conference on Precision Agriculture. In press.

Bramley, R.G.V. and Roth, C.H. 2002. Land use impact on water quality in an intensively managed catchment in the Australian humid tropics. *Marine and Freshwater Research* **53** 931-940.

Bramley, R.G.V., Cook, S.E. and McMahon, G.G. (Eds). 1997. Precision Agriculture - What Can It Offer The Australian Sugar Industry ? Proceedings of a workshop held at the Mercure Inn, Townsville, 10-12 June. CSIRO Land and Water, Townsville. ISBN 0 643 06048 0.

Bramley, R.G.V., Cook, S.E., Cox, D.R.V., McMahon, G.G. and Roth, C.H. 1998. Precision agriculture: What is it and what can it offer the Australian sugar industry ? *Proceedings of the Australian Society of Sugar Cane Technologists* **20**, 188-195.

Bramley, R.G.V., Roth, C.H. and Wood, A.W. 2003. Risk Assessment of phosphorus loss from sugarcane soils – A tool to promote improved management of P fertilizer. *Australian Journal of Soil Research* **41** 627-644.

Bramley, R.G.V., Lanyon, D.M. and Panten, K. 2005a. Whole-of-vineyard experimentation – An improved basis for knowledge generation and decision making. *In:* Stafford, J.V. (*Ed*) Proceedings of the 5th European Conference on Precision Agriculture. Wageningen Academic Publishers, The Netherlands. pp. 883-890.

Bramley, R.G.V., Proffitt, A.P.B., Hinze, C.J., Pearse, B. and Hamilton, R.P. 2005b. Generating benefits from Precision Viticulture through selective harvesting. *In:* Stafford, J.V. (*Ed*). *Precision Agriculture '05*. Proceedings of the 5th European Conference on Precision Agriculture. Wageningen Academic Publishers, The Netherlands. pp. 891-898.

Bullock, D.S. and Bullock, D.G. 2000. From agronomic research to farm management guidelines: A primer on the economics of information and precision technology. *Precision Agriculture* **2**, 71-101.

Cabrera, A. Rodríquez, E., Balmaseda, C. and Ponce de Leon, D. 2002. Variabilidad espacial de los redimientos cañeros y necesidad de fertilizar por sitio específico. *Cultivos Tropicales* **23**, 57-60.

Carberry, P.S., Hochman, Z., Mccown, R.L., Dalgliesh, N.P., Foale, M.A., Poulton, P.L., Hargreaves, J.N.G., Hargreaves, D.M.G., Cawthray, S., Hillcoat, N. and Robertson, M.J. 2002. The Farmscape Approach to Decision Support: Farmers', Advisers', Researchers' Monitoring, Simulation, Communication and Performance Evaluation. *Agricultural Systems* **74**, 141-177.

Chung Tze Cheong, M., Adelaide, S., Appave, R. and Ng Kee Kwong, K.F. 2001. Optimizing the selection of permanent sampling unit of sugar cane fields with geographic information system. *Revue Agricole et Sucriere de l'Ile Maurice* **80/81**, 73-78.

Colvin, T.S. 2006. Precision Agriculture management progress and prospects for corn/soybean systems. *In:* Srinivasan, A. (*Ed*). *Handbook of Precision Agriculture: Principles and Applications.* The Haworth Press Inc., Binghamton, New York. pp. 341-352.

Corwin, D.L., Lesch, S.M., Oster, J.D. and Kaffka, S.R. 2006. Monitoring management-induced spatio-temporal changes in soil quality through soil sampling directed by apparent electrical conductivity. *Geoderma* **131**, 369-387.

Cook, S.E. 1997. Data interpretation and risk analysis for precision agriculture. *In:* Bramley, R.G.V., Cook, S.E and McMahon, G.G. (Eds) Precision Agriculture – What can it offer the Australian sugar industry ? Proceedings of a workshop held in Townsville, 10-12 June, 1997. CSIRO Land and Water, Townsville. pp.77-85.

Cook, S.E. and Bramley, R.G.V. 1998. Precision agriculture - Opportunities, benefits and pitfalls. *Australian Journal of Experimental Agriculture* **38**, 753-763.

Cook, S.E. and Bramley, R.G.V. 2000. Coping with variability in agricultural production – Implications for soil testing and fertilizer management. *Communications in Soil Science and Plant Analysis* **31**, 1531-1551.

Cook, S.E. and Bramley, R.G.V. 2001. Is agronomy being left behind by precision agriculture ? Proceedings of the 10th Australian Agronomy Conference. www.regional.org.au/au/asa/2001/plenery/2/cook.htm

Cook, S.E., Adams, M.L. and Bramley, R.G.V. 2000. What is obstructing the wider adoption of precision agriculture technology ? *In:* Robert, P.C., Rust, R.H and Larson, W.E. (Eds). Proceedings of the 5th International Conference on Precision Agriculture, Minneapolis, Minnesota, USA, 16-19 July 2000. CD ROM.

Cook, S.E., Adams, M.L., Bramley, R.G.V. and Whelan, B.M. 2006. Australia. *In:* Srinivasan, A. (*Ed*). *Handbook of Precision Agriculture: Principles and Applications.* The Haworth Press Inc., Binghamton, New York. pp. 529-566.

Cook, S.E., O'Brien, R.O., Corner, R.J. and Oberthur, T. 2003. Is Precision Agriculture irrelevant to developing countries ? *In*: Stafford, J.V. (*Ed*). Proceedings of the 4th European Conference on Precision Agriculture. Wageningen Academic Publishers, The Netherlands. pp. 115-119.

Corá, J.E. and Marques, J. 2000. The potential for precision agriculture for soil and sugarcane yield variability in Brazil. *In:* Robert, P.C., Rust, R.H and Larson, W.E. (Eds). Proceedings of the 5th International Conference on Precision Agriculture, Minneapolis, Minnesota, USA, 16-19 July 2000. CD ROM.

Corá, J.E., Marques, J. and Pereira, G.T. 2001. The potential for precision agriculture in a sugarcane long term agricultural system in Brazil. *In:* Blackmore, S. and Grenier, G. (Eds) *ECPA 2001 - 3rd European Conference on Precision Agriculture* **2** 785-790. agro Montpellier, Ecole Nationale Superieure Agronomique de Montpellier, France.

Cox, D.R.V. 1997. Precision agriculture in sugarcane production: A view from the Burdekin. *In:* Bramley, R.G.V., Cook, S.E and McMahon, G.G. (Eds) Precision Agriculture – What can it offer the Australian sugar industry ? Proceedings of a workshop held in Townsville, 10-12 June, 1997. CSIRO Land and Water, Townsville. pp. 93-97.

Cox, G.J., Harris, H.D., Pax, R., and Dick, R. 1996. Yield mapping in the cane industry. *In:* Wilson, J.R., Hogarth, D.M., Campbell, J.A. and Garside, A.L. (Eds). *Sugarcane: Research Towards Efficient and Sustainable Production*. CSIRO Tropical Crops and Pastures, Brisbane. pp. 189-193.

Cox, G.J., Harris, H.D. and Pax, R. 1997. Development and testing of a prototype yield mapping system. *Proceedings of the Australian Society of Sugar Cane Technologists* **19**, 38-43.

Cox, G., Harris, H. and Cox, D. 1999. Application of Precision Agriculture to sugar cane. *In:* Robert, P.C., Rust, R.H and Larson, W.E. (Eds). Proceedings of the 4th International Conference on Precision Agriculture, St Paul, Minnesota, USA, 19-22 July 1998. Part B. pp 753-765.

Cuppitt, J. and Whelan, B.M. 2001. Determining potential within-field crop management zones. *In:* Blackmore, S. and Grenier, G. (Eds) *ECPA 2001 - 3ʳᵈ European Conference on Precision Agriculture* **1** 7-12. agro Montpellier, Ecole Nationale Superieure Agronomique de Montpellier, France.

Davis, R.J., Bartels, R. and Schmidt, E.J. 2007. Precision Agriculture technologies - Relevance and application to sugarcane production. National Centre for Engineering in Agriculture Publication 1002265/1, University of Southern Queensland, Toowoomba, Queensland.

Delgado, J.A., Cox, C.A., Pierce, F.J. and Dosskey, M.G. 2005. Precision conservation in North America. *Journal of Soil and Water Conservation* **60**, 340-341.

Diker, K., Heerman, D.F. and Brodahl, M.K. 2004. Frequency analysis of yield for delineating yield response zones. *Precision Agriculture* **5**, 435-444.

Doerge, T.A. 2005. Nitrogen measurement for variable-rate N management in maize. *Communications in Soil Science and Plant Analysis* **36** 23-32.

Doerge, T.A. and Gardner, D.L. 1999. On-farm testing using the adjacent strip comparison method. *In:* Robert, P.C., Rust, R.H. and Larson, W.E. Proceedings of the 4th International Conference on Precision Agriculture, Minneapolis, 19-22 of July 1998, Part A. pp. 603-609.

Dosskey, M.G., Eisenhauer, D.E. and Helmers, M.J. 2005. Establishing conservation buffers using precision information. *Journal of Soil and Water Conservation* **60**, 349-354.

Esquivel, M., Hernández, B., Rodríguez, J., Fernández, F., Ponce, E., Quintana, L., Interián, S. and Alvarez, R. 2005. Precision farming for fruit crops. *In*: Heemskerk, C. and Engvall, M. (Eds) Book of Abstracts - 5ECPA-2ECPLF. Swedish Institute of Agricultural and Environmental Engineering. Uppsala. pp. 85-86.

Erickson, B. 2006. Precision Agriculture in Colombian sugar cane. *Site Specific Management Center Newsletter, Purdue University, September 2006.* www.agriculture.purdue.edu/ssmc/Frames/SSMCnewsletter9_2006.pdf.

Evans, T. 1998. Mapping vineyard salinity using electromagnetic surveys. *The Australian Grapegrower and Winemaker* **415**, 20-21.

Everingham, Y., Jakku, E., Inmann-Bamber, G., Thorburn, P., Webster, T., Attard, S. and Antony, G. 2006. Understanding the adoption of knowledge intensive technologies in the Australian sugar industry – a pilot study. *Proceedings of the Australian Society of Sugar Cane Technologists* **28**, 76-85.

Ferreira, F. and Scheeppers, F. 1999. Applications of satelite technology in the sugar industry. *Proceedings of the South African Sugar Technologists Association* **73**, xliii-li.

Fountas, S., Blackmore, S., Ess, D., Hawkins, S., Blumhoff, G., Lowenberg-DeBoer, J. and Sorensen, C.G. 2005. Farmer experience with Precision Agriculture in Denmark and the US Eastern corn belt. *Precision Agriculture* **6**, 121-141.

Franzen, D.W. 2006. Site-specific nitrogen management in sugarbeet. *In:* Srinivasan, A. (*Ed*). *Handbook of Precision Agriculture: Principles and Applications.* The Haworth Press Inc., Binghamton, New York. pp. 395-411.

Galvão, L.S., Formaggio, A.R. and Tisto, D.A. 2005. Discrimination of sugarcane varieties in Southeastern Brazil with EO-1 Hyperion data. *Remote Sensing of Environment* **94**, 523-534.

