



*Investing in Sugarcane Industry Innovation*

SRDC Technical Report 3/2007

*Precision agriculture options for  
the Australian sugarcane industry*



Australian Government

Sugar Research and Development Corporation





## Foreword

Precision agriculture holds enormous potential to revolutionise farming and harvesting practices in the Australian sugarcane industry.

It is an area of interest for many involved in the industry's growing and harvesting sectors, as more people recognise the impact precision agriculture could have on productivity and profitability.

Sugar Research and Development Corporation encourages industry to seek out new and improved ways of doing things and through this report hopes to encourage others to seek out, and be open to the adoption of new technologies that have the potential to improve their operations.

This Technical Report attempts to identify the opportunities, advantages, limitations, risks and costs of the range of technologies that would be applicable to implementation of precision farming in sugarcane.

This report also highlights areas for future research and development activities which could benefit the industry in implementing precision farming for sugarcane.

Recognised experts in this field, as well as industry innovators, provided their input into this report through two SRDC-commissioned reviews as well as an industry workshop.

The issues identified in the two review papers and from the workshop formed the basis of the SRDC Call in July 2007 for Expressions of Interest in new research proposals.

Through its Research and Development Plan 2007-2012, SRDC emphasises the importance of implementing innovative farming and harvesting systems tailored to meet local needs.

This focus is supported by the Australian Government's Rural Research and Development Supporting Priorities of Innovation Skills and Technology.

The Innovation Skills priority emphasises the importance of producers having the necessary skills to make the best use of research and innovation to Australia's rural industries. Meanwhile the Technology priority recognises the need for ongoing investment in existing and frontier technologies to allow industries to develop and implement innovative solutions.

This is clearly in-line with current industry thinking. The recommendations from workshop participants (outlined on page 4) have clearly identified that ongoing R&D in this area needs to capture both technological advances and the ability of industry to understand and adopt relevant technologies.

Importantly participants recognised the need to make sure R&D in this area is well coordinated and collaborative. Through its investments in R&D, SRDC is committed to ensuring industry can realise the full potential of precision agriculture technologies.

I commend this publication and the reports in contains to you.

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## Contents

Foreword .....	ii
Introduction .....	3
PRECISION AGRICULTURE – AN AVENUE FOR PROFITABLE INNOVATION IN THE AUSTRALIAN SUGAR INDUSTRY OR TECHNOLOGY WE CAN DO WITHOUT? .....	5
Executive Summary .....	6
Acknowledgments .....	7
1. Introduction .....	8
2. Background philosophy and enabling technologies .....	12
2.1. Spatial vs temporal variation and the null hypothesis of precision agriculture .....	15
3. PA around the world .....	17
3.1. Economic benefits from precision agriculture.....	18
3.2. The yield vs quality imperative .....	20
3.3. PA as an environmental management tool .....	22
4. The state of play in the international sugar industry .....	24
4.1. Australia.....	24
4.2. Mauritius .....	28
4.3. South Africa .....	29
4.4. USA .....	29
4.5. Brazil and Cuba .....	30
4.6. Other countries .....	32
5. Soil and topography as a driver of variable crop performance and the need for new approaches to soil sampling and analysis .....	33
5.1. Soil sampling and analysis .....	34
5.2. On-the-go assessment of soil variation using electromagnetic sensing (EM38 and VERIS).....	36
6. Constraints to adoption .....	38
7. Opportunities and research requirements for precision agriculture in the Australian Sugar industry .....	41
7.1. On-farm experimentation .....	42
8. Conclusions and recommendations .....	44
9. References .....	46

PRECISION AGRICULTURE TECHNOLOGIES –RELEVANCE AND APPLICATION TO SUGARCANE PRODUCTION ..... 60

Executive summary ..... 61

Acknowledgements ..... 63

1. Introduction ..... 64

2. Precision Agriculture ..... 66

    2.1 Precision agriculture in the sugar industry ..... 67

    2.2 Technology change and precision agriculture ..... 68

3. Spatial Referencing ..... 69

    3.1 In-field positioning ..... 69

    3.2 Positioning technology pricing ..... 72

4. Remote Sensing ..... 73

    4.1 Satellite/aerial imagery ..... 73

    4.2 Yield forecasting ..... 74

    4.3 Soil properties ..... 75

    4.4 Weeds and pest infestations ..... 76

5. Production Environment monitoring ..... 77

    5.1 Real-time monitoring systems ..... 77

    5.2 Cane yield monitoring ..... 77

    5.4 Harvester performance monitoring ..... 82

    5.5 Proximal sensing systems ..... 84

    5.6 Discrete soil and plant sampling ..... 88

    5.7 Crop modelling ..... 89

    5.8 Climate monitoring ..... 90

    5.9 Investment analysis ..... 91

6. Attribute Mapping ..... 92

    6.1 Geographic information systems ..... 92

7. Decision support systems ..... 95

    7.1 Integrated harvesting and transport management ..... 95

8. Differential action ..... 96

    8.1 Variable rate technology ..... 96

    8.2 Prospective management options ..... 97

    8.3 Road ahead ..... 101

9. Recommendations to Growers..... 102

10. Priorities for Precision Agricultural Research ..... 104

11. Recommended Areas of Investment for SRDC ..... 109

12. References ..... 110



## Introduction

Precision agriculture (PA) has been embraced in other Australian agricultural industries. With the increase in adoption rates of new farming system principles including controlled traffic within the sugarcane industry, many growers and harvesting contractors are turning to PA to improve their profitability and productivity.

Recognising the high level of interest among members of the Australian sugarcane industry in the potential of PA, the Sugar Research and Development Corporation called for projects to review and analyse technologies that are applicable to sugarcane farming and harvesting.

SRDC commissioned two studies following this call. The first was undertaken by CSIRO Sustainable Ecosystems and examined research and experience with PA in a range of cropping industries worldwide over the last 15 years including sugarcane in Australia, Mauritius, South Africa, the USA and South America.

The second study was undertaken by the National Centre for Engineering in Agriculture in partnership with FSA Consulting. Their report describes how PA technologies operate, their uses, opportunities, limitations, risks and costs with respect to precision farming in the sugar industry. The report also describes how PA technologies can be integrated into a management system that will have both economic and environmental benefits for sugarcane production and harvesting.

Both papers are provided in this publication.

These findings were presented at an SRDC-hosted Precision Agriculture workshop on 11 May 2007. The purpose of the workshop was to identify what aspects of precision agriculture would benefit sugarcane farming and harvesting and to determine the priorities for R&D. The reviews were presented by Dr Rob Bramley (CSIRO Sustainable Ecosystems, Adelaide) and Rod Davis (FSA Consulting in partnership with NCEA, Toowoomba).

Approximately 60 people attended representing growers, millers, BSES Limited, productivity service organisations, CSIRO, QDPI&F, universities, agricultural consultants, CANEGROWERS and agribusiness.

The workshop sought to generate priority issues for further R&D to support the Australian sugarcane industry's adoption of PA technologies. These priorities have been identified below.

## *Investing in Sugarcane Industry Innovation*

### **Industry identified areas for further R&D**

The following issues were identified by the workshop participants as worthy of further support. These have been ranked in order number of responses from workshop groups:

- economic benefits of PA (including the relative returns from the range of different PA technologies; for irrigated vs. rain fed systems, etc);
- effective extension delivery and effective communication to improve uptake (including a focus on what farmers want; case studies; learning from other farmers and from other industries);
- building skills in people including training and learning (for farmers, advisors, agribusiness);
- better yield monitor calibration and ground-truthing for increased confidence in the yield maps;
- well integrated and coordinated whole-of-system approach to evaluating PA technology, developing data management systems and education/ communication (and the corollary that numerous stand-alone projects should be avoided) development of standardised data collection, management and analysis protocols;
- well-designed experimentation and case studies that provide statistically-sound results including economic and environmental benefits;
- rigorous and cost-effective sampling and analysis procedures to provide quality data and confidence in interpretation;
- improved understanding and interpretation of the causes of variability;
- improved sensors for measuring CCS and cane quality on-the-go;
- improved application of remote sensing technology;
- measurement of the stability of within-field variability over time;
- determination of the optimum size of practical management zones within fields;
- improved harvester management systems;
- improved data on soil properties and interpretation of soil data;
- improved precision in variable-rate application technology;
- determination of the optimum farming system and standardisation across the industry (including row spacing).

In discussion, it was recognised that accurate yield monitoring and production of high-quality GIS map layers form the fundamental platform for precision agriculture. Highly skilled people are then needed to interpret the causes of within-field variability; and improved variable-rate technology or differential management is required to address that variability. Workshop participants generally supported the need to incorporate economic analysis and communication within R&D programs in all aspects of precision agriculture.

The concept of a well-coordinated R&D program, with all interested parties collaborating in a precision agriculture 'joint venture', was well-supported by the workshop participants.





**PRECISION AGRICULTURE – AN AVENUE FOR PROFITABLE  
INNOVATION IN THE AUSTRALIAN SUGAR INDUSTRY  
OR TECHNOLOGY WE CAN DO WITHOUT?**

By  
RGV Bramley  
CSIRO Sustainable Ecosystems, PMB No 2, Glen Osmond, SA, 5064

## 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 metres). 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 investments in PA – whether these be in terms of pragmatic application by Australian cane growers or with respect to research to facilitate such adoption. This 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.

The following key tasks in R&D will be required to enable implementation of PA in the Australian sugar industry.

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 wine grape 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 cane growing 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 withheld 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 (i.e. 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 CCS 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 (e.g. 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.

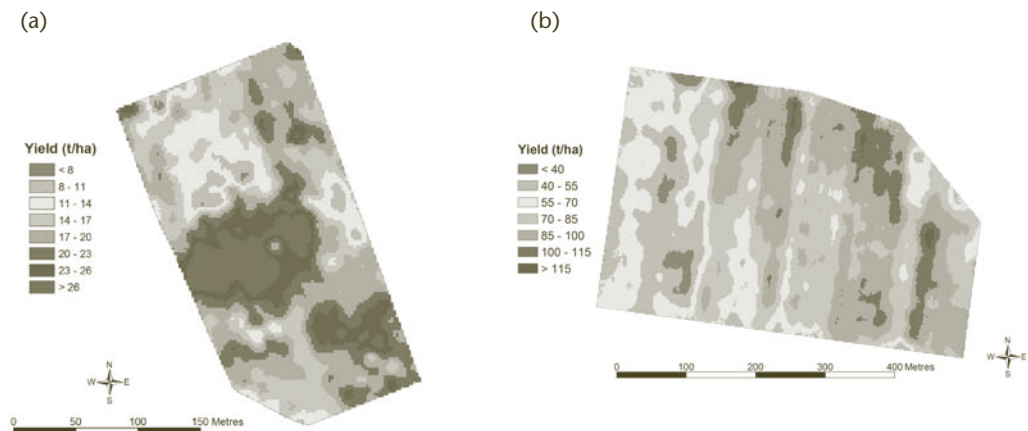
Simultaneous to all of these activities, will be the need to keep abreast of developments in PA in other industries both in Australia and overseas. Support for grower, consultant and researcher visits to technical meetings, centres of expertise and cropping industries in which PA has been successfully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

## Acknowledgments

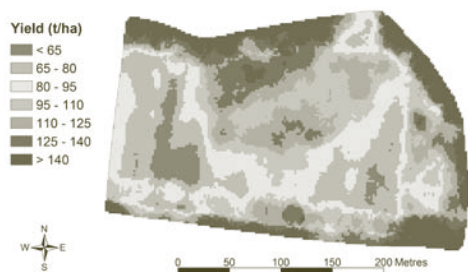
This work was funded by CSIRO and the Sugar Research and Development Corporation. The advice and input of David Cox, Tony Crowley, Jay Hubert, John Markley, Dr Lisa McDonald, Paul Mizzi, Don Pollock, John Powell, Di Prestwidge, Dr Bernard Schroeder, Rajinda Singh, Dr Andrew Wood and Dr Tim Wrigley, who collectively comprised the industry advisory committee for this project, is gratefully acknowledged as is the input and assistance of Tony Webster and Dr Peter Thorburn (CSIRO Sustainable Ecosystems).

# 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.



(c)



(d)

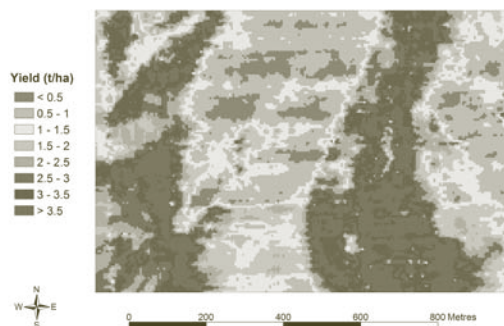


Figure 1. Yield variation in (a) a 4.3 ha Shiraz vineyard in Padthaway, SA (Bramley and Hamilton, 2005); (b) a 22 ha tomato field near Jerilderie, NSW (data kindly provided by Brendan Williams, GPS-Ag); (c) a 12.5 ha block of sugarcane near Ingham, Qld (Bramley and Quabba, 2001, 2002); and (d) a 79 ha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

## Investing in Sugarcane Industry Innovation

The advent of so-called 'Precision Agriculture' (PA; e.g. 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) 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 (e.g. Srinivasan, 2006 and references therein) and, in particular, in Australia (e.g. 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 6<sup>th</sup> time during 2007; the 10<sup>th</sup> Annual Australasian Symposium on Precision Agriculture (see [www.usyd.edu.au/su/agric/acpa/pag.htm](http://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](http://www.spaa.com.au)), an Australian farmer-based group active in the practical use of PA. The journal *Precision Agriculture* has published seven 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.