Gebbers, R. and Lück, E. 2005. Comparison of geoelectrical methods for soil mapping. *In:* Stafford, J.V. (*Ed*) Proceedings of the 5ᵗʰ European Conference on Precision Agriculture. Wageningen Academic Publishers, The Netherlands. pp 473-479.

Gemtos, T.A., Markinos, Ath. and Nassiou, Th. 2005. Cotton lint quality spatial variabiility and correlation with soil properties and yield. *In:* Stafford, J.V. (*Ed*) Proceedings of the 5ᵗʰ European Conference on Precision Agriculture. Wageningen Academic Publishers, The Netherlands. pp 361-368.

Gerhards, R. and Christensen, S. 2006. Site-specific weed management. *In:* Srinivasan, A. (*Ed*). *Handbook of Precision Agriculture: Principles and Applications.* The Haworth Press Inc., Binghamton, New York. pp. 185-205.

Godwin, R.J., Richards, T.E. Wood, G.A., Welsh, J.P. and Knight, S.M. 2003. An economic analysis of the potential for precision farming in UK cereal production. *Biosystems Engineering* **84** 533-545.

Griffin, T.W. and Lowenberg-DeBoer, J. 2005. Worldwide adoption and profitability of precision agriculture. *Revista de Politica Agricola* **14**, 20-38.

Grove, J.H., Pena-Yewtukhiw, E.M. and Thompson, J.A. 2005. Corn grain yield in rolling landscapes: Terrain attributes or surface soil properties ? *In:* Mulla, D.J. (*Ed.*) Proceedings of the 7th International Conference on Precision Agriculture and Other Precision Resources Management, Minneapolis, Minnesota, USA, 25-28 July 2004. pp 457-467.

Hall, A., Lamb, D.W., Holzapfel, B. and Louis, J. 2002 Optical remote sensing applications in viticulture – a review. *Australian Journal of Grape and Wine Research* **8**, 36-47.

Haneklaus, S., Lamp, J. and Schnug, E. 1991. Erfassung der räumlichen Variabilität von Rapserntemengen in Ertragskarten. *Raps* **9**, 142-143.

Harris, H.D. and Cox, G.J. 1997. Yield mapping – current capabilities in yield mapping for sugarcane. Are these limiting to the introduction of PA to the sugar industry ? *In:* Bramley, R.G.V., Cook, S.E and McMahon, G.G. (Eds) Precision Agriculture – What can it offer the Australian sugar industry ? Proceedings of a workshop held in Townsville, 10-12 June, 1997. CSIRO Land and Water, Townsville. pp. 35-41.

Heap, J.W. and McKay, A.C. 2005. Managing soilborne diseases in Australian field crops using precision agriculture and soil DNA tests. *In:* Stafford, J.V. (*Ed*) Proceedings of the 5th European Conference on Precision Agriculture. Wageningen Academic Publishers, The Netherlands. pp. 99-105.

Hernandez, B., Fernandez, F., Ponce, E., Esquivel, M., Rodriguez, J., Quintana, L., Interian, S. and Alvarez, R. 2005. Application of precision farming technologies for sugarcane crop. *In*: Heemskerk, C. and Engvall, M. (Eds) Book of Abstracts - 5ECPA-2ECPLF. Swedish Institute of Agricultural and Environmental Engineering. Uppsala. pp. 119.

Higgins, A.J., Muchow, R.C., Rudd, A.V. and Ford, A.W. 1998. Optimising harvest date in sugar production: a case study for the Mossman Mill region in Australia. I. Development of operations research model and solution. *Field Crops Research* **57**, 153-162.

Holmes, M., Strang, G.C., van Zyl, R., Smithers, J.C. Bezuidenhout, C.N. and Lyne, P.W.L. 2005. Progress on the in-field measurement of cane mass using a Bell loader. *Proceedings of the 79th Annual Congress of South African Sugar Technologists*, 409-411.

Janik, L.J., Merry, R.H. and Skjemstad, J.O. 1998. Can mid infrared diffuse reflectance analysis replace soil extractions ? *Australian Journal of Experimental Agriculture* **38**, 681-696.

Jhoty, I. 2001. La cartographie de la variabilité du rendement: Un moyen stratégique pour améliorer la production de canne a sucre. *Revue Agricole et Sucriere de l'Ile Maurice* **80**, 47-50.

Jhoty, I. 2003. Application of the principles and techniques of precision agriculture to sugar cane. *Revue Agricole et Sucriere de l'Ile Maurice* **82**, 87-91.

Jhoty, I. and Autrey, L.J.C. 2001. Precision agriculture for sugarcane in Mauritius. *Proceedings of the 24th Congress of the International Society of Sugar Cane Technologists*, 17-21 September, Brisbane. ASSCT, Mackay, Australia. pp 47-50.

Jhoty, I., Ramasamy, S., Autrey, L.J.C. and Blackmore, S. 2003. Yield variability in sugar cane. *In:* Robert, P.C., Rust, R.H and Larson, W.E. (Eds). Proceedings of the 6th International Conference on Precision Agriculture and Other Precision Resources Management, Minneapolis, Minnesota, USA, 14-17 July 2002. pp 141-150.

Johnson, R.M. and Richard, E.P. 2002. Evaluation of crop and soil spatial variability in Louisiana sugarcane production systems. *In:* Robert, P.C., Rust, R.H and Larson, W.E. (Eds). Proceedings of the 6th International Conference on Precision Agriculture and Other Precision Resources Management, Minneapolis, Minnesota, USA, 14-17 July 2002. pp 223-231.

Johnson, R.M. and Richard, E,P. 2005a. Utilisation of yield mapping and variable rate lime application in Louisiana sugarcane. *Sugarcane International* **23**, 8-14.

Johnson, R.M. and Richard, E,P. 2005b. Sugarcane yield, sugarcane quality, and soil variability in Louisiana. *Agronomy Journal* **97**, 760-771.

Johnson, R.M., Bradlow, J.M. and Wrona, A.F. 2006. Site-specific management of cotton production in the United States. *In:* Srinivasan, A. (*Ed*). *Handbook of Precision Agriculture: Principles and Applications.* The Haworth Press Inc., Binghamton, New York. pp. 353-378.

Kaspar, T.C., Colvin, T.S., Jaynes, D.B., Larlen, D.L., James, D.E. and Meek, D.W. 2003. Relationships between six years of corn yields and terrain attributes. *Precision Agriculture* **4**, 87-101.

Kaydos, W. 1991. *Measuring, managing and maximising performance.* Productivity Press Inc., Cambridge, Mass.

Keating, B.A., Kingston, G., Wood, A.W., Berding, N. and Muchow, R.C. 1999. Monitoring nitrogen at the mill to guide N fertilisation practice on farm. *Proceedings of the Australian Society of Sugar Cane Technologists* **21**, 10-19.

Khanna, M. and Zilberman, D. 1997. Incentives, precision technology and environmental protection. *Ecological Economics* **23**, 25-43.

Kingston, G. and Hyde, R.E. 1995. Intra-field variation of commercial cane sugar (ccs) values. *Proceedings of the Australian Society of Sugar Cane Technologists* **17**, 30-38.

Kingston, G., Gopang, N., Luo, Y., Shine, J.M., Ezenwa, I.V. and Rice, R.W. 2005. International applications of electromagnetic induction measurements for understanding the impact of soil properties on cane growth. *In:* Proceedings of the International Society of Sugar Cane Technologists Agronomy Workshop – Khon Khae, Thailand, May 2006.

Lamb, D.W. 2000. The use of qualitative airborne multispectral imaging for managing agricultural crops – A case study in south eastern Australia. *Australian Journal of Experimental Agriculture* **40**, 725-738.

Lamb, DW, Weedon, MM, and Bramley, R.G.V. 2004. Using remote sensing to map grape phenolics and colour in a cabernet sauvignon vineyard - the impact of image resolution and vine phenology. *Australian Journal of Grape and Wine Research.* **10** 46-54.

Lambert, D. and Lowenberg-DeBoer, J. 2000. Precision agriculture profitability review. Site-specific Management Center, School of Agriculture, Purdue University. www2.agriculture.purdue.edu/ssmc/.

Lawes, R.A., Wegener, M.K., Basford, K.E. and Lawn, R.J. 2003. A multivariate evaluation of sugarcane farm performance over time based on yield and commercial cane sugar. *In:* Solutions for a better environment. Proceedings of the 11th Australian Agronomy Conference, 2-6 Feb. 2003, Geelong, Victoria. Australian Society of Agronomy. www.regional.org.au/au/asa/2003/c/15/lawes.htm

Lee, W.S., Slaughter, D.C. and Giles, D.K. 1999. Robotic weed control system for tomatoes. *Precision Agriculture* **1**, 95-113.

Leonard, E. and Price, P. (*Eds*) 2006. *GRDC Precision Agriculture Manual*. Grains Research and Development Corporation, Canberra. On CD ROM.

Long, D.S., Carlson, G.R. and Engel, R. 1998. Grain protein mapping for precision management of dryland wheat. Proceedings of the 4th International Conference on Precision Agriculture, St Paul, Minnesota, USA, 19-22 July 1998. Part A. pp 787-796.

Lowenberg-DeBoer, J. 2003. Precision farming or convenience agriculture. *In:* Solutions for a better environment - Proceedings of the 11th Australian Agronomy Conference, Geelong. Australian Society of Agronomy www.regional.org.au/au/asa/2003/i/6/lowenberg.htm#TopOfPage.

Lück, E., Rhulmann, J. and Spangenberg, U. 2005. Physical background of soil EC mapping: laboratory, theoretical and field studies. *In:* Stafford, J.V. (*Ed*) Proceedings of the 5th European Conference on Precision Agriculture. Wageningen Academic Publishers, The Netherlands. pp 417-424.

Machado, S., Bynum, E.D., Archer, T.L., Bordovsky, J., Rosenow, D.T., Peterson, C., Bronson, K., Nesmith, D.M., Lascano, R.J., Wilson, L.T. and Segarra, E. 2002. Spatial and temporal variability of sorghum grain yield: Influence of soil, water, pests and diseases relationships. *Precision Agriculture* **3**, 389-406.

Magalhães, P.S.G. and Cerri, D.G.P. 2007. Yield monitoring of sugar cane. *Biosystems Engineering* **96**, 1-6.

Magri, A., van Es, H.M., Glos, M.A. and Cox, W.J. 2005. Soil test, aerial image and yield data as inputs for site-specific fertility and hybrid management under maize. *Precision Agriculture* **6**, 87-110.

Mallarino, A.P. and Wittry, D.J. 2004. Efficacy of grid and zone soil sampling approaches for site-specific assessment of phosphorus, potassium, pH and organic matter. *Precision Agriculture* **5**, 131-144.

Mallarino, A.P., Oyarzabal, E.S. and Hinz, P.N. 1999. Interpreting within-field relationships between crop yields and soil and plant variables using factor analysis. *Precision Agriculture* **1**, 15-25.

Markley, J. and Fitzpatrick, B. 2004. The development of remote sensing sugar cane yield estimation procedures used by Mackay Sugar Co-operative. Proceedings of the 12th Australian Remote Sensing and Photogrammetry Conference, October, Fremantle. On CD ROM. ISBN 0-9581366-1-0. Spatial Sciences Institute, Canberra.

Markley, J., Raines, A. and Crossley, R. 2003. The development and integration of remote sensing, GIS and data processing tools for effective harvest management. *Proceedings of the Australian Society of Sugar Cane Technologists* **25** CD ROM.

Markley, J., Raines, A., Langham, D.A. and Fleming, G. 2006. Harvest and transport integration – A Mackay Sugar perspective. *Proceedings of the Australian Society of Sugar Cane Technologists* **28** 49-55.

McBratney, A.B. and Pringle, M.J. 1999. Estimating average and proportional variograms of soil properties and their potential use in precision agriculture. *Precision Agriculture* **1**, 125-152.

McBratney, A.B., Minasny, B. and Viscarra Rossel, R. 2006. Spectral soil analysis and inference systems: A powerful combination for solving the soil data crisis. *Geoderma* **136**, 272-278.

McBratney, A.B., Minasny, B. and Whelan, B.M. 2005a. Obtaining 'useful' high-resolution soil data from proximally-sensed electrical conductivity/resistivity (PSEC/R) surveys. *In:* Stafford, J.V. (*Ed*). *Precision Agriculture '05.* Proceedings of the 5th European Conference on Precision Agriculture. Wageningen Academic Publishers, The Netherlands. pp. 503-510.

McBratney, A., Whelan, B., Ancev, T. and Bouma, J. 2005b. Future directions of Precision Agriculture. *Precision Agriculture* **6**, 7-23.

McDonald, L. and Routley, S. 1999. Use of satellite imagery, remote sensing and spatial analysis to determines the area under cane prior to and during the harvest season. Report to the Herbert Cane Protection and Productivity Board. Cooperative Research Centre for Sustainable Sugar Production Report No. 03/99.

McKenzie, N., Bramley, R., Farmer, T., Janik, J., Murray, W., Smith, C., and McLaughlin, M. 2003. Rapid soil measurement – a review of potential benefits and opportunities for the Australian grains industry. Client report for the Grains Research and Development Corporation, GRDC Contract No: CSO00027. GRDC / CSIRO Land and Water, Canberra. Available at www.grdc.com.au/growers/res_summ/cs027/contents.htm

McKenzie, C. and Woods, S.A. 2006. Potential of precision farming with potatoes. *In:* Srinivasan, A. (*Ed*). *Handbook of Precision Agriculture: Principles and Applications.* The Haworth Press Inc., Binghamton, New York. pp. 379-394.

McNeill, J.D. 1980. Electromagnetic terrain conductivity measurement at low induction numbers. Technical Note TN-6, Geonics Ltd, Mississauga, Ontario, Canada.

Meyer, J.H., Wood, R.A., Nixon, D.J., Rampersad, A.L., Schroeder, B.L. and Schumann, A.W. 2004. The SASEX fertiliser advisory service: A review of 50 years of service to the South African sugar industry. *Proceedings of the South African Sugar Technologists Association* **78**, 359-371.

Miao, Y., Robert, P.C. and Mulla, D.J., 2005. Spatial and temporal variability in corn yield and quality responses to N fertilization with an eastern Illinois no-till field. *In:* Mulla, D.J. (*Ed.*) Proceedings of the 7th International Conference on Precision Agriculture and Other Precision Resources Management, Minneapolis, Minnesota, USA, 25-28 July 2004. pp 961-976.

Molin, J.P., Menegatti, L.A.A. and Manzzoni, C. 2004. Yield mapping from manually harvested sugar cane in Brazil. *In:* Mulla, D.J. (*Ed.*) Proceedings of the 7th International Conference on Precision Agriculture and Other Precision Resources Management, Minneapolis, Minnesota, USA, 25-28 July 2004. pp 627-637.

Moore, G.A. and Tyndale-Biscoe, J.P. 1999. Estimation of the importance of spatially variable nitrogen application and soil moisture holding capacity to wheat production. *Precision Agriculture* **1**, 27-38.

Muchow, R.C., Wood, A.W., Higgins, A.J. and McDonald, L.M. 1998. Developing cane supply and harvest schedules that enhance whole industry profitability. *Proceedings of the South African Sugar Technologists Association* **72**, 42-49.

Muchow, R.C., Higgins, A.J., Andrew, W.T. and Haynes, M.A. 2000. Towards improved harvest management using a systems approach. *Proceedings of the Australian Society of Sugar Cane Technologists* **22**, 30-37.

Muchow, R.C., Higgins, A.J., Rudd, A.V. and Ford, A.W. 1998. Optimising harvest date in sugar production: a case study for the Mossman Mill region in Australia. II. Sensitivity to crop age and crop class distribution. *Field Crops Research* **57**, 243-251.

Pagnano, N.B. and Maghalhães, P.S.G. 2001. Sugar cane yield measurement. *In:* Blackmore, S. and Grenier, G. (*Eds*). *ECPA 2001 - 3rd European Conference on Precision Agriculture* **2** agro Montpellier, Ecole Nationale Superieure Agronomique de Montpellier, France. pp. 839-843.

Pannell, D.J. 2006. Flat earth economics: The far-reaching consequences of flat payoff functions in economic decision making. *Review of Agricultural Economics* **28**, 553-566.

Pannell, D.J., Marshall, G.R., Barr, N., Curtis, A., Vanclay, F. and Wilkinson, R. 2006. Understanding and promoting adoption of conservation practices by rural landholders. *Australian Journal of Experimental Agriculture* **46**, 1407-1424.

Panten, K. and Bramley, R. 2006. A new approach to viticultural experimentation. *Australian and New Zealand Grapegrower and Winemaker – Annual Technical Issue* **509a**, 7-11.

Persson, A., Pilesjö, P. and Eklundh, L. 2005. Spatial influence of topographical factors on yield of potato (*Solanum tuberosum* L.) in central Sweden. *Precision Agriculture* **6**, 341-357.

Pierce, F.J. and Nowak, P. 1999 Aspects of Precision Agriculture. *Advances in Agronomy* **67**, 1-85.

Praat, J-P., Bollen, A.F. and Mowatt, A. 2006. Characterising spatial variation in quality. *In:* Kiwi 2006 – 6th International Kiwifruit Symposium, Rotorua, February 2006. Also in press *Acta Horticulturae*.

Pracilio, G., Adams, M.L., Smettem, K.R.J. and Harper, R.J. 2006. Determination of spatial distribution patterns of clay and plant available potassium contents in surface soils at the farm scale using high resolution gamma ray spectrometry. *Plant and Soil* **282**, 67-82.

Pringle, M.J., McBratney, A.B., Whelan, B.M. and Taylor, J.A. 2003. A preliminary approach to assessing the opportunity for site-specific crp management in a field, using yield monitor data. *Agricultural Systems* **76**, 273-292.

Proffitt, T., Bramley, R., Lamb, D. and Winter, E. 2006. *Precision Viticulture – A new era in vineyard management and wine production.* Winetitles, Adelaide.

Qian, P. and Schoenau, J.J. 2002. Practical applications of ion exchange resins in agricultural and environmental soil research. *Canadian Journal of Soil Science* **82**, 9-21.

Rawlins, S.L. 1997. Precision agriculture: The state of the art and lessons from overseas for the Australian sugar industry. *In:* Bramley, R.G.V., Cook, S.E and McMahon, G.G. (Eds) Precision Agriculture – What can it offer the Australian sugar industry ? Proceedings of a workshop held in Townsville, 10-12 June, 1997. CSIRO Land and Water, Townsville. pp. 25-33.

Reuter, H.I., Giebel, A. and Wendroth, O. 2005. Can landform stratification improve our understanding of crop yield variability ? *Precision Agriculture* **6**, 521-537.

Reyns, , P., De Baerdemacker, J., Vanongeval, L. and Geypens, M. 2006. Site-specific measurement and management of grain quality. *In:* Srinivasan, A. (*Ed*). *Handbook of Precision Agriculture: Principles and Applications.* The Haworth Press Inc., Binghamton, New York. pp. 271-316.

Rhoades, J.D. 1992. Instrumental field methods of salinity appraisal. *In: Advances in measurement of soil physical properties: Bringing theory into practice.* Soil Science Society of America Special Publication No. 30. SSSA, Madison, WI.

Richard, E.P., Meyer, J., Korndorfer, G.H., Kingston, G., and Dunkleman, J.W. 2001. Innovative approaches to sugarcane productivity in the new millenium: A review of the 2000 Agronomy workshop. *Proceedings of the 24th Congress of the International Society of Sugar Cane Technologists*, 17-21 September, Brisbane. ASSCT, Mackay, Australia. pp 22-26.

Robert, P.C. 2002. Precision Agriculture: a challenge for crop nutrition management. *Plant and Soil* **247**, 143-149.

Robertson, M. and Brennan, L. 2006. Is spatial variability worth managing differently for tactical decisions ? *In:* Leonard, E. and Price, P. (*Eds*) 2006. *GRDC Precision Agriculture Manual*. Grains Research and Development Corporation, Canberra. On CD ROM.

Robertson, M., Isbister, B., Maling, I., Oliver, Y., Wong, M., Adams, M., Bowden, W. and Tozer, P. 2006. Managing spatial and seasonal variability within field can improve the profitability of WA grain production. Proceedings of the 13th Australian Agronomy Conference. www.regional.org.au/au/asa/2006/plenery/2/cook.htm

Roel, A. Pettygrove, G.S. and Plant, R.E. 2006. Site-specific rice management. *In:* Srinivasan, A. (*Ed*). *Handbook of Precision Agriculture: Principles and Applications.* The Haworth Press Inc., Binghamton, New York. pp. 319-339.

Roloff, G. and Focht, D. 2006. Brazil. *In:* Srinivasan, A. (*Ed*). *Handbook of Precision Agriculture: Principles and Applications.* The Haworth Press Inc., Binghamton, New York. pp. 635-656.

Rouse, J.W., Haas, R.H., Schell, J.A. and Deering, D.W. 1973. Monitoring vegetation systems in the Great Plains with ERTS. Proceedings of the 3rd ERTS Symposium, NASA SP-351 **1** (US Government Printing Office, Washington DC). pp 309-317.

Runge, E.C.A. and Hons, F.M. 1999. Precision Agriculture – Development of a heirachy of variables influencing crop yields. *In:* Robert, P.C., Rust, R.H and Larson, W.E. (Eds). Proceedings of the 4th International Conference on Precision Agriculture, St Paul, Minnesota, USA, 19-22 July 1998. Part A. pp 143-158.

Saraiva, A.M., Hirakawa, A.R., Cugnasca, C.E., Pierossi, M.A. and Hassuani, S.J. 2000. A weighing system for grab loaders for sugar cane yield mapping. *Precision Agricluture* **2**, 293-309.