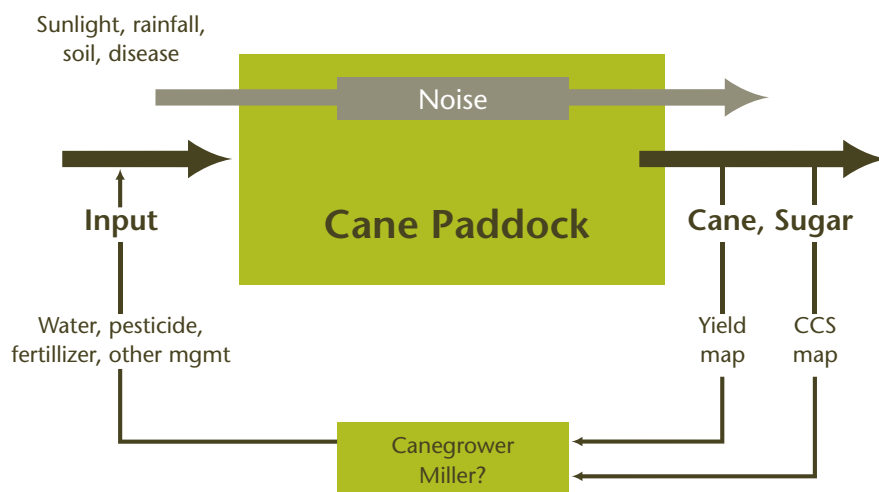
Since the idea of PA as ‘information-intensive’ agriculture (Fountas *et al.*, 2005) is a central theme, the use of controlled-traffic and GPS guidance systems are not canvassed in any detail in this review as their application neither generates nor requires detailed information about crops or soils 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.



**Figure 2. Sugarcane production as a partially controllable input-output process. Whilst some things cannot be controlled (e.g. 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.**





The philosophy behind the move towards more targeted management and the tools on which it depends have been discussed widely elsewhere (e.g. 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 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 either by 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).

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 GPS, 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

## Investing in Sugarcane Industry Innovation

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 (e.g. 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 (i.e. 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 (e.g. 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 (e.g. Hall *et al.*, 2002), the consequent prediction of yield (e.g. Almeida *et al.*, 2006), or some index of crop quality (e.g. 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 that the predominance of a 'closed canopy' over most of the growing season means that effort need not be put into removal of inter-row (i.e. 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 precision agriculture

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 (i.e. within field) variation (e.g. 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 (e.g. wheat and lupins) which may have quite different fertiliser 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 led 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 (e.g. 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 (e.g. Proffitt *et al.*, 2006), the perennial nature of the crop and consequent demonstration 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.

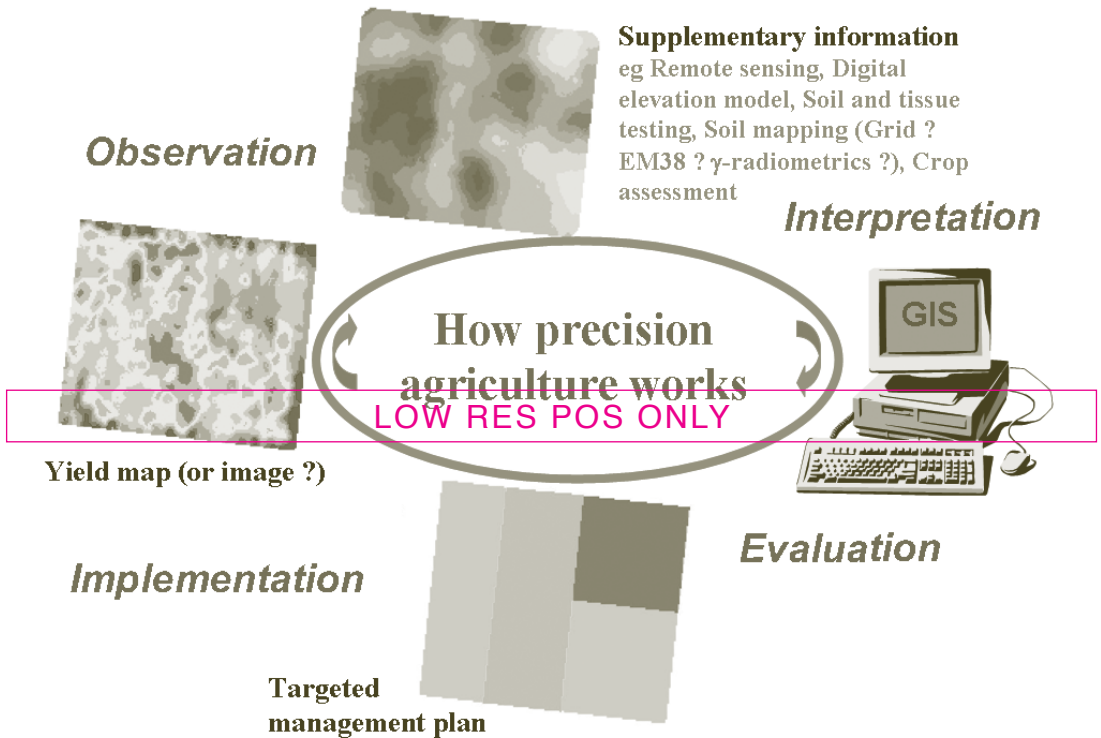


Figure 3. Precision agriculture is a continuous cyclical process.



### 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, sugar beet, 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 (e.g. 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 (e.g. 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 (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), sugar beet (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 fertilisers and other soil amendments (e.g. 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 precision agriculture

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 analyses of their own economic performance! Nevertheless, early studies (e.g. 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 fertilisers 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.

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 (e.g. sugar beet), but will be break-even at best for bulk commodities (e.g. corn); one presumes that sugarcane fits into the same class as sugar beet 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) 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 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 and 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 financial investment that the grower is willing to make in getting someone else to do this for him/her (see Section 6). Perceptions about 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 (e.g. additional yield), the benefit:cost trade-off, or whether the benefit is large enough to justify the additional effort required in doing something new (i.e. 'Can I be bothered?'), amongst a whole raft of other possible considerations (e.g. Pannell *et al.*, 2006).

For this reason, a participative farming systems approach (e.g. 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 (e.g. 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) fertiliser application (e.g. 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.*, 2005b). 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 (i.e. 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 fertilisation 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 fertiliser use (e.g. 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 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, it is clear that opportunities arise for product segregation based on factors such as fruit quality and market demand. 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 *et al.* (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 the 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 (e.g. 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 fertilisers.

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 fertiliser 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.* (2005a) have explored the use of PA to minimise the detrimental effects of N fertiliser 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 (e.g. Bramley and Roth, 2002), the need to use sustainable best practice, and the relatively high rates of fertiliser 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 (e.g. Bramley *et al.*, 2005b) in addition to a focus on yield optimisation.

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' fertiliser 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 fertiliser 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.

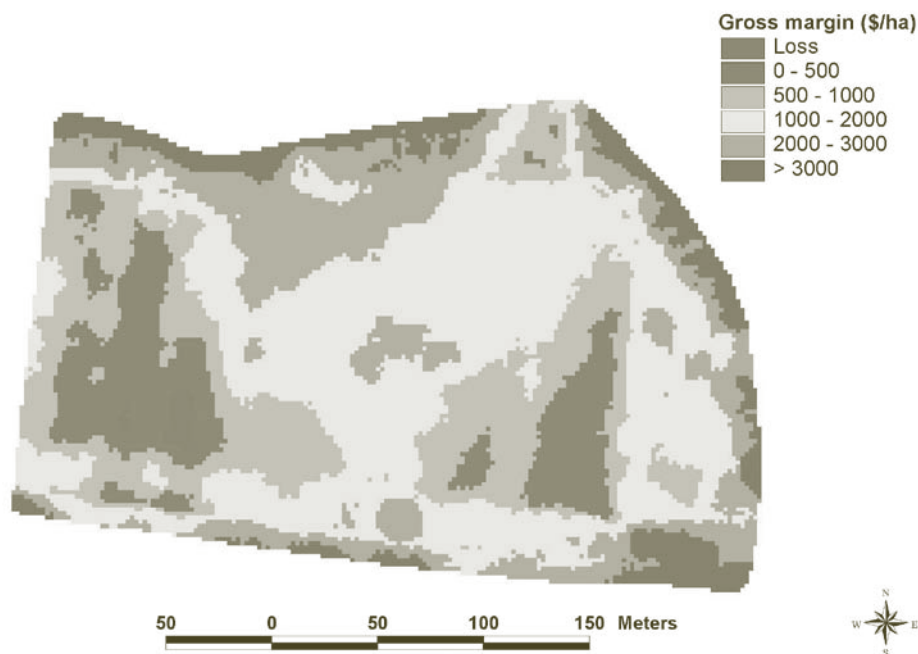
For all practical purposes, there was no further coordinated development of PA in the Australian industry beyond the 1999 season, other than the exploratory work on the use of controlled traffic in cane production (Smith, 2001; David Cox – pers. comm.).

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) are therefore significant, as is the development of a new Australian yield monitor (see [www.jaisaben.com/](http://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 (e.g. Pringle *et al.*, 2003), yield variation showed marked spatial structure.



**Figure 4. Variation in gross margin in a 12 ha block of sugarcane (1<sup>st</sup> ratoon) in the Herbert River District, 1998 (Data of Bramley and Quabba, 2001, 2002).**

This strongly suggests that both zone-based and continuous variable rate management may have potential in sugarcane 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 tonnes of cane/ha and coefficient of variation (CV) of 35%, can be expected to show yield variation in the range of 30 to 170 t/ha. 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 to 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) outputs yield in t/ha, 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 regard to the latter, 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 (e.g. 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 questions of what the desirable on-ground resolution of remotely sensed imagery should be for application to PA in sugarcane and 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.

## Investing in Sugarcane Industry Innovation

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 (e.g. 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 (e.g. Arkun *et al.*, 2000; 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 (i.e. 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 (e.g. 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 (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 fertilisers, 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 mechanised ‘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 Scheepers, 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 fertiliser 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) of similar order of magnitude to that seen in Australia (Bramley and Quabba, 2001, 2002; 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.

## Investing in Sugarcane Industry Innovation

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 was 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' (i.e. 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) 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 information on clay content, in addition to much improved weather forecasting, was required if variable rate N fertiliser 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 (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 fertilisation.



Sparovek and Schnug (2001) conducted a theoretical evaluation of the differential application of P fertiliser and optimisation of mechanical operations such as planting and harvesting in a 77 ha area in south-eastern Brazil. The optimisation of mechanical operations was focussed mainly on the opportunity to minimise the risk of soil erosion.

It was concluded that whilst 'measurable advantages' were not apparent in the case of P fertilisation, 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 mechanised systems in Brazil coupled with the fairly low cost of fertilising 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 after 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 in both 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 synchronises 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 (e.g. 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 (e.g. 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 data mining 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 five US corn belt 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 (e.g. 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 fertiliser 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 (e.g. 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 fertiliser requirement, since areas with high moisture-dependent yield potential may need more fertiliser 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 (e.g. EM38) soil maps, followed by appropriate targeted soil sampling and analysis for the purposes of making fertiliser 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 (i.e. fertiliser recommendations).

As indicated, the approach adopted in the US is grid-based sampling (e.g. Robert, 2002), typically at an intensity of around 1 sample for every 1.5 ha (Mallarino and Wittry, 2004). Some authors (e.g. Magri *et al.*, 2005) have even suggested that grid sampling at 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 (i.e. 5 samples/ha) to one per 1.6 ha (i.e. 0.6 samples/ha) with zone based sampling and sampling based on local (1:12,000) 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) 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 (e.g. Janik *et al.*, 1998; Bramley and Janik, 2005; van Vuuren *et al.*, 2006; Viscarra Rossel *et al.*, 2006), perhaps combined with soil inference systems (e.g. McBratney *et al.*, 2006), or through the development of new sensors that can be used either *in situ* (e.g. Skogley, 1992; Qian and Schoenau, 2002) or on-the-go (e.g. 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'.

**Table 1. Technologies for rapid soil sensing (derived from McKenzie *et al.*, 2003)<sup>A</sup>.**

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)	<i>In situ</i> 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.
□-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.

<sup>A</sup> 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.

## Investing in Sugarcane Industry Innovation

With respect to real-time on-the-go sensing of soil properties, it is also worth pointing out that a farmer very rarely makes a fertiliser 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 fertiliser 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 (e.g. 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 (e.g. EM38) or resistivity (e.g. 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 (e.g. 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 (e.g. 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 (e.g. 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 principles 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 (i.e. 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 been 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  $\pm 2$  cm in the  $x$ ,  $y$  and  $z$  planes<sup>1</sup>) 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 is certainly worthy of investigation by the Australian sugar industry.

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<sup>1</sup> Note that in Australia, standard GPS is accurate to about  $\pm 6$  m 95% of the time; differential GPS (with a commercially subscribed satellite differential correction) is accurate to  $\pm 0.5$ -1 m in the  $x$  and  $y$  planes, but is only accurate to several m in the vertical ( $z$ ) plane.