Schmidt, E.J., Gers, C., Narciso, G. and Frost, P. 2001. Remote sensing in the South African sugar industry. *Proceedings of the 24th Congress of the International Society of Sugar Cane Technologists*, 17-21 September, Brisbane. ASSCT, Mackay, Australia. pp 241-246.

Schmidt, E.J., Singels, A. and Gers, C.J. 2004. Sugar forecasting techniques in South Africa: Research and application. *Proceedings of the Australian Society of Sugar Cane Technologists* **26**, 1-13.

Schnug, E., Haneklaus, S. and Lamp, J. 1991. Continuous large scale yield mapping in oilseed rape fields and application of yield maps to CAF. *Oilseeds* **9**, 13-14.

Schroeder, B.L., Wood, A.W. and Kingston, G. 1998. Re-evaluation of the basis for fertilizer recommendations in the Australian sugar industry. *Proceedings of the Australian Society of Sugar Cane Technologists* **20**, 239-247.

Schroeder , B.L., Wood, A.W., Moody, P.W. and Panitz, J.H. 2005. Sustainable nutrient management – Delivering the message to the Australian Sugar Industry. *Proceedings of the 79th Annual Congress of South African Sugar Technologists*, 206-219.

Schumacher, J.A., Kaspar, T.C., Ritchie, J.C., Schumacher, T.E., Karlen, D.L., Venteris, E.R., McCarty, G.W., Colvin, T.S., Jaynes, D.B., Lindstrom, M.J. and Fenton, T.E. 2005. Identifying spatial patterns of erosion for use in precision conservation. *Journal of Soil and Water Conservation* **60**, 355-362.

Selige, T., Böhner, J. and Schmidhalter, U. 2006. High resolution topsoil mapping using hyperspectral image and field data in multivariate regression modeling procedures. *Geoderma* **136**, 235-244.

Shibusawa, S., Ehara, K., Okayama, T., Umeda, H. and Hirako, S. 2005. A real-time multi-spectral soil sensor: Predictability of soil moisture and organic matter content in a small field. *In:* Stafford, J.V. (*Ed*) Proceedings of the 5th European Conference on Precision Agriculture. Wageningen Academic Publishers, The Netherlands. pp. 495-502.

Skogley, E.O. 1992. The universal bioavailability environment/soil test unibest. *Communications in Soil Science and Plant Analysis* **23**, 2225-2247.

Smith, M.A. 2001. The use of GPS guidance systems and controlled traffic in mechanised cane farming. *Proceedings of the 24th Congress of the International Society of Sugar Cane Technologists*, 17-21 September, Brisbane. ASSCT, Mackay, Australia. pp 51-52.

Sparovek, G. and Schnug, E. 2001. Soil tillage and precision agriculture. A theoretical case study for soil erosion control in Brazilian sugar cane production. *Soil and Tillage Research* **61**, 47-54.

Srinivasan, A. (*Ed*). 2006. *Handbook of Precision Agriculture: Principles and Applications.* The Haworth Press Inc., Binghamton, New York.

Stafford, J.V. 2006. The role of technology in the emergence and status of Precision Agriculture. *In:* Srinivasan, A. (*Ed*). *Handbook of Precision Agriculture: Principles and Applications.* The Haworth Press Inc., Binghamton, New York. pp. 19-56.

Swinton, S.M. and Lowenberg-DeBoer, J. 1998. Evaluating the profitability of site-specific farming. *Journal of Production Agriculture* **11** 439-446.

Stoorvogel, J. and Bouma, J. 2005. Precision agriculture: The solution to control nutrient emissions ? *In:* Stafford, J.V. (*Ed*) Proceedings of the 5th European Conference on Precision Agriculture. Wageningen Academic Publishers, The Netherlands. pp 47-55.

Taylor, J., Whelan, B., Thylén, L., Gilbertsson, M. and Hassall, J. 2005. Monitoring wheat protein content on-harvester – Australian experiences. *In:* Stafford, J.V. (*Ed*) Proceedings of the 5th European Conference on Precision Agriculture. Wageningen Academic Publishers, The Netherlands. pp 369-375.

Tenkorang, F. and Lowenberg-DeBoer, J. 2004. Observations on the economics of remote sensing in agriculture. Newsletter of the Site-specific Management Center, Purdue University. www.agriculture.purdue.edu/ssmc/FRames/2004March_TheEconomicsRemoteSensingAgriculture3_gregedits1.htm

Thorburn P.J., Biggs J.S., Weier K.L. and Keating B.A. (2002). Nitrate in groundwaters of intensive agricultural areas in coastal northeastern Australia. *Agriculture Ecosystems and Environment*, 94: 49-58.

Tisseyre, B., Taylor, J.A. and Ojeda, H. 2006. New technologies to characterize spatial variability in viticulture. *In:* Van Leeuwen, C., Roby, J-P., Marguerit, E. and Fanet, J. (Eds). 2006. *Terroirs Viticoles 2006* 1, 3-5 Juillet, Bordeaux. ENITA de Bordeaux. pp. 204-217.

Viator, H.P. and Downer, R.G. 2005. Site-specific nitrogen fertilization of sugarcane. *In*: Heemskerk, C. and Engvall, M. (Eds) Book of Abstracts - 5ECPA-2ECPLF. Swedish Institute of Agricultural and Environmental Engineering. Uppsala. pp. 309.

Viscarra Rossel, R.A., Thylén, L., McBratney, A.B. and Gilbertsson, M. 2005. Development of an on-the-go soil sensing system for determinations of soil pH and lime requirement. *In:* Mulla, D.J. (*Ed.*) Proceedings of the 7th International Conference on Precision Agriculture and Other Precision Resources Management, Minneapolis, Minnesota, USA, 25-28 July 2004. pp 81-92.

Viscarra Rossel, R.A., Walvoort, D.J.J., McBratney, A.B., Janik, L.J. and Skjemstad, J.O. 2006. Visible, near infrared, mid infrared or combined diffuse reflectance spectroscopy for simultaneous assessment of various soil properties. *Geoderma* **131**, 59-75.

van Meirvenne, M. 2003. Is the soil variability within the small fields of Flanders structured eough to allow precision agriculture ? *Precision Agriculture* **4**, 193-201.

van Vuuren, J.A.J., Meyer, J.H. and Claassens, A.S. 2005. Potential use of near infrared reflectance monitoring in precision agriculture. *Communications in Soil Science and Plant Analysis* **37**, 2171-2184.

Wathes, C.M., Kristensen, H.H., Aerts, J-M. and Berckmans, D. 2005. Is precision livestock farming an engineer's daydream or nightmare, an animal's friend or foe, and a farmer's panacea or pitfall ? *In:* Cox, S. (*Ed*). *Precision Livestock Farming '05.* Proceedings of the 2nd European Conference on Precision Livestock Farming. Wageningen Academic Publishers, The Netherlands. pp. 33-46.

Whelan, B.M and McBratney, A.B. 2000. The "Null Hypothesis" of Precision Agriculture management. *Precision Agriculture* **2**, 265-279.

Whelan, B.M. and McBratney, A.B 2003. Definition and interpretation of potential management zones in Australia. *In:* Solutions for a better environment. Proceedings of the 11th Australian Agronomy Conference, 2-6 Feb. 2003, Geelong, Victoria. Australian Society of Agronomy. www.regional.org.au/au/asa/2003/c/15/whelan.htm

Wijkmark, L., Lindholm, R. and Nissen, K. 2005. Uniform potato quality with site-specific potassium application. *In:* Stafford, J.V. (*Ed*) Proceedings of the 5th European Conference on Precision Agriculture. Wageningen Academic Publishers, The Netherlands. pp 393400.

Williams, B.G. and Baker, G.C. 1982. An electromagnetic induction technique for reconnaissance surveys of soil salinity hazards. *Australian Journal of Soil Research* **20**, 107-118.

Williams, B.G. and Hoey, D. 1987. The use of electromagnetic induction to detect the spatial variability of the salt and clay contents of soils. *Australian Journal of Soil Research* **25**, 21-27.

Wong M. T. F. and S. Asseng 2006. Determining the causes of spatial and temporal variability of wheat yields at sub-field scale using a new method of upscaling a crop model. *Plant and Soil* **283**, 209-221.

Wong, M.T.F., Asseng, S. and Zhang, H. 2005. Precision agriculture improves efficiency of nitrogen use and minimises its leaching at within-field to farm scales. *In:* Stafford, J.V. (*Ed*) Proceedings of the 5th European Conference on Precision Agriculture. Wageningen Academic Publishers, The Netherlands. pp 969-976.

Wong, M.T.F., Stone, P.J., Lyle, G. and Wittwer, K. 2005. PA for all – is it the journey, destination or mode of transport that's most important ? *In:* Mulla, D.J. (*Ed.*) Proceedings of the 7th International Conference on Precision Agriculture and Other Precision Resources Management, Minneapolis, Minnesota, USA, 25-28 July 2004. pp 576-585.

Wongmaneeroj, A. and Hongprayoon, C. 2004. Correlation and spatial variability of soil properties affecting to sugarcane yield in Kamphaeng-Saen soil. *Kasetsart Journal (Natural Sciences)* **38**, 109-112.

Wood, A.W., Bramley, R.G.V., Meyer, J.H. and Johnson, A.K.L. 1997a. Opportunities for improving nutrient management in the Australian sugar industry. *In:* Keating, B.A. and Wilson, J.R. (Eds) *Intensive Sugarcane Production: Meeting the Challenges Beyond 2000.* CAB International, Wallingford, UK.

Wood, A.W., Kingston, G. and Schroeder, B.L. 1997b. Opportunities for improved management of sugarcane through more precise targeting of inputs. *In:* Bramley, R.G.V., Cook, S.E and McMahon, G.G. (Eds) Precision Agriculture – What can it offer the Australian sugar industry ? Proceedings of a workshop held in Townsville, 10-12 June, 1997. CSIRO Land and Water, Townsville. pp. 13-23.

Wood, A.W., DiBella, L.P., Pace, R.M. and Schroeder, B.L. 2005. Optimising season length to increase industry profitability in the Herbert River District, Quuensland, Australia. *Proceedings of the South African Sugar Technologists Association* **79**, 443-446.

Wrigley, T. and Moore, S. 2006. *Public Environment Report 2006*. Canegrowers, Brisbane.

Zaman, Q.U. and Schumann, A.W. 2005. Performance of an ultrasonic tree volume measurement system in commercial citrus groves. *Precision Agriculture* **6**, 467-480.

Zaman, Q.U. and Schumann, A.W. 2006. Nutrient management zones for citrus based on variation in soil properties and tree performance. *Precision Agriculture* **7**, 45-63.

Zhang, M., Zhihao, Q. and Xue, L. 2005. Remote sensed spectral imagery to detect late blight in field tomatoes. *Precision Agriculture* **6**, 489-508.

Appendix 2.

**Report on a workshop held between the project team and Industry Reference group –
February 22, CSIRO Davies Laboratory, Townsville.**

Summary

Fifteen industry personnel representing the growing, harvesting, milling, productivity services, consultant, research and extension sectors attended a panel meeting to discuss the draft review 'Precision Agriculture – An avenue for profitable innovation in the Australian sugar industry, or expensive technology we can do without'. Each participant was given the opportunity to present their experiences with precision agriculture and how their lessons could be incorporated into the review. A session on the strengths, weaknesses, opportunities and constraints of precision agriculture for the Australian sugarcane industry confirmed much of the input given by the panel members. The recommendations from the draft review were each discussed individually and changes made for incorporation into the final review.

List of Attendees:

Name	Organisation
Rob Bramley	CSIRO, Adelaide
David Cox	Grower, Burdekin
Tony Crowley	Consultant, Mackay
Jay Hubert	Grower, Bundaberg
John Markley	Mackay Sugar
Lisa McDonald	CSR Sugar, Burdekin
Paul Mizzi	Grower, Herbert
Don Pollock	Burdekin Productivity Services
John Powell	Qld Mechanical Caneharvesters Association, Mackay
Di Prestwidge	CSIRO, Brisbane
Bernard Schroeder	BSES, Bundaberg
Peter Thorburn	CSIRO, Brisbane
Tony Webster	CSIRO, Mossman
Andrew Wood	CSR Sugar, Herbert
Tim Wrigley	Canegrowers, Brisbane
Apologies	
Les Robertson	SRDC, Brisbane
Rajinder Singh	Grower, Atherton Tableland

1. **Overview of SRDC review into PA**

SRDC has asked for a review of precision agriculture (PA) to be written by a team from CSIRO led by Rob Bramley. A brief overview of the reasons behind this review were presented and summarised below.

\# The sugarcane industry is making rapid recent progress in implementation of controlled traffic systems and base station networks in many Australian sugarcane regions.

\# Potential exists for sugarcane industry to add value to this investment by moving into precision agriculture.

\# SRDC recognise these opportunities and have asked for industry to provide input into where (if any) investment in precision agriculture would benefit the Australian sugarcane industry.

\# This panel review meeting is to provide input into one of two concurrent reviews being undertaken for SRDC to explore these opportunities. This review focuses on the agronomic aspect of precision agriculture, with the other review focussing on the engineering aspects.

2. Introductory comments on the draft review

Prior to this panel meeting all attendees had read the draft review and were asked to prepare feedback on the review.

A brief overview of the draft review was given by Rob Bramley, highlighting the general areas of the draft review (background philosophy and enabling technologies, PA around the world, soil and topography as drivers of variable crop performance, constraints to adoption, opportunities and research requirements for PA in the Australian sugar industry, conclusions and recommendations).

3. Panel feedback on the draft review

All participants had been asked to make a short presentation of their experience with precision agriculture and how their individual lessons from these experiences can be incorporated into the review.

All participants were asked to consider whether it is possible to use a well documented case study from previous experiences of the panel review members to highlight how precision agriculture can make a contribution to the Australian sugar industry.

The following highlights the significant points from each panel members presentation.

Wood

\# In the Herbert region the move towards technologies that utilise GIS (electronic consignment, base station network, yield monitors, base cutter monitors) has been driven by HCPSC

\# NIR is being installed in the mills (on the milling train) which has the potential to measure variability for a number of attributes

\# Challenges in the Herbert are how is the data managed and how is data interpreted

\# It is likely that extension services will have to use one-on-one extension with growers and close collaboration with technology providers

\# The potential use of NIR in the mill, coupled with spatial locations of each bin, is likely to be cheaper and more available than on 'on-the-go' sensors

\# On-the-go sensors could measure more than c.c.s

\# Potential systems could include yield mapping, weed mapping (and selective spraying), variable rate application and levelling

\# GPS is useful for guidance and controlled traffic

<u>Cox</u>

\# There is a need for commercial grower services in the industry

\# Guidance is beneficial for reducing compaction and increasing the energy efficiency of in-field operations

\# GIS is already widely used in the industry, and therefore an accepted technology

\# Site specific management (variable rate application) is potential use

\# Systems for interpreting satellite imagery are needed

\# There is a need to know what is driving variability, e.g. what do we do with poor yielding zones

\# Systems for interpreting EM mapping are needed (what does EM correlate to?)

\# Adversity is the driver of innovation (NRM, record keeping, economics, nutrient management planning risk assessment)

\# Spatial data can be used to assist the analysis of research data

\# Variety and plant breeding evaluation

\# Value add to block productivity data

\# Soil mapping – 3D model

<u>Mizzi</u>

\# Technology must be user friendly to growers

\# Dollars in the back pocket drives innovation

\# Technology must be proven and work or growers will not take up

\# Changes need to be introduced gradually, starting with those that work

<u>Hubert</u>

\# There is a need for growers to understand the difference between guidance and precision agriculture

\# We need to know what to do with variation (reduce or enhance)

\# There is a need for software (with a grower friendly Graphical User Interface)

\# If a grower adopts guidance, the same system should be compatible and used for precision agriculture

\# Change needs to be gradual

\# Variable input already happens in many farms, PA is a more informed and precise way of doing this

\# Grower attitudes are a stumbling block to adoption

\# Grower input is needed into research

\# Research should be industry wide, not regionalised

\# Growers should be taken on the research journey

<u>McDonald</u>

\#   How do we make the best use of the data

\#   There is a need for central data storage with multi compatibility (assists FMS, nutrient management plans)

\#   In mill NIR measurements will be happening, how can these be related back to the paddock

\#   There is already a base station network to facilitate guidance, don't repeat for PA

\#   Need to foster ability of people to use PA, particularly interpreting and communication on-ground

\#   Include 'yield decline' systems in PA

<u>Wrigley</u>

\#   Progress will be made when the technology is cost effective

\#   Targeted application of herbicides in an opportunity

\#   How do we collect data and implement systems

<u>Powell</u>

\#   Yield monitors and auto base cutter height technology must be cost effective

\#   Guidance technology is implemented by planting contractors and harvesters

\#   There is a need that data loggers on harvesters have efficient processing

\#   Opportunity for electronic consignment

<u>Crowley</u>

\#   There is a necessity that agronomists operate spatially

\#   What is the right number of management zones

\#   Whole industry needs to have knowledge of and be committed to PA

\#   The more data the better (yield, soils, remote sensing…)

<u>Markley</u>

\#   Yield mapping over time tells a more complete story than one years data

\#   Remote sensing issues – the growing condition will influence, pixel resolution impacts, issues with cloud cover when using satellites

\#   Further development is needed to remote sense pest and disease effects

\#   It may be possible to remote sense soils boundaries

\#   Electronic consignment and on-line measurement is a possibility

\#   Opportunity exists for variable rate application

\#   There is a need for systems and operator skills to convert data into VRA maps

\#   There is a need to determine the ideal pixel size

\#   Datasets must be consistent, reliable and cost effective

\#   Most likely scenario is that users will pay for systems

\#   It is important for the industry not to set unobtainable targets

4. Industry R,D&E capability

Bernard Schroeder (BSES) and Peter Thorburn (CSIRO) were given the opportunity to present to the panel members a brief outline of their respective organisations capacity to provide input to PA in the sugar industry. The panel members are quite satisfied the industry has a strong support to research and extend PA technologies from these two organisations. It was also noted by the panel that there are many technological aspects of PA which are best left to private industries to develop and market. Many technologies utilised in PA are quite mature, not requiring any public research investment. Private companies are likely to generate a profit from these technologies, and therefore research organisations should not 'get in their way'.

5. Future of PA in Australian sugar industry

The panel group was facilitated through a session where the strengths, weaknesses, opportunities and constraints of PA were listed. Each was discussed separately and a summary of the main points from discussion are listed below.

Strengths

Other industries in Australia (particularly the grains industry) are further down the track of implementing PA. The sugar industry should repeat what worked well for them while not make the same mistakes they made.

Other industries such as grains and viticulture have documented PA implementation guidelines, these can be reviewed.

EM mapping is a mature technology that will work well for sugarcane soils.

Much of the technology used for PA has been in use in other industries and works well. This technology can be transferred to the sugar industry.

PA utilises multiple levels of data for better decision making, as sugarcane is historically a data rich industry, the industry should be well positioned to utilise this data.

Remote sensing data is quite cheap when a whole region acquires it. Because sugarcane takes up such a large footprint in the landscape, it can be quite cheap to the industry.

Weaknesses

There is an obvious gap in the skills capacity in industry now because very few growers are practicing PA.

There are no algorithms for converting yield monitoring raw data into usable yield maps.

There is a great deal of uncertainty in the industry of what PA actually is. Many believe PA is guidance and controlled traffic only.

The reasons for why yield varies in-block in the sugar industry are currently not very well understood.

Farm equipment is generally not up to the task of applying variable rates (eg fert applicator) currently and a major investment by growers is needed to update.

Opportunities

\# Smaller growers could centralise PA implementation around harvesting and contracting groups. Larger farmers may be able to 'go alone' on implementation.

\# There are some documented examples of how immediate savings could be made from variable applications (eg gypsum in the Burdekin).

\# There are potentially significant environmental benefits that could be made from implementing PA. Addressing NRM needs for an industry adjacent to the Great Barrier Reef is important.

\# Economic benefits are likely to occur.

\# PA has the potential to increase irrigation efficiency.

\# It may be possible to develop a NQ version of SPAA, using PA as a research tool.

Constraints

\# Benefits don't return immediately, financial gains take approx 5 years to start to come through.

\# Implementation of PA is a process that takes time, temporal stability is needed prior to VRA, which will take a number of years to evaluate on each block.

\# There is quite a high cost of 'buying in' to PA

\# Currently there is a lack of trained people in PA in the sugar industry.

6. The final review recommendations[A]

The draft reports recommendations were presented one-by-one to the panel group. There was discussion about the appropriateness of each recommendation and feedback recorded. Recommendations 1-5 are classed as essential for the industry and recommendations 6-8 as desirable.

Recommendation 1: Access to calibrated yield monitoring systems and the associated development of a robust protocol for yield map production (cf Bramley and Williams, 2001).

\# When the recommendation as it appears above was fleshed out there was strong support for it. Feedback from the panel members suggested this recommendation needed to be re-worded.

Recommendation 2: Assessment of the most appropriate and cost-effective spatial resolution for remotely sensed imagery and of the optimal time of image acquisition. Associated with this, an evaluation of the merits of airborne compared to satellite-based remote sensing platforms should be carried out.

\# Panel members were happy with this recommendation.

Recommendation 3: Case studies highlighting the utility (and shortcomings) of the various tools of PA in delineating management zones within sugarcane blocks should be undertaken in each of the major canegrowing regions. These should include investigation of relationships between yield, indices of crop quality, soil properties and terrain attributes as the basis for more targeted management and evaluation of the merits of selective harvesting based on ccs variation. Initiation of these case studies is arguably the most important of the various tasks identified here.

\# The panel members were happy with this recommendation, however asked that the use of ripeners and variable management of irrigation water be added.

[A] Note that at the time of this workshop, the recommendations were a little different to the final recommendations presented in Appendix 1.

\#   The panel members also wanted to insert a reference to concurrently conducting an assessment of the economic merits of implementing PA.