## 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 (e.g. 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 (e.g. Wong *et al.*, 2005b), the obvious question is: why is it so?

Whilst there is now plenty of evidence in the scientific literature of an economic benefit accruing from PA (see Section 3.1), 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 (e.g. 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. 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) 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). The commodity-specific nature of some technologies (i.e. 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 the skill base and, in particular, the 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 fertiliser 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 fertiliser 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, 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) which, given the focus on VRA fertiliser 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.* (2005b) 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 precision agriculture in the Australian Sugar industry

In spite of the evidence from grains and winegrapes (see Section 2.1) 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 that might be set up by the Australian sugar industry.

Desirably, the first three should be tackled together, albeit in chronological sequence, with economic evaluations of the answers 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.

## Investing in Sugarcane Industry Innovation

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 (i.e. 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.

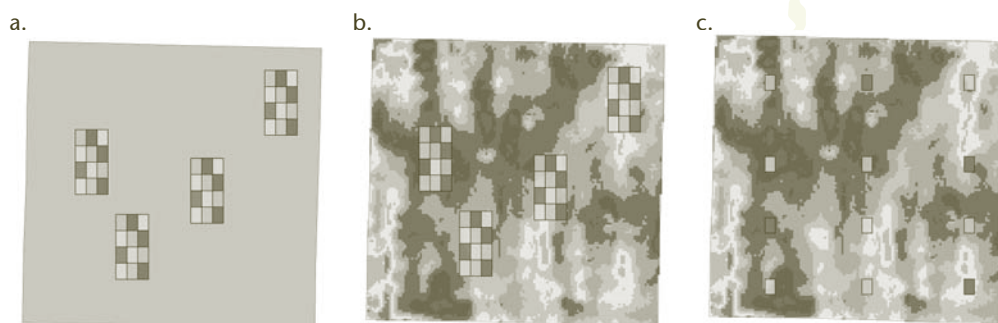
Of course, like a vineyard manager, a sugarcane farmer has to manage the whole field and farm, not just a few plots. The effects of the sort of spatial variation shown in Figures 1 and 5 therefore raise questions about how experiments should best be done – whether as part of a scientific research project, 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, 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.



**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)

## 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 withheld 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 (i.e. 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 CCS 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 (e.g. 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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**PRECISION AGRICULTURE TECHNOLOGIES –  
RELEVANCE AND APPLICATION  
TO SUGARCANE PRODUCTION**

By  
R Davis, R Bartels and E Schmidt  
National Centre for Engineering in Agriculture, FSA Consulting



## Executive summary

This report has reviewed precision agriculture technologies currently in use or applicable to sugar cane production. The various concepts and technologies that will make up tomorrow's precision agriculture are still emerging.

Precision agriculture (PA) includes a wide array of site-specific technologies varying from growers using markers to partition a field into management zones to on-board computers interfacing with satellites to pinpoint precise coordinates within a field. Some of the more basic site-specific technologies include aerial photography and soil survey maps. These technologies provide a producer with site-specific information to aid in management decisions. Another more sophisticated technology includes optical sensors that allow on-the-go information to be collected and processed, and inputs to be dispensed according to computerised decision rules as a tractor moves through a field. Global positioning systems (GPS) are a technology that allows site-specific information to be collected through interface with satellites. A GPS receiver can be attached to machinery such as tractors and harvesters.

For example, GPS technology can be used for guidance or with a yield monitor on a harvester to measure within-field yield variability. This information can then be converted from raw data into a yield map using precision farming computer applications. A database of yield variability over time can be used with other information, such as a topographical map of the field, to make crop management decisions for the specified field.

In addition, using this array of PA technologies, the sugar industry is able to respond to pest and disease as evidenced by the recent smut outbreak, accurately forecast its crop, map its entire industry and derive transport efficiencies from just-in-time delivery schedules.

Much research has been undertaken on the individual components of the PA management cycle. The challenge is to for the industry to integrate these for whole of system gain.

The application of PA within the sugar industry is occurring at a number of varying scales of management including:

- **Regional scale:** Application of PA at a regional level is currently available with the development of site-specific fertiliser recommendations for areas like the Herbert and Bundaberg districts rather than industry generalised recommendations. This has been based on the principle that soil type, based on easily recognisable field properties, can be used as the basis for varying rates of nutrients applied.
- **Mill scale:** A number of sugar mills have or are currently developing integrated cane harvest management systems to facilitate marketing and logistics, planning mill start dates, cane transport arrangements, harvest groups base daily loadings and harvesting schedules. These systems use modern computer and communication technologies to integrate data and systems and to develop tools that assist individual decision-making as well as support whole-of-industry management strategies.

- **Farm scale:** Farm mapping data provided by GIS provides the basis of a number of business processes including crop estimation, harvest management, productivity analysis, irrigation management and disease control.
- **Block/field scale:** Yield mapping and variable rate application within an individual block. With the exception of the districts with larger block sizes (e.g. Burdekin), block scale implementation of PA may not be appropriate for growers individually. However it may be appropriate within the bounds of a grower cooperative or similar framework.

PA enabling technologies are commercially available and have become cost effective to Australian cane growers. Thus, it is not so much a question of why or how; rather, the question to be addressed by cane growers is 'when and how do we make the right decisions about investing in new technology to ensure profitability?' Whilst widespread adoption might promote and even necessitate significant change within the industry, the fact that PA lends itself to incremental adoption means that such change will be manageable. Having at least some information is better than having none, and it would therefore be appropriate for the sugar industry to begin the adoption process sooner rather than later.

The key to making money from PA is for growers or harvesting contractors to choose an aspect of the technology that provides rapid and certain benefits across a wide area of their enterprise. With the advent of cheaper GPS guidance systems, and growing evidence of the efficiency gains that can be made with them, more growers and harvesting contractors are investing in this part of the PA equipment suite.

Growers and harvesting contractors now have a good choice of programs at their disposal to assess risks to their business and to identify potential productivity and cost saving initiatives. These can be utilised to assess whether or not investment in PA is feasible for their enterprise. Existing programs that may be used to evaluate the benefits of PA range from simple capital investment calculators to broader farm management support tools.

In addition, cane growers now have the benefit of being able to learn from a broader range of experiences of other industries (e.g. cotton, wine) in addition to those of the early adopters growing cereals.

Technology gaps, adoption/commercialisation gaps and research opportunities identified for PA for sugarcane production and harvesting are summarised in Table 2.



# Acknowledgements

This report has been written predominately using the authors' experiences in sugar and related industries and unpublished and published information on precision technologies that are being applied or could be applied to improve the cost efficiency and reduce the environmental impact of sugarcane production and harvesting.

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# 1. Introduction

The development of a range of new technologies has brought agriculture and agricultural equipment to a whole new level of sophistication. First hypothesised in the early 1990's, Precision Agriculture (PA) is a crop management philosophy that utilises these new technologies to produce crops in a more sustainable fashion.

The Australian sugar industry is faced with a long term trend of reducing value of production and increasing input costs. The industry has rapidly adopted guidance technology based on global positioning systems (GPS) with many cane growers now having access to high precision GPS technologies. However, there remains a wide range of uncertainties and conflicting opinions that make the next step for PA a daunting prospect for cane growers, therefore the adoption of PA has been slow.

PA has gained a significant amount of publicity in recent years, especially in other farming systems such as cotton, grain growing and viticulture. Growers have been confronted by a flood of rapidly developing technologies and techniques (often very costly) that claim to aid in all aspects of farm management. With a few notable exceptions, PA is still a relatively new concept in the sugar industry. However, it will happen in the sugar industry. PA technologies have the potential to improve the commercial viability and environmental sustainability of sugarcane production and harvesting.

To a degree, PA within the sugar industry has been driven by the advent of various new technologies, particularly the coupling of real-time positioning using GPS. The rapid adoption of GPS guidance and tractor steering technology and the direct benefits of reduced overlap and increased productivity have made cane growers acutely aware of the potential benefits of new technologies. With the initial adoption of these technologies, cane growers are seeing the benefits of more efficient operations with some cane growers claiming that they have halved their labour requirements.

There is thus an urgent need to increase knowledge of PA across the industry to ensure that adoption decisions are made on an informed basis that learns from other agricultural industries both domestically and internationally. Specifically, the industry needs to know how these technologies can:

- reduce the break even cost of production;
- improve the quality of life;
- improve environmental sustainability;
- boost associated research;
- reduce production risks; and
- increase productivity and profitability.

Further, the limitations of the technologies need to be known.



## *Investing in Sugarcane Industry Innovation*

Based on these requirements, Davis *et al.* (2007) prepared a review of published and unpublished information on precision technologies that are being applied or could be applied to sugarcane production and harvesting in Australia. In addition, a brief review of applicable developments within international sugar industries was also undertaken. Their report describes how these technologies operate, their uses, opportunities, limitations, risks and costs with respect to precision farming in the sugar industry. It also describes how they can be integrated into a management system that will have both economic and environmental benefits for sugarcane production and harvesting. The technologies discussed may also have application to cane railway transport, logistics and milling.

This paper is a summary of aspects of the review of Davis *et al.* (2007).

## 2. Precision Agriculture

Precision Agriculture (PA) is the spatial and temporal management of agricultural production for profit. The challenge in agriculture has always been to manage the enormous variability of the agricultural production environment in a profitable manner. As management in agriculture has always been concerned with spatial and temporal variability, this is not a new concept. Today PA is associated with newer technologies and management support systems that are being used to advance management and operations across the agricultural enterprise. These new technologies provide an increasingly better insight for management into what is happening in the field.

The modern concept for PA focuses on managing and interpreting the information and knowledge gleaned through the agricultural cycle using the ever increasing array of new technologies available to growers. Figure 1 shows that the PA management cycle has five key conceptual components. These are production environment monitoring, attribute/yield mapping, decision support (using models and GIS), differential actions based on the previous steps and spatial referencing.

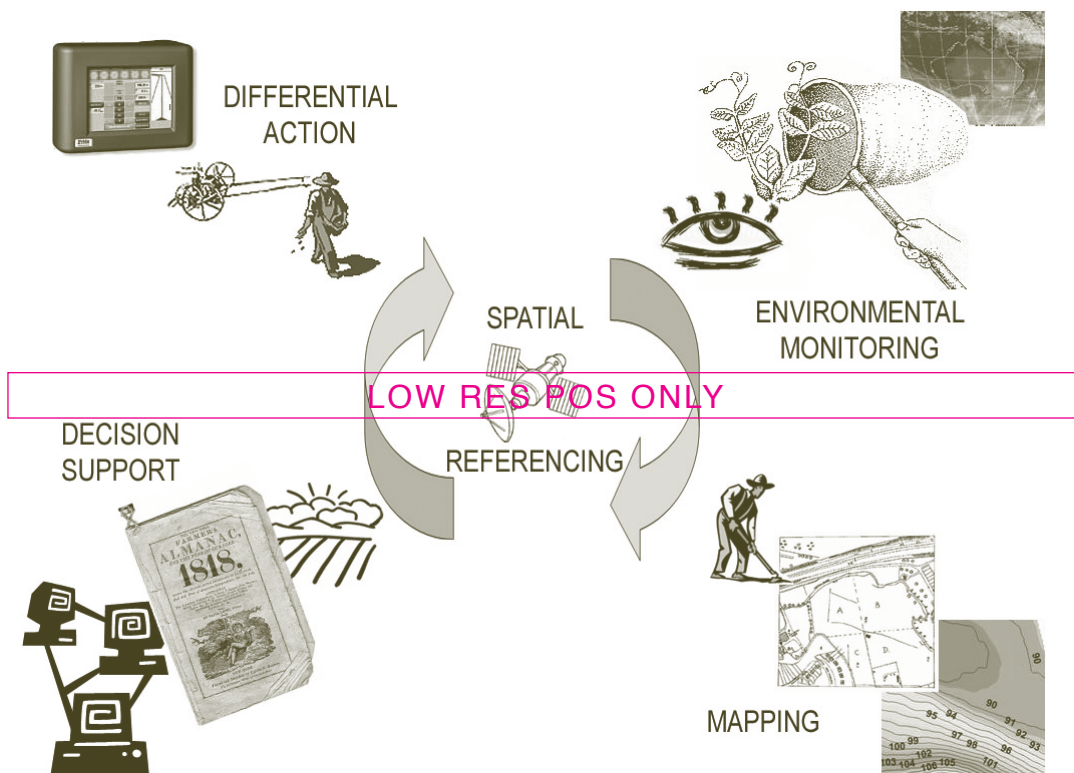


Figure 1. Diagrammatic representation of the five key conceptual components of precision agriculture



PA information can be used by growers and advisers to improve cropping decisions, crop agronomy and the efficiency of farming operations. These parameters may include soil type, soil organic matter, plant nutrient levels, topography, water availability, weed pressure, insect pressure, etc. and an additional purpose, that of environmental protection (McBratney and Whelan, 2001).

### **2.1 Precision agriculture in the sugar industry**

In all other industries, PA starts with yield maps and analysis of yield variability. In the sugar industry, there are few accurate yield maps but other tools used in PA are increasingly common. This has led to a situation where the sugar industry's perception of the term PA is very different to other agricultural industries that use yield maps as the starting point for precision agriculture. PA is currently being investigated by the sugar industry with many industry participants seeing this minimalist adoption as an end in itself. However, the integration of these technologies presents the industry with much more opportunity as drivers of cultural and industry reform.

The extent to which PA technologies and methods are used in sugarcane production and harvesting depends on the purpose. When you ask growers what PA means to them, you get a number of different answers depending on their perspective. These include, but are by no means limited to, GPS technology, controlled traffic farming, zero/minimum tillage farming, tractor/harvester guidance, yield monitoring, variable rate fertilising, harvesting feedback etc.

All of these answers are indeed part of PA and valid because what an individual grower or contractor wants from PA depends primarily on the economic or management pressures motivating them to strive for more control of their sugar production or harvesting enterprise.

In addition to these benefits, there are two further, sometimes forgotten, benefits of PA. Firstly, information and understanding that growers gain from seeing maps of variability in soils, crops or pests, translates into improved cropping decisions and greater efficiency over time. Secondly, there is the potential for growers to use PA for their own on-farm trials, where new varieties, fertiliser type or rate, or soil or pest management can be tested on a small area and the results assessed cheaply using yield or other PA data. The impact of these benefits may not be immediate but can be far reaching (Anon 2006).

Thus, while 'full scale' PA may seem like a pipe dream, PA is already here although in a different form to the idealised concept of 'full scale' PA.

One of the underlying concepts of PA is that a canegrower can improve profit and protect the environment by reducing over- or under-application of expensive inputs by better matching crop inputs and agronomy to the specific characteristics of particular parts of a block or farm.

PA is potentially more profitable as it may increase crop production revenue and/or reduce input costs. However, PA cannot help yield and improve profit unless a canegrower already has the basics of good production and environmental management in hand.

Within the Australian sugar industry, interest in PA has grown over the past decade and continues to grow across a range of scales. These include regional, mill, farm and field/block scales. This interest has been driven by the following factors:

- the advent and integration of technologies that allow the efficient collection of geographically located (spatial) information;
- an increase in the range of variables affecting crop performance that can now be addressed using PA. Research is developing PA tools to improve the management of disease, weeds, nutrition and the timeliness of operations;
- the tools needed for PA (GPS for positioning and guidance, remote sensing technologies, maps of variation in soils and crops, variable-rate technology (VRT) and yield monitors to some extent) have become increasingly available and affordable;
- accessibility of state and federal government financial support for these technologies.

### **2.2 Technology change and precision agriculture**

One of the limitations and challenges with the adoption of PA is the continuing change of technologies. Today's growers are faced with a bewildering array of technologies with many evolving at exponential rates. Therefore the difficulty is how to assess the benefits of these technologies when often the technologies are superseded just as growers are gaining an understanding of them.

Growers are adept at making incremental improvements to farming technologies and management systems. The downside of an incremental approach to the new technologies is the management of the data layers. Much of the longer term benefit of PA, derives from being able to analyse time series of multiple data layers. To reliably store the data and then make it available in a format that is easily analysed and interpreted is difficult for an individual grower.

Significant investment has been directed at centralised storage and analysis by milling companies and data are made available to growers and mills via the internet. The rationale behind these approaches is sound as very few growers have the knowledge and skills to correct inconsistencies, manage overlays, maintain and interpret the data, especially when the records need to be kept over long periods of time. This makes maintaining and mining the data much more efficient.

The following sections of this paper provide a summary of the five conceptual components shown in Figure 1.





## 3. Spatial Referencing

Spatial referencing is central to the PA management cycle. The main tool used for spatial referencing is the GPS but other options include the use of field maps and other surveying/positioning techniques such as remote sensing.

Enabling technologies are required when contemplating such a precise approach to sugarcane production and harvesting. The availability and cost-effectiveness of a multitudinous array of new technologies has made the concept of PA a reality. These technologies have reached a level that allows a canegrower and/or harvesting contractor to measure, analyse and manage within-field variability that was previously known to exist but was unmanageable from a practical point of view.

### 3.1 *In-field positioning*

Being able to take a measurement or make an application at a precise position is the key to successful PA. Nearly all in-field positioning for PA at an operational level is undertaken using a GPS. GPS positioning is effectively the cornerstone of modern PA.

There are currently three satellite positioning constellations that are deployed around the earth:

- the NAVSTAR Global Positioning Systems (GPS) owned by the government of the United States of America;
- the Global Navigation Satellite System (GLONASS) controlled by the Russian government; and
- Galileo, a constellation being deployed by the European Union, that should be in operation by 2010.

Although GPS is one of three satellite positioning constellations, the term GPS has become a generic term for any satellite positioning system. While NAVSTAR GPS dominates the market, increasingly GPS receivers are being sold that can utilise more than one of the constellations to further improve GPS positioning reliability and availability as well as improving the position fix.

One of the limitations with any rapidly involving technology like GPS is that the terminology can be confusing and there are no generally accepted standards. While some standards for assessing static accuracy of GPS exist for most agricultural applications, within the sugar industry GPS is predominantly used in a dynamic manner for guidance systems.

## *Investing in Sugarcane Industry Innovation*

The sugar industry has seen the rapid adoption of positioning technologies particularly GPS in recent years. This has been driven by motivated growers to improve existing farming methods, the associated adoption and integration with new farming systems incorporating concepts such as controlled traffic and the need to be precise about machine placement. This all contributes positively to efficient and effective use of rain and irrigation, along with other inputs such as the soil, nutrients and pest management.

- Within the sugar industry, the largest number of GPS users is in guidance and auto-steering. This is mainly because of the more immediate benefits of guidance. When properly installed and operated, such benefits include:
  - generation of straighter rows with no wide or narrow guess rows;
  - establishment of controlled traffic lines to minimise compaction areas within fields;
  - operation of equipment at higher ground speeds;
  - Reduced operator fatigue;
  - Improved utilisation of machinery (less machinery per hectare);
  - reduced amount of overlapping of sprayers and fertiliser equipment beyond that of the current foam marker or marker arm systems; and
  - downloading of topographical and operational information on application areas for future reference.

This has opened up a whole raft of opportunities including precise ground preparation, seed placement, row and inter-row operations, harvester and haulout guidance, reduced driver fatigue, operations continuing outside of daylight hours and efficiency gains.

There are a wide range of products on the market that enable on-the-go position determination as well as allowing guidance in the field. Guidance systems can basically be divided into three categories visual, assisted steering and hitch guidance. The assisted steering systems are the predominant form of system in use within the sugar industry. Table 1 shows a selection of guidance products that are commercially available. As these technologies are constantly evolving it is best to confirm on the suppliers/manufacturers web site, the current status of the product.



**Table 1 - Selected commercial products for agricultural vehicle guidance**

Product range	Main web site	Visual cue	Assisted steering	Notes
Zynx	<a href="http://www.kee.com.au">www.kee.com.au</a>	Yes	Yes	Australia manufacturer
Canlink	<a href="http://www.farmscan.net">www.farmscan.net</a>	Yes	Yes	Australia manufacturer
Farmlap	<a href="http://www.farmscan.net">www.farmscan.net</a>	Yes	Yes	Australia manufacturer
Cultiva	<a href="http://www.cultiva.com">www.cultiva.com</a>	Yes	Yes	national distribution
Saturn	<a href="http://www.rinex.com.au">www.rinex.com.au</a>	Yes	Yes	Australia manufacturer
e-drive	<a href="http://www.outbackguidance.com">www.outbackguidance.com</a>	No	Yes	national distribution
Outback	<a href="http://www.outbackguidance.com">www.outbackguidance.com</a>	Yes	Yes	national distribution
RowGuide	<a href="http://www.agguide.com.au">www.agguide.com.au</a>	Yes	Yes	Australian manufacturer active in sugar industry
RigGuide	<a href="http://www.agguide.com.au">www.agguide.com.au</a>	No	Yes	Australian manufacturer active in sugar industry
LightGuide	<a href="http://www.agguide.com.au">www.agguide.com.au</a>	Yes	no	Australian manufacturer active in sugar industry
Auto-Guide	<a href="http://www.globaltech.agcocorp.com">www.globaltech.agcocorp.com</a>	No	Yes	Active in sugar industry
Arro	<a href="http://www.beeline.com.au">www.beeline.com.au</a>	No	Yes	Australian manufacturer/active in sugar industry
AutoFarm	<a href="http://www.gpsfarm.com">www.gpsfarm.com</a>	No	Yes	national distribution/active in the sugar industry
AccuTrak	<a href="http://www.accutrak.ca">www.accutrak.ca</a>	No	Yes	national distribution
EZ-Guide	<a href="http://www.ez-guide.com">www.ez-guide.com</a>	Yes	No	national distribution/active in the sugar industry
AgGPS Autopilot	<a href="http://www.autopilotgps.com">www.autopilotgps.com</a>	No	Yes	national distribution/active in the sugar industry
Ez-Steer	<a href="http://www.ez-steer.com">www.ez-steer.com</a>	No	Yes	national distribution/active in the sugar industry
AutoTrac	<a href="http://www.deere.com">www.deere.com</a>	Yes	Yes	national distribution/active in sugar industry
Legacy	<a href="http://www.teejet.com">www.teejet.com</a>	Yes	Yes	national distribution
CenterLine	<a href="http://www.teejet.com">www.teejet.com</a>	Yes	No	national distribution
Guideline	<a href="http://www.teejet.com">www.teejet.com</a>	Yes	No	national distribution
AccuGuide	<a href="http://www.caseih.com">www.caseih.com</a>	No	Yes	national distribution/active in sugar industry
IntelliSteer	<a href="http://www.newholland.com">www.newholland.com</a>	No	Yes	national distribution/active in sugar industry
Auto Pilot	<a href="http://www.fp-engin.dk">www.fp-engin.dk</a>	No	No	no national distribution/computer vision
Robocrop	<a href="http://www.garford.com">www.garford.com</a>	No	No	no national distribution/computer vision
Ultra Guidance PSR	<a href="http://www.reichhardt.org">www.reichhardt.org</a>	No	Yes	no national distribution/ultrasound/GPS
Auto Guide	<a href="http://www.sukup.com">www.sukup.com</a>	No	No	no national distribution/feeler based hitch guidance
Tracker IV	<a href="http://www.orthman.com">www.orthman.com</a>	No	No	no national distribution/GPS based hitch guidance
Acura Trak	<a href="http://www.suncomarketing.com">www.suncomarketing.com</a>	No	No	no national distribution/feeler based hitch guidance
Row Crop Navigator	<a href="http://www.automaticag.com">www.automaticag.com</a>	No	No	no national distribution/feeler based hitch guidance
Furrow Guide	<a href="http://www.agguide.com.au">www.agguide.com.au</a>	No	Yes	Australia manufacturer/GPS based hitch guidance
AgGPS Implement Steering	<a href="http://www.trimble.com">www.trimble.com</a>	No	Yes	national distribution / GPS based hitch guidance

Not only is GPS usually used while the receiver is in motion, but for many PA applications growers are concerned with the relative accuracy. This means that a GPS receiver that is inaccurate but precise over a short period of time may be able to give good relative positioning across the field. The relative accuracy from one pass to the next can be adequate for many agricultural applications.

However, there are methods to reduce the error component of the position fix. These can be classed into atmospheric error and improvements in the technology categories. The most accurate way is to use a base station. As the base station does not move the atmospheric errors can be calculated. This error can then be transmitted to a mobile unit which can then correct for the atmospheric errors.

Growers in most cases have individually purchased GPS systems incorporating base station and rovers. Networked RTK GPS is a completely different approach to calculating and communicating base station information to the mobile unit (i.e. tractor). This approach offers an opportunity to the sugar industry with the potential to rapidly increase the number of users through a reduction in the cost of the technology. Community network based GPS are already being implemented within Queensland, with networks being established in the Maryborough, Isis, Bundaberg and Herbert River areas, representing about 25% of the sugarcane industry. The majority of new planting in these areas will soon make use of GPS and possibly controlled traffic, along with row spacing that matches machinery.

This area, along with developments in communication technology (i.e. wireless networks, broadband internet etc.), should continue to be one area of focus for PA research and development.

### **3.2 Positioning technology pricing**

A major limitation with the adoption of PA is the perceived cost of the enabling technologies. There is a common misconception that PA requires large capital investment with an extended pay-back period. This is not necessarily true. A GPS-autosteer guidance system with 10 or 2 cm accuracy will cost between \$20,000 and \$60,000 depending on the accuracy required and source of correction signal. This will enable a grower to reduce spray overlap or to establish permanent rows for controlled traffic cropping, and can provide immediate savings or gains.

For a large cropping program, the time needed for a positive return on this investment could be as little as two seasons (ignoring additional potential benefits from reduced operator fatigue, night spraying etc.). Cheaper guidance systems are available and may be a good investment for growers who just want something more accurate than a foam marker.

Low cost hand held GPS receivers can be purchased in the \$200 to \$500 range. These units are useful for rough mapping but are not suitable for vehicle guidance. Basic visual guidance products start at about \$4,000 but can cost more than \$30,000 depending on additional features and GPS used. At the other end of the spectrum an RTK GPS system with assisted steering installed on a tractor and the required base station can cost more than \$65,000.



## 4. Remote Sensing

Remote sensing refers broadly to measuring reflected electromagnetic energy using a camera or sensor. Application of this technology to agriculture makes use of a wide range of instruments, from airborne cameras to sensors mounted on orbiting satellites. Satellite imagery, as well as similar airborne imagery, allows mapping patterns of soil and vegetation with greater detail than that obtained by yield monitors or soil sampling, and without convolution inconsistencies. Remote sensing provides a great deal of fundamental information relating spectral reflectance and thermal remittance properties of soils and crops to their agronomic and biophysical characteristics at scales that may range from small patches within a field to large regions (Pinter *et al.*, 2002). This makes it an attractive tool for PA decisions in many environments, particularly with regard to soil characterisation, non-destructive monitoring of plant growth and detection of environmental stresses that may limit crop productivity.