Recommendation 4: Evaluation of the utility of whole-of-block approaches for sugarcane agronomic experimentation and the development of site specific criteria for interpretation of soil test data and development site-specific management strategies.

\#   The panel members were satisfied with this recommendation.

Recommendation 5: Training and extension support in PA data acquisition, management and analysis should be developed and provided to leading growers and consultants and the emergence of local service providers in these aspects of PA, in addition and as opposed to equipment sales, should also be encouraged. As part of this activity, a possible role for groups like the Herbert Resource Information Centre (HRIC) and SPAA should be considered and encouraged.

\#   The panel members pointed out that generally free service is not valued as highly as fee-for-service. The sugar industry has a history of free service, and consequently the value given to that advice has diminished.

\#   Panel members wanted to add a reference to the various productivity services operating in the sugar industry.

Recommendation 6: Development of an on-the-go sugar (ie ccs) sensor for use during harvesting.

\#   Panel members wanted this recommendation to be moved from being a 'desirable' recommendation to an 'essential' recommendation.

\#   Panel members also highlighted that it may be appropriate that sensors for other quality (or impurity) parameters also be investigated.

Recommendation 7: Evaluation of the most appropriate ways of integrating existing Sugar Mill data collection systems with PA applications.

\#   Panel members wanted this recommendation to be moved from being a 'desirable' recommendation to an 'essential' recommendation.

Recommendation 8: Evaluation of the merits of developing a sensor (or sensors) for key sugar impurities and, if deemed economically attractive, initiation of a sensor development program (see item 6).

\#   Reference to this recommendation can be deleted when it is incorporated into recommendation 6.

Summary: Simultaneous to all of these activities, will be the need to keep abreast of developments in PA in other industries both in Australia and overseas. Support for grower, consultant and researcher visits to technical meetings, centres of expertise and cropping industries in which PA has been successfully implemented would therefore be highly valuable.

\#   There was a consensus from the panel members that it is worth evaluating the economic and environmental performance of farming systems using PA.

7. Evaluation and wrap up

The panel members were satisfied they have provided input into this review. A draft version of the changes to the review will be sent to all members for final input. All panel members were advised there will be a PA workshop at this year's ASSCT in Cairns in May where they could provide further input.

Appendix 3.

SRDC Precision Agriculture Workshop – Project Evaluation and R+D prioritisation.
11th May - Sofitel Reef International, Cairns

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SRDC Precision Agriculture Workshop – Project Evaluation and R+D prioritisation.
11th May - Sofitel Reef International, Cairns

Summary

The SRDC facilitated workshop session on Precision Agriculture was evaluated through a questionnaire developed between CSIRO and NCEA. Thirty six participants completed the questionnaire with a high ranking given to the potential for precision agriculture to contribute to the Australian sugarcane industry (8.25 out of 10). Dr Rob Bramley (CSIRO) and Dr Rod Davis (NCEA) both made two presentations in which their perspectives on the current state of PA and recommendations as to how it might be adopted by the sugar industry were outlined. Participants were then asked to rank the potential of different aspects of PA to the future Australian sugarcane industry and gave high rankings for yield monitors (8.97/10), GPS/GIS systems (8.92/10), attribute mapping (8.28/10), remote sensing (7.94/10), soil sensing (7.89/10) and variable rate application (7.74/10). Participants were asked to rank which aspects of PA they though required research and development for and ranked skills development for industry personnel (9.00/10), economic benefits of PA (8.86/10), yield monitor (8.80/10), environmental benefits of PA (8.63/10), experimental methodology (8.17/10) and quality sensors (8.12/10) highly. Feedback also suggested a coordinated industry approach to researching and implementing PA as well as investigation into identification of causes and management of variability were important. When asked on the expected benefits of implementing PA participants rated economic and environmental benefits very highly.

Industry Questionnaire

Results Summary

Q1; Today's workshop has increased my understanding of Precision Agriculture. (1 = Not at all, 10 = Very much so)

| Average	Minimum	Maximum	Respondents
6.39	1	10	36

Q2; How much potential do you think there is for Precision Agriculture to contribute to the future Australian Sugarcane Industry. (1 = None, 10 = Very much)

| Average	Minimum	Maximum	Respondents
8.25	7	10	36

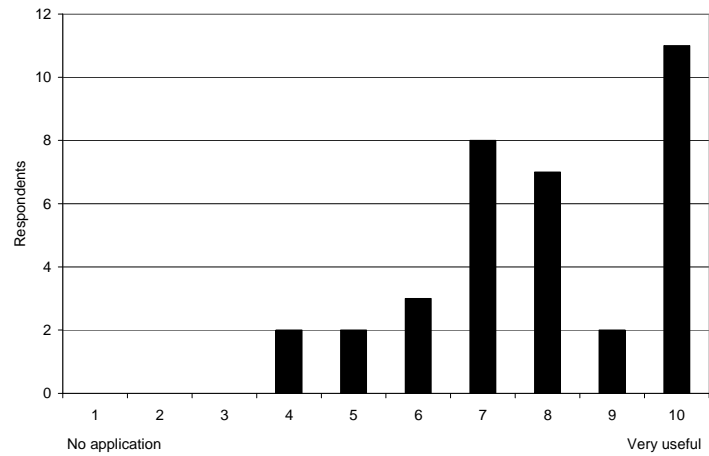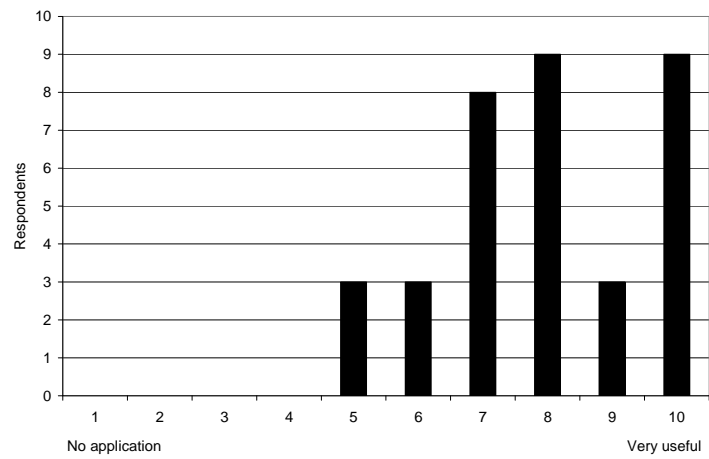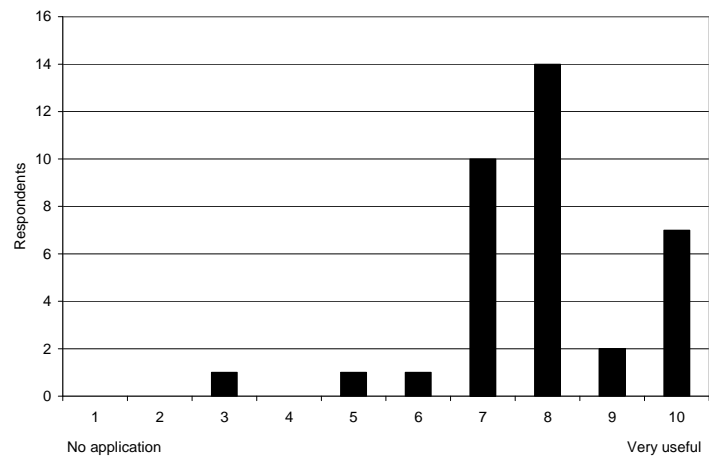**Q3; Of the following aspects of Precision Agriculture, how much do you think they can be applied in the future Australian Sugarcane Industry. (1 = No application, 10 = Very useful)**

	Average	Minimum	Maximum	Respondents
GPS/GIS systems	8.92	7	10	36
Yield Monitor	8.97	5	10	36
Quality sensors (eg CCS Monitor)	7.89	4	10	35
Remote Sensing	7.94	5	10	35
Soil sensing systems	7.89	3	10	36
Attribute mapping	8.28	5	10	36
Selective harvesting	6.19	1	10	36
Variable rate application (nutrient, chemical, water, variety…)	7.74	3	10	35

Q4; Of the following aspects of Precision Agriculture, how much research and development would you like to see for application to the future Australian Sugarcane Industry. (1 = No R&D, 10 = Strongly support R&D)

	Average	Minimum	Maximum	Respondents
Positioning techniques (other than GPS)	5.85	1	10	33
Yield Monitor	8.80	5	10	35
Quality sensors (eg CCS Monitor)	8.12	3	10	33
Remote Sensing	7.70	3	10	33
Soil sensing systems	7.74	1	10	35
Attribute mapping	7.79	4	10	34
Systems for determining in-field management zones	7.86	1	10	35
Selective harvesting	5.80	1	10	35
Variable rate application (nutrient, chemical, water, ripeners, variety…)	7.54	3	10	35

Economic benefits of implementing PA	8.86	7	10	35
Environmental benefits of implementing PA	8.63	3	10	35
Appropriate experimental methods	8.17	2	10	35
Skills development of industry personnel in PA	9.00	6	10	35

Q5; Are there any other areas of research and development you would like to see into Precision Agriculture in the Australian Sugar Industry. Summary of answers.

\#   A coordinated industry approach (7)

\#   Identification of variability, causes and management of and machinery to apply variable rates (6)

\#   Protocols and training for whole system data management and interpretation (4)

Q6; What benefits do you think Precision Agriculture will bring to the Australian Sugarcane Industry? Summary of answers.

\#   Improved productivity and economic outcomes (18)

\#   Improved environmental outcomes (12)

\#   Increased understanding of variability and how to manage (4)

Q7; What aspects of today's workshop has been most beneficial to you. Summary of answers.

\#   Presentations (8)

\#   Interactions with the industry participants (8)

\#   Discussions (5)

\#   Increased understanding of PA (8)

\#   Setting a plan to move forward (2)

Q8; Any further comments you would like to make on the Precision Agriculture workshop. Summary of answers.