Numerous studies in sugarcane in Australia and overseas (Lee-Lovick and Kirchner, 1990, 1991; Noonan, 1999; Schmidt *et al.*, 2000, 2004; Gers, 2003; Everingham *et al.*, 2005) have demonstrated associations between crop canopy reflectance, crop biomass, leaf area index and crop yield at different spatial scales. The strength of remote sensing is the opportunity to learn more about crop growth variability while the crop is still growing. Benefits can be realised by combining this information with soil and yield maps or crop models in developing an integrated crop management program.

The major challenge to be tackled in the future is making the interpretation process more automatic, generic and mechanistic rather than relying on empirical, location-specific remote sensing solutions for crop management (Dobermann *et al.*, 2004). Lessons can be learned from other industries such as viticulture, grains, cotton etc.

### 4.1 Satellite/aerial imagery

Remote sensing systems based on satellites and piloted aircraft are the two major platforms that have been commonly used to collect remote sensing image data for agricultural purposes. Another platform that has recently been introduced is the use of unmanned aerial vehicles (UAVs) (Jensen *et al.*, 2003).

Remote sensing procedures utilising optical satellite (Landsat ETM) image data have provided the opportunity for rapid and detailed yield and harvest assessments of various agricultural crops. Earlier trials of Landsat image data sets for estimating sugar cane yields in Australia were not successful due to problems linking image and field data sets accurately (Lee-Lovick and Kirchner, 1990, 1991). More recent applications have been highly successful in accurately estimating yields down to the cane-block level and mapping the extent of harvested, flooded and diseased areas (McDonald and Routley, 1999; Noonan, 1999). However, a major limitation of these procedures has been the inability of sensors, such as Landsat, to provide usable data where cloud has obscured the satellite's view of the land surface, as is the case for most of tropical and sub-tropical regions of Queensland. In these areas cloud cover (> 6/8) occurs most frequently in the mornings, coincident with satellite overpass time, during the months October – April (Colls and Whittaker, 1990). The development of operational Synthetic Aperture Radar (SAR) sensors, such as the Radarsat-1 C-band satellite sensor, has provided the potential to acquire remotely sensed imagery independent of weather conditions (Knight *et al.*, 2001).

## Investing in Sugarcane Industry Innovation

The key potential of SAR sensors for the sugar industry is that they may provide image data responsive to the structural characteristics of vegetation. In addition, this technology has been evaluated for sugar cane yield estimation and delineation of harvested cane from unharvested cane (McDonald and Routley, 1999; Noonan, 1999).

### 4.2 Yield forecasting

Yield forecasting has widespread potential application on a mill scale as early and accurate estimates of the size of the sugarcane crop can facilitate the planning of mill start dates, cane transport arrangements, harvest groups base daily loadings and harvesting schedules and also assist marketers with forward selling sugar.

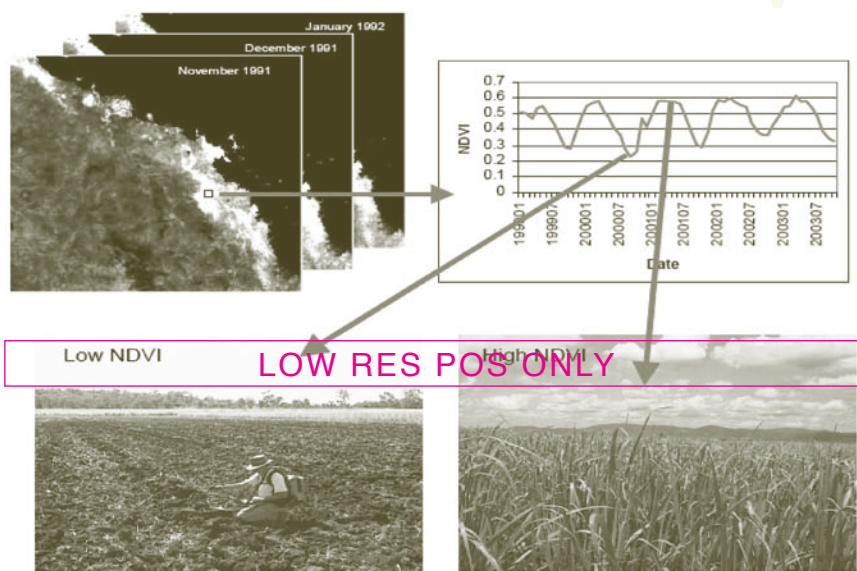
Remote sensing data from satellite imagery offers another approach to crop forecasting.

Mackay Sugar has traditionally used a proportional re-estimating program to predict the size of remaining crop to be harvested during a harvest season. This program formulates an actual to estimate yield ratio for the calculated harvested area, and then applies that ratio to the remaining crop estimate. The re-estimate is used as the base for a harvest management system. This process required considerable input from field staff to calculate the area harvested on a regular basis and a less labour intensive method to calculate harvested area needed to be developed. Satellite imagery was adopted as it offered the opportunity to capture a snap shot of the whole district instantly and subsequent analysis of the images using change detection techniques could be used to calculate area harvested (Markley *et al.*, 2003). Imagery used for change detection has included Spot II and IV multispectral images plus Landsat7<sup>TM</sup> ETM. Changed detection methods have been developed and refined to overcome problems associated with the changing nature of the crop including severely drought-affected cane. Results showed that area detection from satellite imagery analysis was within 2% of area calculated from other means such as harvester GPS tracking and manual area calculation (Markley *et al.*, 2003).

For the Australian sugar industry, limited research has been performed on the suitability of crop and remote sensing models for forecasting terminal sugarcane yields which are defined as the average yield across all mills with a common shipping point. Even less research has been conducted on the ability of these models to commence predictions during the early (e.g. December) stages of the growing season. The most commonly used vegetation index is the normalised difference vegetation index (NDVI) which provides a measure of the area of green leaf canopy that is intercepting sunlight. Figure 2 shows an example of an NDVI time series from 1999 to 2003 taken from the archive for a single one km pixel in northeast Queensland.

Everingham *et al.* (2005) reported on a comparison of crop and remote sensing models for providing marketers with regularly updated forecasts throughout the growing season. They, like Schmidt *et al.* (2000), investigated if the integrated NDVI signal (i.e. area under the NDVI curve) could be correlated with terminal yields. They combined the NDVI areas for these pixels into a principal component index. This index and terminal yields were used to compute a predictive correlation. Whilst the remote sensing model was validated statistically, Everingham *et al.* (2005) outlined a number of advantages and disadvantages with the remote sensing yield forecasting method and found it difficult to accurately explain why the remote sensing model under- or over-performed in certain years. One limitation is the effort required to capture and process the necessary NDVI data. An advantage of remote sensing models over climate-driven crop models is their ability to directly record the condition of the crop and monitor disease outbreaks such as orange rust, which occurred in year 2000.





**Figure 2. Interpretation of an NDVI time signal for a one km square pixel (Everingham *et al.* 2005)**

Further work is aimed at using the remote sensing model operationally to forecast yields for marketers and to assess the financial benefits of using this strategy to gauge if yield forecasting methods can truly value add to the QSL management of sugar supplies (Everingham *et al.*, 2005).

### 4.3 Soil properties

Remote sensing techniques permit estimation of many significant soil properties over large areas and also provide the ability to monitor temporal changes through repeated observations over time. Limited research has been undertaken within the sugar industry on utilising remote sensing techniques to investigate soil properties.

Remote sensing can access the productive potential of land and can sometimes highlight areas where potential problems such as erosion, water-logging and salinity might occur. It can be used for the identification of various soil properties including soil moisture, soil mineralogy and other soil characteristics including texture (sand and clay content) and organic matter content.

Multi-spectral remote sensing is often limited by difficulties in relating measures of land surface reflectance to soil variables controlling crop performance. However, the increasing resolution of satellite data in time and space should increase the relevance to crop production. Temporal remote sensing should provide indications of growing season length and net primary productivity. Differences in the soil-water regime relating to both plant-available water capacity and waterlogging should be discernable but considerable research is required (McKenzie *et al.*, 2003).

#### **4.4 Weeds and pest infestations**

Herbicides and pesticides are two of the most expensive controllable costs of sugar production. Rapidly improving remote sensing technology and image processing means there is the potential to significantly reduce these expenses. Conventional weed and pest mapping techniques are expensive, time consuming and are generally not repeated frequently enough to monitor important changes in infestations. They are also inefficient where the target weeds and pests cover a wide geographic area.

Reliable, up-to-date information on weed abundance, distribution, and change over time is essential for all aspects of broadscale weed management. Such information is necessary to evaluate control strategies, prevent spread to clean areas and improve weed management.

Remote sensing offers a low cost, repeatable alternative for mapping and monitoring weed infestations over large areas, although with several limitations. For remote sensing to be successful, the target weeds must have distinct reflectance differences from background vegetation, soil and harvest residue. For detection by current multispectral sensors, these differences must be great enough to compensate for the broad spectral bands and the pixel size of the sensor. Detection may also be limited by the density of the weed infestation.

Determining weed species via multi or hyperspectral imagery continues to be difficult and remains the focal point of current agricultural research (Thorp and Tian, 2004). The development of robust proximal on-the-go sensors to detect weeds and integrated variable rate application spray systems provide a more appropriate approach to weed management for the sugar industry.

The use of remote sensing techniques to aid in pest management is still in its infancy and more research is required to demonstrate the full capabilities of this technology. The mobility of insects makes their site-specific management considerably more challenging than less mobile species. Whereas weeds and nematodes can be found in a fairly narrow layer just above or just below the soil surface, flying insects may occupy vast three-dimensional areas in and around the crop (Stewart *et al.*, 2005).





## 5. Production Environment monitoring

Factors affecting crop yield, along with the crop yield itself, must be monitored. At present, measurement of soil (texture, nutrient concentrations, pH etc.) and crop (nutrient concentrations, disease etc.) factors remains reliant on systematic manual sampling and analysis in the laboratory. Research is under way worldwide into real-time analytical soil sensors that will eventually automate soil and crop sampling and analysis procedures in the field. The use of surrogate information (colour and temperature variation in soil and crop) gathered by remote sensing can also be used.

### 5.1 Real-time monitoring systems

Real-time monitoring systems are an essential component of any PA system. These systems predominantly measure variability in crop yield and quality. The spatial analysis and evaluation of crop production management at a within-field level is provided through crop yield monitoring and mapping.

Real-time yield monitors have been developed for grain, cotton, horticultural and forage crops and are designed to record the harvested portion of a crop. Grain yield monitors were released commercially in the mid-1990s and have been a standard attachment to 90% of harvesting machines sold in Australia since 2000.

A yield monitor determines and records yield data by measuring the mass or volume of a harvested crop per unit area on-the-go with little or no disruption to the harvesting operation. When linked to GPS, geo-referenced yield maps can be created that graphically illustrate crop yield variability.

The essential components of a yield monitoring system are a mass flow sensor, ground speed sensor, yield monitor/display, DGPS receiver and a data logger. Data is recorded on the data logger from the sensors and geo-referenced with positional data from the DGPS receiver.

Yield maps are a very important piece of information. However, yield maps are not the only types of maps that can be produced using GPS technology and real-time monitoring systems. Theoretically, any variable for which a sensor can be built can be mapped. This may include sugar content, harvester performance and monitoring (speed, cutting time, cane loss, cane supply quality, ground job, area harvested etc.), soil characteristics (moisture, compaction), weed, disease and pest populations etc.

### 5.2 Cane yield monitoring

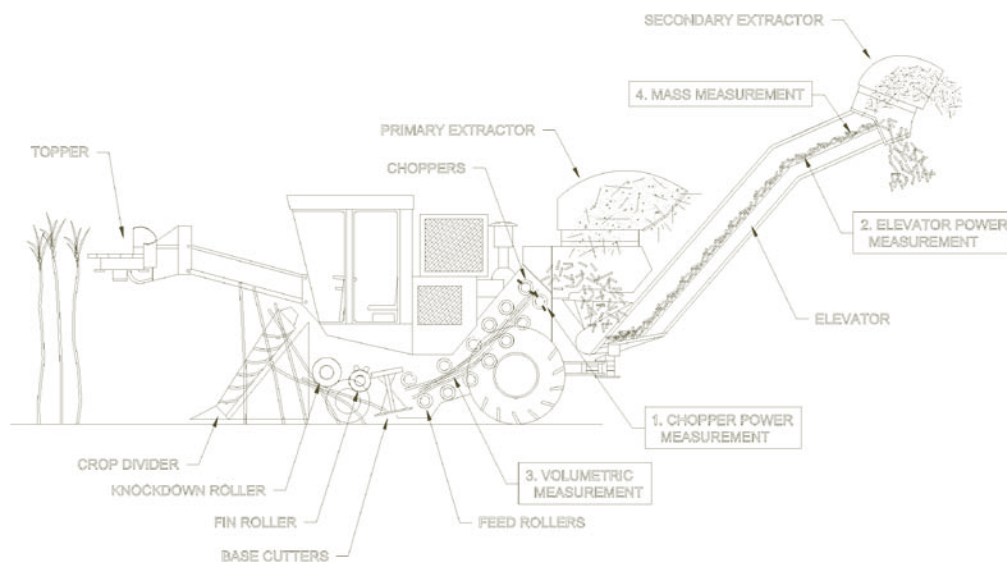
The basic technology is available for yield monitoring of sugar cane with the exception of the mass flow sensor (Cox, 2002). Much research has been undertaken on the development of a yield monitor for sugarcane. Several developers have indicated they are very close to delivering a system; however, there still remains no commercially available yield monitor.

## Investing in Sugarcane Industry Innovation

Most of the actual developments try to measure cane yield using one of four techniques defined by Cox (2002) as:

- chopper power measurement - uses the hydraulic power required to chop the sugar cane into billets as an indicator of the mass flow rate;
- elevator power measurement - uses the hydraulic power required to elevate the billeted sugar cane into the 'haul-out' vehicle as an indicator of the mass flow rate;
- volumetric measurement - uses the separation distance between the feed rollers of the harvester feed train as a volumetric indicator of the mass flow rate; or
- mass measurement - involves weighing the cane flow through the elevator of the harvester as it passes over a weighing platform defined as the 'weigh pad'.

Cox (2002) evaluated the four techniques simultaneously by placing various sensors on a single harvester and comparing the sensor outputs with the mass flow rate as measured by a weigh truck. The locations of sensors for each of these techniques on the harvester are shown in Figure 3. Cox also found that each technique had potential, but also inherent problems and limitations.



**Figure 3. The location of the four mass flow sensing techniques throughout the sugarcane harvester (Cox, 2002)**

Recent developments in harvester monitoring and performance have seen the mounting on harvesters of various configurations, of systems incorporating sensors to allow the status of the machine to be determined. These systems typically monitor elevator on/off and engine on/off and incorporate GPS to allow tracking and harvester 'state' to be defined. Recently these systems have been expanded to include additional sensors to monitor harvester components including chopper pressure, feed train roller pressure, feed train roller opening and elevator pressure. The specific purpose of the additional sensors is to collect data to allow estimation of harvest yield.



### 5.2.1 Chopper power measurement

Cox (2002) found chopper power measurement to be quite erratic and noisy, with spikes at a relatively high frequency. A number of factors that influenced chopper power were identified and shown to be a significant source of error in calibration curves.

In addition, harvesting conditions (green v burnt), crop factors (hardness etc.) were also found to vary the requirements for chopping power. The chopper power technique would therefore need to be calibrated for each different condition to be useful for yield monitoring purposes. That is, changes in crop variety, green/burnt cane and even crop age would have to be calibrated. Every time a new field is entered the sensor would have to be recalibrated. This is standard practice for grain yield monitors (Cox, 2002).

One advantage of the chopper pressure approach is that they could provide a cheap and easy way for growers to collect data to generate yield maps. However, there is still a lot of work to do to make the system more accurate. The limitation of the recent attempts at this approach is that chopper hydraulic pressure and not power is used.

### 5.2.2 Elevator power measurement

Cox (2002) evaluated the potential of elevator power as a mass flow sensor. He found the elevator pressure/power traces to have similar features to the chopper power measurement with high spikes at a frequency similar to the rotational speed of the hydraulic motors and lower frequency spikes due largely to the variation in sugar cane flow rate. However, these fluctuations are somewhat smoother than those for the chopper power measurements.

A high variation in the free running power was observed and attributed to the force required to overcome friction from the multitude of rotating and sliding elements. This force can change significantly due to changes in the components of the elevator such as the elevator chain and foreign matter build up.

Cox found a large degree of scatter in the calibration data and therefore a large amount of error, but it was slightly better than that for chopper power. If the variation in the free running power of this technique could be reduced or monitored, the accuracy could improve dramatically.

### 5.2.3 Volumetric measurement

A substantial improvement on the power measurement techniques was found for this simple technique. Although the method is volumetric, the benefit of this technique is its simplicity.

Cox (2002) found that irregular feeding of sugar cane through the harvester influenced feed roller separation. This finding was supported by Davis and Norris (2000, 2002) who quantified the effects of harvester feeding ability in green cane.

The volumetric technique has a stable baseline but the gradient of the calibration line is significantly affected by crop conditions. If it is to be used to sense mass flow rate then factors affecting its accuracy, such as cane density variation and feed rate variations, need to be examined.

The enormous variability of the cane cropping environment (such as variety, class etc.) and machine operational factors (such as chopper speed, blade wear, chain wear, mud build up on elevators, inconsistent feeding, extractor performance etc.) makes the accurate calibration of indirect measurements such as chopper and elevator power and feed roller displacement very difficult. The most recent attempts at using these methods for yield estimation only utilise hydraulic pressures, not power. Therefore, at best, these methods only offer a relative measurement of yield across a block and ideally should be used in combination with each other and pressure measurement extended to power. The advantage of these methods lies in their sensor simplicity, ease of installation and cost. Work is ongoing to evaluate the various measurements against actual yield. However, it is the belief of the authors that there is still a lot of work to do to make these systems more accurate.

#### 5.2.4 Mass measurement (weigh pad)

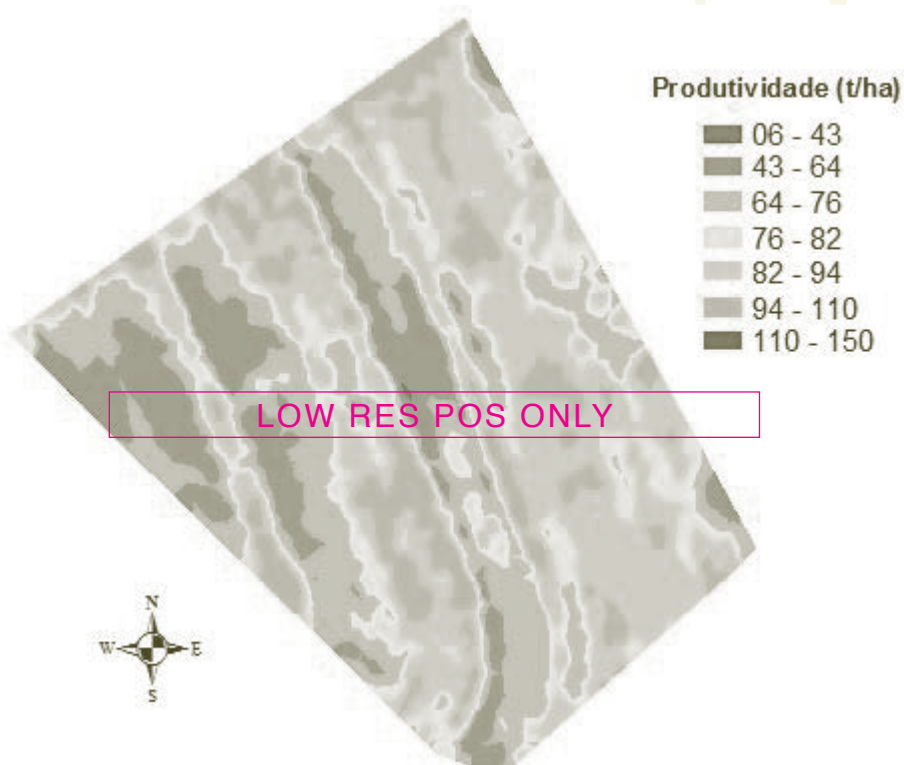
A weighing technique, known as the 'weigh pad', offered the most potential for improvement and potential to accurately measure the mass flow rate with a single calibration under all conditions when compared to the indirect mass flow rate methods (Figure 4; Cox, 2002).



**Figure 4. Topside view of weigh pad installed in a Cameco harvester (Cox, 2002)**

Cane yield monitoring systems based on weigh pads have been developed and trialed in several countries (Cox, 2002; Benjamin, 1998; Benjamin *et al.*, 2001; Pagnano and Magalhaes, 2001). A yield map produced in Brazil is shown in Figure 5.





**Figure 5. Sugar cane yield map of 43ha area in Brazil (Cerri and Magalhaes, 2005)**

Direct measurement offers the most accurate method for estimation of cane yield as this method is independent of cropping environment and machine component operational parameters. It can provide an absolute measurement of yield spatially across a block with a single calibration under all conditions. However, this system is not without its limitations, including build up of debris around the weighing platform, installation and cost. Advances in technology and thinking into the design and layout of the weighing platform system will lead to the commercial release of robust and accurate systems based on this technology. This presents an opportunity to the industry.

For sugarcane production, the full benefits of PA are severely constrained by the lack of an accurate and reliable spatial yield monitoring solution. Within the industry a number of attempts have been made to monitor yield variation across a block, ranging from discrete yield monitoring systems based on mass measurement systems to the current focus of monitoring chopper pressure, feed train roller displacement and elevator power. The advantages and limitations of these methods have been previously discussed.

## Investing in Sugarcane Industry Innovation

Accurate yield monitoring will close the PA cycle to enable the use of precision farming tools and analysis that allow spatially based farming management and associated variable rate applications. However, yield maps are not knowledge. If these maps are to be of any real value, data generated from them must be incorporated into the decision making, analysis, and overall planning process of the cane growing operation. The value of a yield map is in its interpretation.

### 5.3 Sugar yield monitoring

Traditionally, the grower conducts static measurements of sugar concentration in the field with a handheld refractometer. More accurate measurements are later conducted at the mill. To date there has not been a method developed to reliably measure sugar concentration in real time that may be applied to the harvesting process.

McCarthy and Billingsley (2002) developed a robust low cost refractometer together with signal conditioning algorithms to enable sucrose content to be measured during harvesting. To date this technology is not commercially available.

In addition to sugar yield monitoring, there are studies aimed at developing a reliable in-field technique for measuring sugar juice on trash (Sichter *et al.*, 2005). If proved to be reliable, the potential of this technique for monitoring sugar yield in real-time should also be investigated.

Further research on technologies to facilitate the monitoring of sugar yield in real-time presents opportunities for the industry as the implementation of PA at a block scale can provide information for differential management of the harvest process (i.e. harvesting best practice) to increase industry profitability and minimise the risk of adverse environmental impacts.

### 5.4 Harvester performance monitoring

A major opportunity for the sugar industry is to significantly increase industry profitability without increasing capital investment by reducing field losses of cane and juice during mechanical harvesting. The loss of juice and cane fragments with gathering, basecutting, chopping and extraneous matter extraction through primary and secondary fans is largely invisible. Adopting harvesting best practice (HBP) with attention to extractor fan speed, pour rate, feed train and chopper speed synchronisation, basecutter height control and row profile, row length and cane presentation, not only increases the amount of cane delivered to mills but also reduces the potential for environmental impacts associated with sugar juice entering waterways and causing de-oxygenation (Jones, 2004).

Various technologies have been researched and developed to provide machine performance feedback or automate machine operations to favour higher harvesting efficiency and higher sugar recovery. These include automatic basecutter height control, synchronising component speed with ground speed and cane loss monitoring. The aim of these technologies is to optimise on-the-go the interaction between machine components and the crop to transfer as much of the sugar standing in the field to the mill whilst minimising extraneous matter (EM) and dirt in the supply. Therefore, these technologies are an important component of a PA system in that they provide information for differential management of the harvest process (i.e. HBP) to increase industry profitability and minimise the risk of adverse environmental impacts.



Numerous studies have illustrated the impact of dirt in the cane supply (Clarke *et al.*, 1988; Steindl, 1998; Wright, 2003). Kroes and Forsell (1999) found that while some of the dirt in the cane supply was attached to the cane stalks, tops and leaves, most of the dirt was loose or bound to roots. The loose dirt results from the crop divider shoes, knockdown roller position and base cutter depth. The latter has a significant effect on dirt in the cane supply (Henkel *et al.*, 1979).

The development of automatic basecutter height control systems has occurred with systems that rely on interaction with the soil to gauge basecutter height, non-soil contact or ground height sensing methods or a combination of both. Recent developments have been based on monitoring basecutter hydraulic pressure. The advantage of this approach is that it is relatively simple and robust. Automatic basecutter height controllers are commercially available.

#### 5.4.1 Cane loss monitors

There have been several attempts to measure cane loss through the extractor system. Dick and Grevis-James (1992) developed a cane loss monitor based on the principle that the impact of billets on the primary extractor hood could be detected clearly and distinguished from other noise sources. McCarthy *et al.* (2002) measured the vibrations produced by billet impacts on the blades of the primary extractor fan. Thus, the fan blades replaced the extractor hood as the sensor location to detect cane billets passing through the extractor with the resulting output of hit counts providing a relative index of cane loss.

Whiteing *et al.*, (2004) compared the performance of the hood and fan mounted sensors and showed that both systems predicted mass material flow and therefore cane loss through the extractor fan very well. This was because both sensors gave a good measurement of total cane and trash flow through the primary extractor and cane loss is directly related to this total material flow.

No commercial product is available to provide feedback to the operator on material flow or cane loss through the extractor.

#### 5.4.2 Harvester monitoring systems

In 1997, a state-wide research program funded by SRDC commenced. It was aimed at facilitating the adoption of harvesting best practice by demonstrating harvesting and farming practices that improve profitability and the financial impact on growers and harvesters. As part of this research, Agnew *et al.* (2002) fitted a number of harvesters with logging equipment to measure and record machine performance once during every minute of operation. This was the first attempt at combining technology to comprehensively monitor machine performance and resulted in the BSES Ltd publishing 'The *Harvesting Best Practice Manual for Chopper-Extractor Harvesters*' (Sandell and Agnew, 2002). This manual described harvester machine factors that affect the efficiency of cane harvesting and the final recovery of sugar. Subsequently SRDC released a review of sugar cane harvesting practices and options for improvement in 2004. This also incorporated a number of economic analyses of harvesting best practice scenarios (Jones, 2004).