\#   There is a need for a coordinated approach (5)

\#   A good initiative (3)

<u>Industry Questionnaire</u>

<u>Results: Raw Data Charts</u>

21

Q1; Today's workshop has increased my understanding of Precision Agriculture.
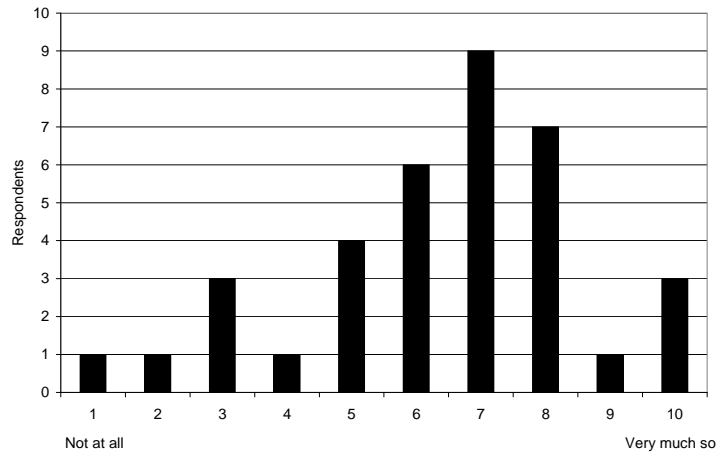
Q2; How much potential do you think there is for Precision Agriculture to contribute to the future Australian Sugarcane Industry.
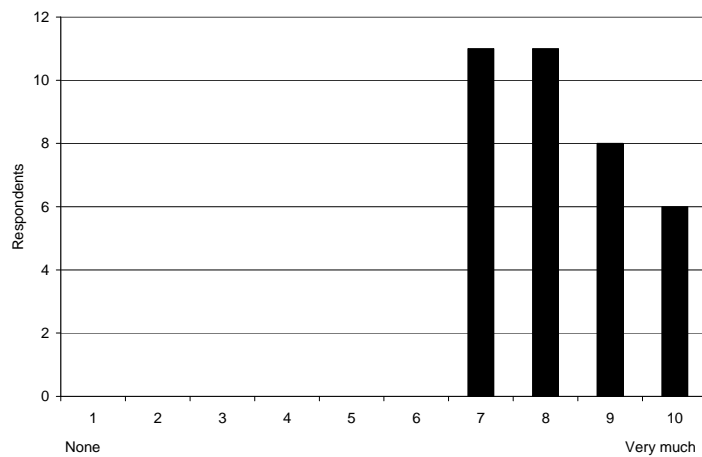
Q3; Of the following aspects of Precision Agriculture, how much do you think they can be applied in the future Australian Sugarcane Industry.

GPS/GIS systems
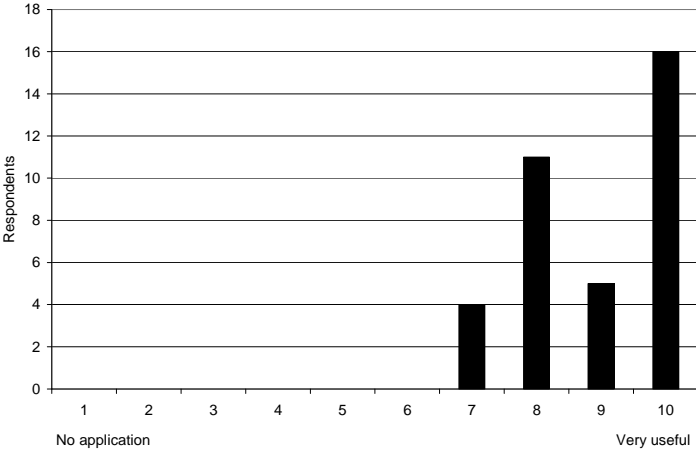
Yield monitor
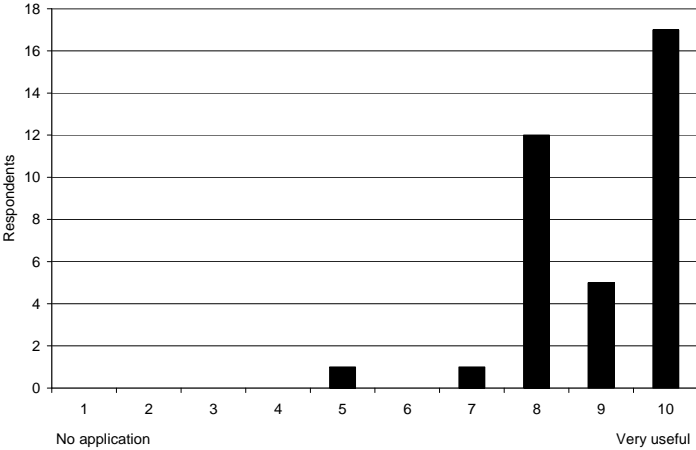
Quality sensors (eg CCS monitor)

Remote sensing


Soil sensing systems

Attribute mapping
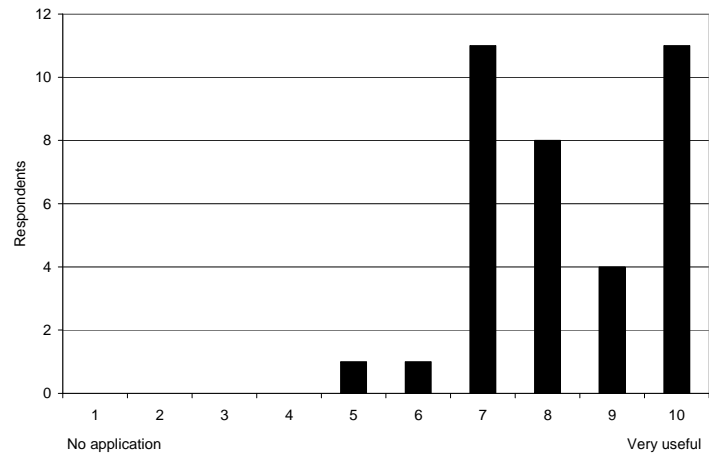
Selective harvesting
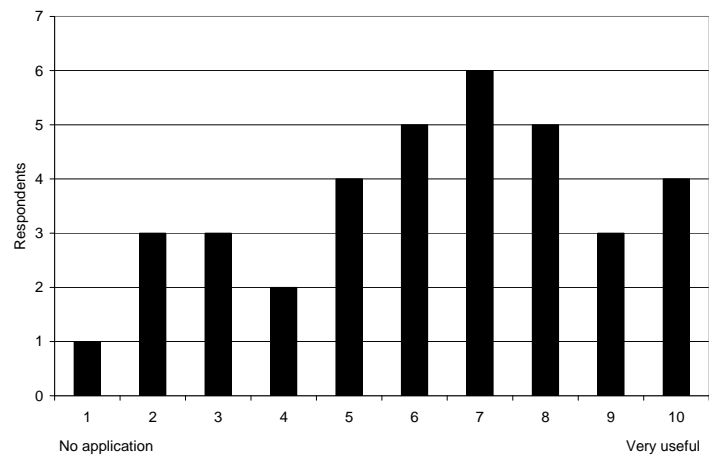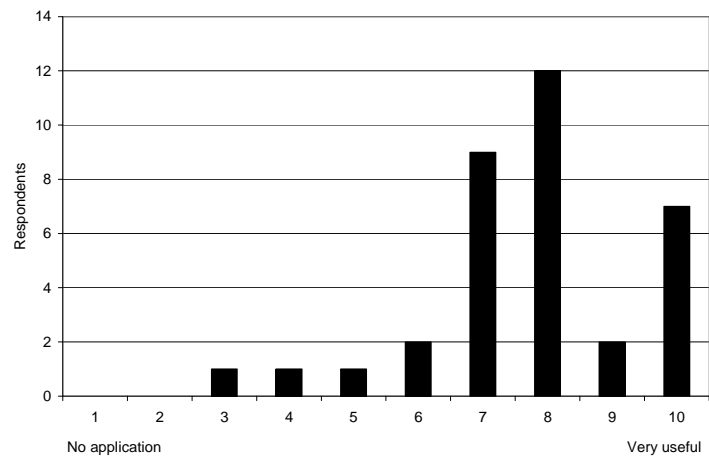
Variable rate application (nutrient, chemical, water, variety…)

Q4; Of the following aspects of Precision Agriculture, how much research and development would you like to see for application to the future Australian Sugarcane Industry.

Positioning techniques (other than GPS)
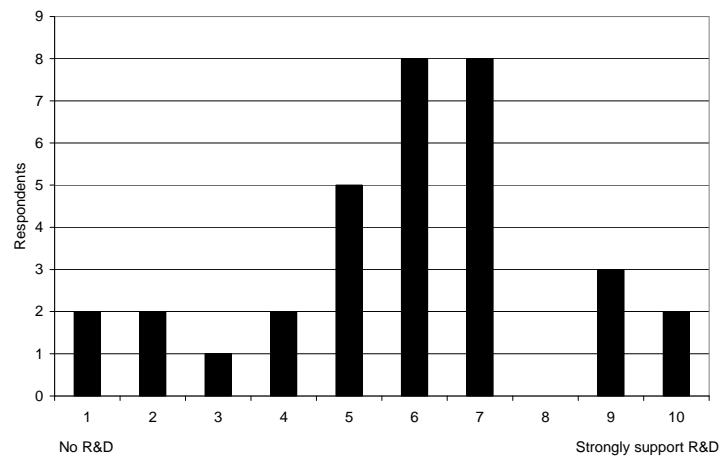
Yield monitors

Quality sensors (eg CCS monitor)

CSE018 - Precision Agriculture in the Australian sugar industry
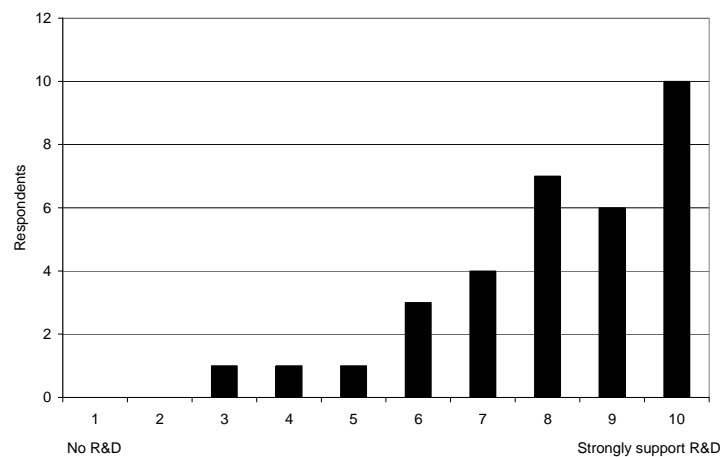
Remote sensing