Further development and application of machine performance monitoring has occurred as a result of subsequent work on harvesting pricing structures (Willcox *et al.*, 2005) and integrating harvest and transport (Markley *et al.*, 2003, 2006; Crossley and Dines, 2003, 2004).

## Investing in Sugarcane Industry Innovation

A limitation to the adoption of electronic harvester monitoring units has been the unavailability of commercial 'off-the-shelf' systems for harvesters. Previous systems were either adapted from systems in use in other industries or purpose built from individual commercial products (i.e. logger, sensors, GPS, modem etc.). However, a number of commercial off-the-shelf systems are now available and are cost effective.

Current developments are extending these to expert systems that will provide advice on operating within HBP guidelines. The system will read data from the sensors fitted on a harvester, interpret real time data using HBP logic to guide the operator, provide options to display data collected on a screen and collate data to give HBP index reports. For example this system may suggest ranges of reasonable fan speeds based on ground speed and yield estimate.

All commercially available harvester performance systems can be configured to individual monitoring requirements. The driving force to implement this technology will be the production of harvester performance reports that can be used to track and monitor the efficiencies of harvesters for differential harvest pricing and to monitor key performance indicators for growers and contractors.

### 5.4.3 Harvest monitoring

Emerging technologies are currently being implemented to enhance operations through an integrated approach to establishing communication links from the relevant databases to harvesters and locomotives automatically. Integrated harvest and transport management systems offer the sugar industry significant improvements over existing harvest and transport operations. Technologies have already been implemented in a number of mill areas such as Mackay Sugar (Markley *et al.*, 2006) and NSW Sugar milling co-operative (Crossley and Dines, 2004) to enhance operations and add value to harvest and transport management.

## 5.5 Proximal sensing systems

Most data collected for PA, with the exception of yield monitoring and remote sensing, is performed by manual sampling and laboratory analysis. The cost and time required for traditional soil sampling and chemical analysis are much too high for economic use in PA (Viscarra Rossel and McBratney, 1988a). This has led to the widespread interest in the development of real-time or near real-time sensing systems.

Ground-based sensors offer the opportunity to automate the collection of crop, soil and weed data at a spatial resolution that is not economically feasible with manual sampling methods. Increasing the intensity of sampling will result in a more accurate characterisation of the within-field variability. A number of sensors that provide real-time geo-referenced data have been developed or are in the progress of being developed for PA purposes.

### 5.5.1 Soil sensors

A major use of soil sensors is to provide spatially dense data layers at relatively low cost. This information can be used in combination with other data (i.e. soil sampling, crop scouting, yield maps, digital elevation models, remote sensing) to (i) divide a field or landscape into smaller sub-units (e.g. management zones), (ii) guide soil sampling, or (iii) improve the precision of maps of primary attributes if those are correlated with data layers obtained from sensors.





A number of methods that rely on spectroscopic principles or direct sensing of soil extracts are available. However, implementation of the technology for real-time soil measurement is hindered by the need for a rapid specimen collection and difficulties in extracting the soil solution. Hence, for real-time measurement, several geophysical methods can be used to determine the ease with which an electrical current can be made to pass through soil and deeper regolith. These methods rely on either electromagnetic induction or resistivity and they can be used to characterise large volumes of soil (with depths from less than 1 m to several hundred metres), although the extent of measurement is often not specified with any great precision (McKenzie *et al.*, 2003).

Electromagnetic induction survey, or EM survey as it is widely known, has become very popular in Australia, particularly to support PA. This technique has also been used extensively within the sugar industry and, when coupled with DGPS, provides a rapid mapping tool.

Soil electrical conductivity (EC) mapping quickly and accurately characterises soil differences within a cropping paddock. EC measurements are influenced by soil properties such as texture, cation exchange capacity, drainage conditions, organic matter, salinity and subsoil characteristics. Variation in measured soil electrical conductivity is mainly caused by variation in salinity, soil texture, soil moisture, and organic matter content (Corwin and Lesch, 2003). The most common use of soil EC survey maps generated by these instruments remains the identification of soil sampling points for stratified sampling. The data are used either alone or in conjunction with yield, elevation and remotely-sensed images to pin-point areas of difference. EC survey maps have also been used in the grains industry to identify field areas with high salt load within the rooting zone, variation in clay content and estimated plant available water content, and areas having soil moisture remaining at harvest (possibly indicative of subsoil constraints) (O'Leary, 2006). Electromagnetic soil survey techniques are becoming more widely used in viticulture for delineating spatial variations in soil type and/or texture in established vineyards (Bramley, 2001; Lamb, 2005) and have also been utilised in the sugar industry by a number of researchers investigating soil sodicity and salinity (Kingston, 1985; Nelson and Ham, 1998; Nelson, 2001).

The resistivity of soil (i.e. the inverse of conductivity) can be measured by passing a voltage to electrodes placed in the soil. The technique has been used for a long time in geophysics, and various configurations of electrodes can be used to control the volume and depth of measurement. Resistivity measurements using conventional equipment are slower than electromagnetic induction and physical interpretation of results can be complex. The soil factors noted previously affect resistivity measurements in the same way.

Several commercial systems are available to measure the resistivity of soil. One system, the Veris 3100, is currently in use within the sugar industry (Tony Crowley, pers. comm.) It is used predominantly in the Prosperpine, Mackay and Sarina regions, however it can be towed behind a vehicle and has been used in the Bundaberg area (Clinton Scott, pers. comm.). It can be used to gain an understanding of soil variation at high spatial resolution and to assist with practical agronomic decision making. When used appropriately (i.e. with thorough ground truthing of measured soil properties), the method is invaluable for mapping selected soil properties. Figure 6 shows a map of soil EC (0-90 cm) obtained with a Veris 3100 instrument.



**Figure 6. A map of soil EC (0-90 cm) obtained with a Veris 3100 instrument at Baralaba, Central Queensland (Kelly and McDonald, 2005)**

Ground-penetrating radar (GPR) is a subsurface imaging technique that uses the reflection of very short pulses of electromagnetic energy from dielectric discontinuities in the ground to form an image of the subsurface. Although it has been applied successfully to many field situations, GPR has not been widely used because the methodology and instrumentation are still in the research and development phase. Methods of measuring moisture profiles have been published (Davis and Annan, 2002; Huisman *et al.*, 2003; McKenzie *et al.*, 2003). However, we are not aware of any practical implementations or commercial instruments based on these techniques.

Ion-selective field effect transistors (ISFETs) are integrated circuits with ion-selective membranes applied to the gate of the sensor. ISFETs can be used to measure concentrations of the relevant ions in a soil solution. These include nitrate (Birrell and Hummel, 2001), pH, lime requirement (Viscarra Rossel and McBratney, 1998b), calcium, potassium, sodium and ammonium (Birrell and Hummel, 2001). The major challenge for implementation of ISFET technology is construction of robust equipment for high-speed specimen collection and solution extraction. Research has been conducted into the applicability of flat-surface combination ion selective electrodes to measure soil properties (particularly pH) on moist soil samples directly (Adamchuk *et al.*, 2003). Progress has been made but considerable refinement of this technology is needed, particularly to deal with difficult Australian soils (e.g. hard-setting soils, sodic clays, non-wetting sands) (McKenzie *et al.*, 2003).



### 5.5.2 Crop sensors

As the sugar industry moves towards minimum tillage farming systems to reduce the cost of farming it is becoming increasingly dependent on herbicides. Precision spray technology that targets specific weeds has the potential to revolutionise weed management by maximising production and reducing herbicide usage while reinforcing minimum tillage concepts.

Sensors under development vary from simple colour detectors to complex machine vision systems, whose ultimate goal is to use colour, shape and texture features of plant material to separate weeds and crops as well as to identify populations of different weed species. These sensors are typically mounted on fixed-boom sprayers

A number of commercial companies have developed technologies capable of distinguishing green plants from bare ground. The Weedseeker® uses an optical sensor to measure infrared and near infrared reflectance and the presence of chlorophyll and is a self contained unit (Figure 7). It can detect any green plant but it cannot distinguish between a green target (weeds) and green plant (crops). Essentially when a green plant is detected a solenoid is activated that turns the spray nozzle on and off.



Figure 7. Weedseeker® sensor (Source: Ntech Industries)

Automated detect and spray equipment used for the eradication of weeds has never been utilised in the sugar industry. No existing technology can reliably distinguish green weeds from green plants (sugarcane) based on image analysis and success in this area will represent a major technical breakthrough.

Spray the weeds not the paddock technology offers the sugar industry potential reductions in herbicide usage in turn leading to a greater range of herbicide options by allowing for more expensive herbicide products to be considered. In addition, combined with GPS, the technology will also be able to map weed infestation across a field.

## Investing in Sugarcane Industry Innovation

Much research has been conducted to develop optical sensors that measure reflectance or absorption of light by leaves or the entire crop canopy to facilitate adjustments of crop management during growth. On-the-go sensing of crop reflectance at wavelengths that are sensitive to biomass and/or leaf greenness has received much recent attention, particularly within the context of real-time, in-season nitrogen (N) management (Raun *et al.*, 2002; Schmidhalter *et al.*, 2003 in Dobermann *et al.*, 2004). Current technologies vary in terms of types of sensors used, sensor configurations (number, height, angle, etc.), spectral and spatial resolution, wavelength indices used for interpretation, and decision algorithms.

A number of real-time crop sensing and N application systems have been developed with current application in broadacre cereal cropping, cotton, vineyards, pastures and orchards. These systems are based on corrective N management concepts in which vegetation indices for estimating crop biomass and N status is identified and translated into decisions for N fertiliser needs (Schroeder *et al.*, 2000).

Whilst weed sensors offer opportunities for the sugar industry, the application of plant sensors in particular N-sensors in on-the-go technology is limited due to the current temporal fertilising applications which occur at planting, and approximately 12 weeks after planting and ratooning.

### 5.6 Discrete soil and plant sampling

Discrete soil and plant sampling refers to the manual sampling of variables within a field using either a grid-based or statistically based random sampling strategy. Discrete sampling may be undertaken using one of three methods; traditional composite, grid or directed sampling.

Traditional composite sampling has generally been implemented by the sugar industry in the past, especially for soil and plant nutrient testing and pest and disease monitoring. In essence, the aim of such a sampling regime is to obtain an estimate of an attribute to represent the whole field. A significant shortcoming of composite sampling is that it does not provide any indication on the extent to which variability is occurring within a field. Hence, such an approach to sampling has some serious limitations for uniform crop management and is unsuitable for PA as it does not provide any measure of the spatial variability that is present in the field.

A grid sampling system uses a systematic method to select sampling points but assumes there is no logical reason in the way patterns may vary within a field. The rigid shape of the grid means that sample density does not depend on actual variability within the field. Grid schemes are convenient to locate and can be easily inputted into a GIS. Grid sampling may be the best option where there is little or no prior knowledge of the within-field variability (Stewart *et al.*, 2005).

Directed or stratified sampling is based on spatial patterns defined by some prior knowledge or observation from a field. There are many data sources which can be utilised for directed sampling purposes. The most efficient sampling design involves the incorporation of all data layers that can provide information on the local spatial variability of an attribute in question. Aerial photographs, satellite imagery, yield monitor maps, soil survey information, digital elevation models and grower experience can all be useful in directed sampling schemes for measuring soil and crop production variation (Stewart *et al.*, 2005).



Nutrient management and fertiliser inputs for sugarcane production in Australia are one example of a paradigm shift from a set of generalised recommendations across the industry towards sets of soil-specific nutrient management guidelines for use at district level and ultimately facilitating the use of nutrient management plans at block and farm scales (Schroeder *et al.*, 2006). This includes the concept of 'whole-of-crop-cycle' fertiliser recommendations, using both soil and leaf analysis, which is being promoted within the industry.

Nitrogen management is also improving as new farming systems like controlled traffic, minimum till and legume fallow are adopted along with other sampling techniques such as leaf analysis. This has already led to a reduction in fertiliser inputs of 20% over the last 6-7 years because of better soil health properties (Wrigley and Moore, 2006).

This type of approach will not only enable more informed decision making on-farm and the identification of blocks requiring special management but will also help to demonstrate that growers in the industry are being environmentally responsible with respect to their fertiliser management. In addition the location of the Australian sugar industry along the east coast of Queensland adjacent to the Great Barrier Reef also places additional pressures on the industry to demonstrate that it is adopting best management practices that ensure that soil fertility is sustained and that any nutrient wastage is effectively eliminated.

Soil-specific nutrient management offers a significant opportunity to the sugar industry. As such, the industry is well on its way to developing the capability to employ this approach to fertiliser management at a regional scale. The next challenge will be the extension of this framework to a farm/block scale. However, with the level of GPS technology and GIS systems already in use within the industry this may not be that difficult.

### 5.7 Crop modelling

Crop simulation models or even more complex soil-landscape-crop simulation models are increasingly used in PA research, but their complexity has often hampered the use of modelling in making practical decisions on input use (Dobermann *et al.*, 2004).