Soil sensing systems

Attribute mapping

Systems for determining in-field management zones
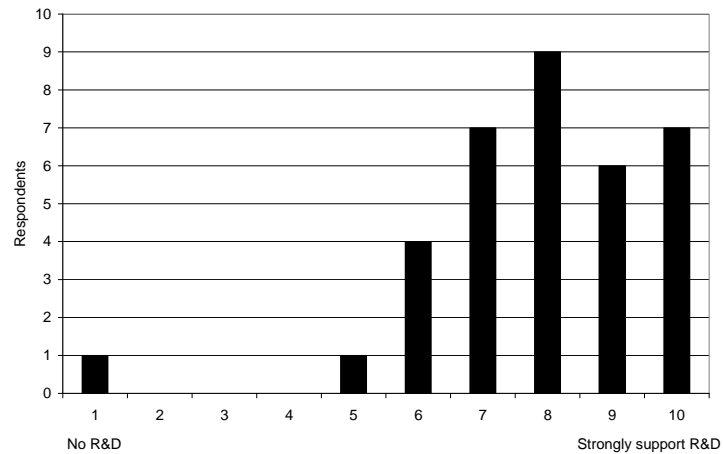
Selective harvesting
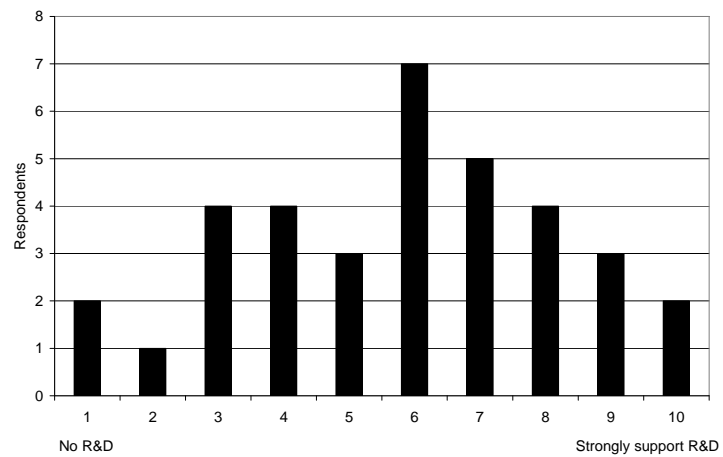
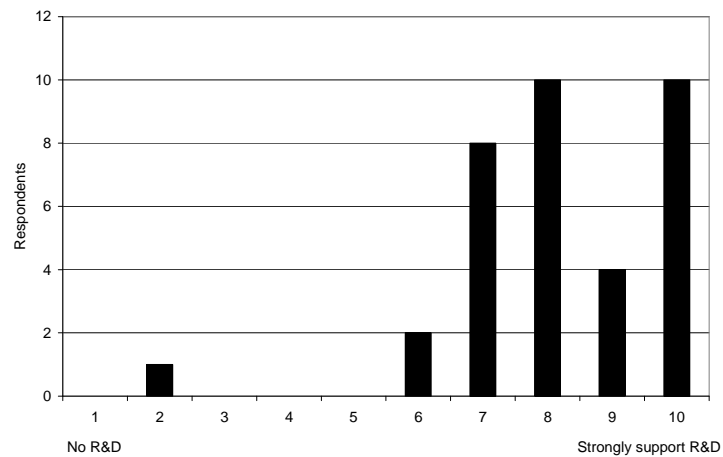**Variable rate application (nutrient, chemical, water, ripeners, variety…)**
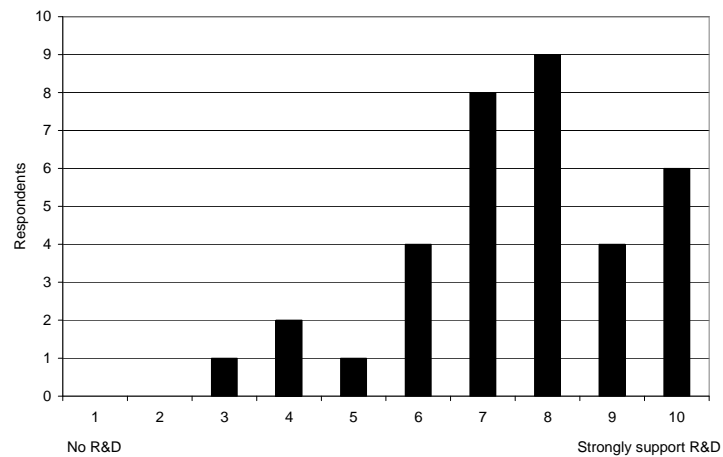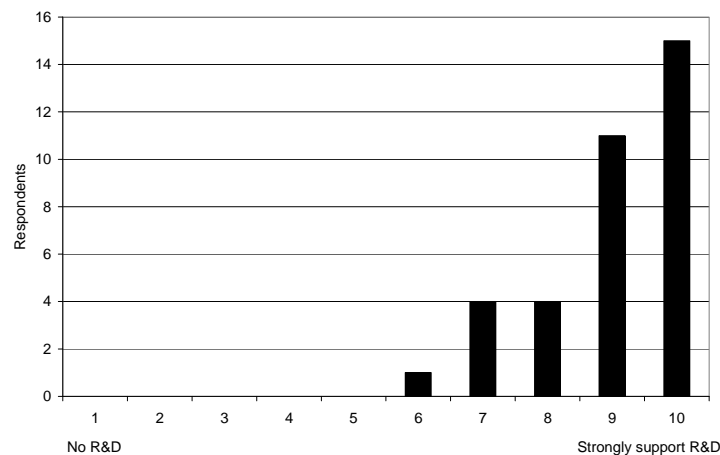
Economic benefits of implementing PA
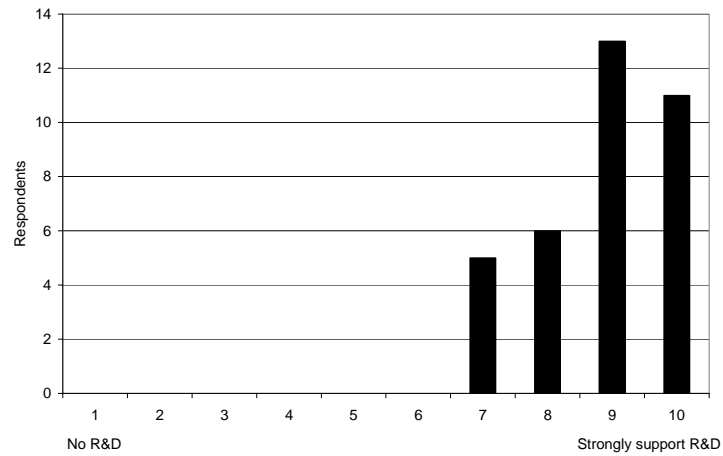
Environmental benefits of implementing PA
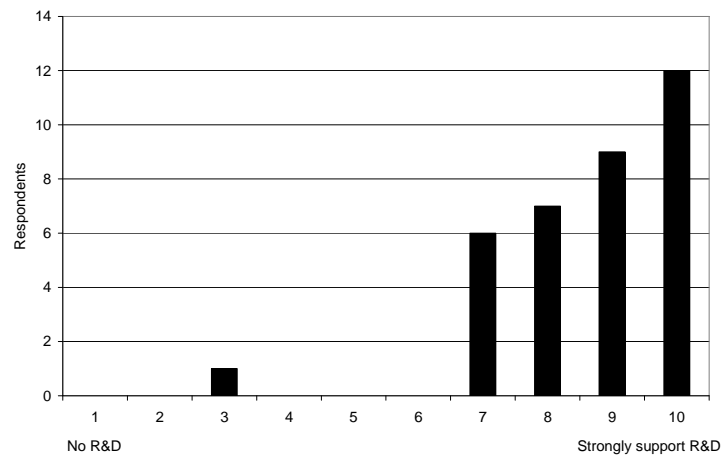
Appropriate experimental methods

Skills development of industry personnel in PA

Q5; Are there any other areas of research and development you would like to see into Precision Agriculture in the Australian Sugar Industry.

Protocols for data management
Precision fertiliser placement and variable amounts
Evaluate high resolution data (eg 1m pixel) to identify variability in cane field, and yield potential
Identify management to reduce variability
An industry endorsed R&D team
Stakeholders need to be involved throughout the development. Researching the system over 5-10 years and then delivering it to industry is not ideal
Definitely a coordinated approach rather than as single projects
I really think the whole approach needs good coordination. It is the next step of the SYDJV and should be approached in a similar way
The above is adequate coverage for now, just will require some more research on unravelling cause of in-field variation
Training and data extraction software
Calibrating yield monitor
The evolution of current data systems GPS/GIS to provide for the analysis and interpretation
Case studies identifying problems and feedback
Other uses for cane than sugar
Coordinated approach across industry so issues investigated once (not repeated in smaller projects) and projects linked so can validly relate issues of the various projects.
Utilise farm model concept that would utilise researcher and grower working together to implement and document gain, economically, environmentally and socially
Steps being taken to overcome the aging agronomist and missing soil scientist thoughts into PA in Australia
PA in ANOVA application for soil
An investigation into variable rate machinery (eg fertiliser) rig to ensure it is accurately applying
Application of soil ameliorants in zero till systems
Coordinated research across whole industry to prevent different areas going their own way
Weed sensors
Full recording software so the system becomes single entry for any data from grower to mill to payment therefore allowing whole of system economic health

Q6; What benefits do you think Precision Agriculture will bring to the Australian Sugarcane Industry?

Rationalisation of the sugar industry
100% increase in productivity
Higher productivity and quality
Reduced off site impacts
Inputs based on determined (zonal) yield potential
A fine environmental record
More cost-effective use of inputs to maximise output
Reducing environmental impacts of over applying inputs
Better understanding of in-field variation and hopefully production gains
Focus on causes of yield variability in the field
It will provide the next quantum leap if done properly
Economic
Environmental
Dollars to growers, miller and industry
Allow growers to have a better understanding of productivity constraint
Hopefully provide a mechanism to maximise profitability
Hopefully more money and better public understanding
Economic due to better management and lower inputs
Yield increases, ccs increases, environmental benefits
Economic environmental sustainable management
Environmental sustainability
Farm economic improvements
Maximise productivity with environmental sustainability
Builds a robust system for consistently high production
Sustainability
Take the industry forward
Future
Ultimate management tool
Lots
Some economic but potentially environmental
Make growers more aware of how to manage the farm for economic and environmental sustainability
Greater profitability and sustainability
Improve cost management and environmental outcomes
Allows the time for further value adds to be identified and implemented
Increase farmer sustainability
Lower net costs
More realistic 'picture' of yield potential
Achievement and demonstration of stewardship

Q7; What aspects of today's workshop has been most beneficial to you.

All – many thanks
We seem as though we covered every topic
Just listening and getting my head around the topic – implications for the future
Access to skilled industry personnel
The content of the presentations and seeing general agreement on the "needs" from the audience
Update on PA
Discussion in group environment
Opportunity to give our opinion
Presentations by invited speakers
What is known
Learning others point of view
Meeting of other key players
Obtain a broader view of PA interests within the sugar industry

Cross communications between participants
A lot of new knowledge
Future potential
A deeper understanding
Industry participation
Set a plan for a total industry approach
Understanding where PA is at present and what needs to be done
More understanding PA
Both of the guest speakers
Network
Future R&D directions and funding
Drawing common approach to moving forward
Meeting the people and changing my ideas
Learnt much more about PA from presenters
Rob Bramley's presentation on PA in viticulture
Bramley's presentation
Table discussions
Papers presented – very good
General comments from participants

Q8; Any further comments you would like to make on the Precision Agriculture workshop.

Some concern about "group think"
Next step – coordinated R&D programmes
A coordinated approach is essential
A danger of being seduced by technology
A really think that there is a good chance of self interest groups taking over unless SRDC really gets the coordination right
Workshop was very good, only how this, and how much of this can be implemented in real life situation and adopted by the growers
A good conference
I do not think individuals without understanding or skills have the ability to make a valued assessment on this issue. Therefore a skilled group to assess the starting point (a review) is most important. The sooner SRDC embraces this the better. The private sector and individuals are already setting up different standards across the region.
Agree there needs to be a group overseeing the application of PA in the sugar industry
Need a follow up at next ASSCT meeting when systems have evolved a bit more
Good initiative, hope something happens this time!
GPS RTK and yield monitors development is taken care of by commercial firms and does not need R&D although standard protocols need to be set for them to meet