The key Australian sugarcane cropping systems model APSIM-Sugarcane (Keating *et al.*, 1999; Lisson *et al.*, 2000; Thorburn *et al.*, 2001b) has evolved and emerged as one of the more powerful modelling tools currently available to the sugar industry. A key feature of APSIM, which distinguishes it from many vegetation specific models, is the central position of the soil rather than the vegetation.

Crop modeling should also play a major role in improving water and nitrogen management by more quantitative prediction of crop yield, water and N needs during the growing season. APSIM-Sugarcane has been and is being used as the essential tool in a wide range of industry studies (Inman-Bamber *et al.*, 1999, 2000, 2002, 2005, 2006; Brennan *et al.*, 1999; Lisson *et al.*, 2003; Keating *et al.*, 1997; Gardner *et al.*, 2000; Hurst *et al.*, 2003; Thorburn *et al.*, 2000, 2001c, 2003a, b, 2004, 2006 a, b; Park *et al.*, 2003).

## Investing in Sugarcane Industry Innovation

There are also opportunities for using simplified crop models in site-specific management, particularly with regard to making nitrogen decisions before planting and during early growth.

The challenge for the industry is to make these models robust enough for practical decision-making, limit the amount of input variables needed, minimise the need for local model calibration, and use models for exploring management options *a priori* as well as in real-time during the growing season.

For example, models describing the optimal N concentrations with increasing crop biomass for a certain yield target could be used in conjunction with actual weather data and sensed crop reflectance to make quantitative N application decisions on-the-go.

However, if industry is to benefit from information produced from knowledge intensive technologies, it is essential that researchers and industry understand better the technology development process and appropriate adoption pathways.

### 5.8 Climate monitoring

The sugar industry operates under extreme variability in climate. Knowledge of future climate conditions can therefore assist with forward planning for farming, harvesting, milling and marketing operations. There are key decision points within the growing season when a range of tactical decisions, such as nutrient applications, can be made or modified according to seasonal conditions. Stored soil water, rainfall and rainfall distribution are key factors determining yield potential, so weather to date and outlooks for the rest of the season are important factors to consider.

Seasonal forecasting is a rapidly evolving area and considerable advances have been made in recent years, providing farmers with a growing number of seasonal outlooks.

Numerous research projects into seasonal climate forecasts have been undertaken for the sugar industry (Everingham *et al.*, 2002a,b; Antony *et al.*, 2002). Everingham *et al.* (2002b) examined the capability of the 'user-friendly' SOI phase system (Stone *et al.*, 1996) to target climate forecasts for the needs of the industry across different sectors of the value chain and demonstrated several ways in which climate forecasts can be used to plan activities for the growing, harvesting, and marketing sectors of the industry. They concluded that whilst climate forecasts cannot provide certainty about the likely climatic conditions, they can reduce the uncertainty associated with many industry decisions.

Studies on the economic benefit of seasonal climate forecasting for the sugar industry have also been undertaken. For example, Antony *et al.* (2002) assessed the benefits across the farming, harvesting and milling components of the supply chain using a case study with four scenarios of the Herbert region.

Numerous interactions occur between soil, crop and climate, which are often difficult to identify and manage. Management decisions that relate to climate are also made at different times of the year and with different levels of significance for different farming systems. This is why the use of crop simulation models has been identified as essential to integrate and quantify processes and factors that interact across the different dimensions of the production system, the soil, the climate, the crop and its management. Everingham *et al.* (2006) demonstrated the use of three different knowledge intensive technologies (irrigation modelling, nitrogen modelling and climate forecasting) in case studies in the Tully, Plane Creek, Bundaberg and northern NSW regions.



## 5.9 Investment analysis

The first question a grower or harvesting contractor will ask about PA is 'How much will it cost?' This question is somewhat easy to answer as commercial suppliers will be able to supply quotations for enabling technologies. Secondly, 'What benefit can I expect?' is more difficult to answer as PA is not a certain path to profitability, but a management tool that enables better decisions. Better decisions allow better control of the system and could mean a decision that produces an outcome that is more profitable, less risky or of more consistent quality (Cook, 1997).

The key to making money from PA is for growers or harvesting contractors to choose an aspect of the technology that provides rapid and certain benefits across a wide area of their enterprise.

Growers and harvesting contractors now have a good choice of programs at their disposal to assess risks to their business and to identify potential productivity and cost saving initiatives (Wrigley and Moore, 2006). These can be utilised to assess whether or not investment in PA is feasible for their enterprise.

## 6. Attribute Mapping

Once data on spatial variability has been collected, it is necessary to capture, store (manage), integrate and analyse the data. Advancements in computing technologies have led to the development of software that is capable of undertaking these tasks. These are called spatial information systems. Using spatial information system software it is possible to integrate or link data and information that would otherwise be difficult to associate. For example, imagery from satellites, aerial photography, digital elevation and electronic tabular data can be analysed and new variables derived.

Although a spatial information system is often thought of as a single piece of software, it should be considered in broader terms as part of an information management system. One of the major strengths of a spatial information system is its ability to link numerous databases of information within a system whereby it is possible to visualise and view data in a spatial context.

The power of a spatial information system lies in its ability to relate different layers of information covering the same location and be able to derive conclusions about the spatial relationship. The majority of data has some form of geographic component and can therefore be referenced to geographical locations such as points, lines or areas. Hence, these systems are known as geographic information systems (GIS).

### 6.1 Geographic information systems

Central to the GIS system is the database, which is comprised of two elements; a spatial database that records the location and an attribute database that describes the characteristics or qualities at each of the locations. Each measured variable from a field that is geo-referenced becomes a unique data layer that can be overlaid and visually and mathematically correlated or interpreted. For example, a GIS for precision farming may contain information on cane yield, topography, soil nutrient concentrations and soil textural properties at the same point for numerous locations throughout a field (Stewart *et al.*, 2005).

GIS systems for agriculture are typically various farm mapping software packages. For a PA application, the uses for potential GIS systems are enormous. However, they come at the cost of time, money and energy in training to be able to use the software. These resources are something that in most cases an average producer is unable to spare. However, with systems in place, consultants with training and expertise in using the software are shouldering the initial costs of the software and are able to satisfy grower's requirements. The advent of Web-based GIS in the near future will give a grower the potential to effectively map his property using a differential GPS receiver, send the data to a consultant and, within hours, log on from home to the consultant's Web-based GIS software and access a GIS map of his property with simple analysis tools, without the costs, or time and energy in learning to use the software.

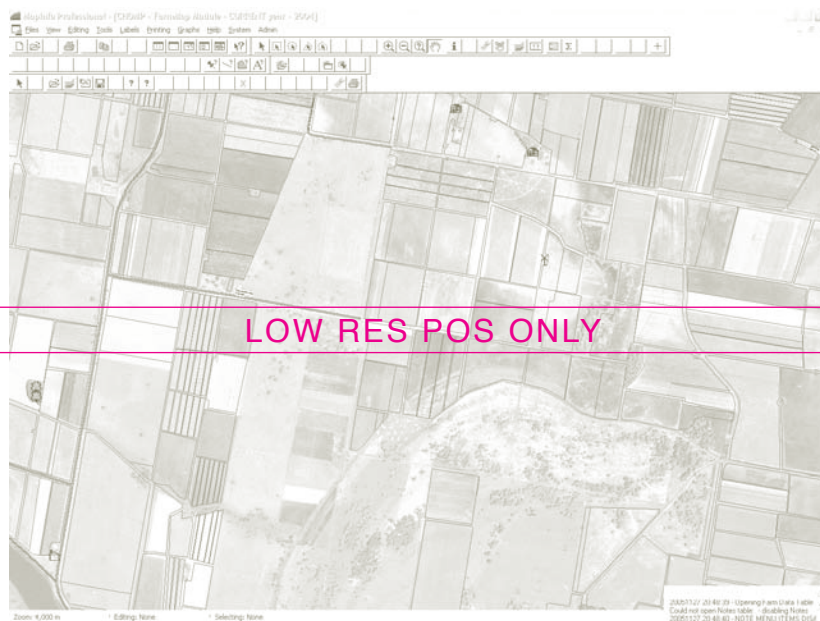




The sugar industry is the only agricultural industry that, through its operational framework, collects large resources of base mapping data about the crop. Data is collected by mills for their business of crop estimation and harvest planning. This information is valuable for other purposes including research, optimisation studies and disease response. Hence a number of customised GIS are utilised in the sugar industry. These include the following examples.

### 6.1.1 FarmMap

FarmMap is a customised GIS product developed specifically for the sugar industry to centrally manage farm mapping and data. FarmMap is designed to store attributes at the farm and block level such as owners, variety, class, estimates and area. It is simple to use and is generally operated by the cane inspectors who have little formal GIS training. The FarmMap system is now used by 22 out of the 27 mills in Australia, including mills from Mackay Sugar, Bundaberg Sugar, Sunshine Sugar, CSR Burdekin Mills and Sugar North. The main purpose of FarmMap is to provide cane inspectors with customised tools to map farms, maintain data about those farms and produce good quality maps (Figure 8). FarmMap is now extending to include harvest recording, harvest tracking, activity reporting, productivity analysis, telemetry and transport logistics.



**Figure 8. An example of block maps from FarmMap (Crossley, 2006)**

### **6.1.2 CHOMP**

Centralised Harvest Operations Management Plan (CHOMP) is a customised GIS that enables cane-inspectors to maintain harvest progress records from a map interface. The system uses harvester tracking data interpreted by Agtrix and satellite interpretation of cut areas or traditional consignment data to define cut areas. It then associates deliveries with the areas they came from. A wide range of tools are available to manually edit this data and look for consignment errors. The system will also integrate crop data such as variety, production data generated from CHOMP and land attributes such as soils to create a database suited to detailed spatial analysis of productivity. CHOMP also serves to link weighbridge and laboratory data to the spatial data, creating thematic maps depicting spatial change in yield, CCS and other analysed cane data.

### **6.1.3 FRANK**

A harvester tracking and productivity reporting system.

### **6.1.4 Land and water management plans**

A system to generate maps for Land and Water Use Management Plans (LWMP) for the Bundaberg region in 2003 was developed by AgTrix. This was done using RWUEI Stage 1 funding and was aimed at supporting a series of workshops that would guide growers through the process of preparing their own LWMP. The concept was that growers would be provided with plans of their farms with the best available natural resource information, and these would be used as a base to mark their own required infrastructure onto these maps.

### **6.1.5 Farm productivity analysis**

Productivity reporting systems that include spatial representations of fields as part of the data provide the ability to analyse performance through time through spatial analysis. Agtrix has developed a system for the Bundaberg area to allow analysis of farm productivity. This system generates a spatial layer of base productivity by intersecting spatial data from blocks (FarmMap), harvested areas and productivity (CHOMP) and land attributes (soils, climate). This system provides a set of tools to analyse relationships and benchmark farm production. A map is generated automatically for each farm showing yield spatially and soil type. A table accompanies the map to illustrate the performance of the grower against others with the same variety, class and soil type. This system can display a graph of the influence of two attributes on production.



## 7. Decision support systems

Information about variability within the field doesn't solve any problems unless there is some kind of decision support system (DSS) to make site-specific recommendations. Therefore, DSSs are an important component of the PA management system and will become the main link to convert the spatial data collected into detailed management recommendations at the grower level.

Decision support combines traditional management skills with PA tools to help growers make the best management choices or 'prescriptions' for their crop production system. Their role is to integrate data sources with expert knowledge and decision models to aid in making strategic decisions for both the short- and long-term. Basically they operate by combining a crop model, which contains technical knowledge on crop growth, with economic and environmental considerations. Ideally a DSS will provide the user with a number of possible courses of action in response to some hypothetical scenarios.

Once enough spatial data has been collected to determine a management size, the tools available for environmental modelling can then be applied to estimate the amount of a crop production input or the affects of alternate management strategies on these different regions within the field. The integration of these models into a GIS environment to permit their use at the within-field scale will prove invaluable in the future.

### 7.1 *Integrated harvesting and transport management*

A number of sugar mills have, or are currently developing integrated cane harvest management systems to facilitate marketing and logistics, planning mill start dates, cane transport arrangements, harvest groups base daily loadings and harvesting schedules. These systems use modern computer and communication technologies to integrate data and systems and to develop tools that assist individual decision-making as well as support whole-of-industry management strategies. Mackay Sugar Cooperative Association Ltd (Markley *et al.*, 2003, 2006) and NSW Sugar Milling Cooperative (Crossley and Dines, 2004) have developed successful systems.

## 8. Differential action

Much PA research is involved with monitoring and information gathering. However, it is important that the ultimate goal is to be able to implement site-specific management using variable rate application. Spatial variability may be dealt with through operations such as planting rate, tillage, fertiliser, soil ameliorants, irrigation, herbicide and pesticide application etc. which may be varied in real-time across a field. Using the DSS, a treatment map can be developed to adjust rate control mechanisms in the field. Yield monitoring at harvest can be used to assess applied treatment effects and refine yield potential goals for the subsequent season.

### 8.1 Variable rate technology

Variable rate technology (VRT) allows rates of inputs, for example fertiliser, irrigation water, seed, chemical, soil ameliorants and operations such as tillage, to be varied within a paddock. The concept of the site-specific application of crop production inputs is dependent on machinery with the capacity to accurately vary application rates within a field.

Site-specific management is not a new concept. Many growers have been selectively managing certain areas within areas for many years. Developments in DGPS and VRT give growers the ability to implement site-specific management in a much more precise manner and without the need for extra in-field work.

Different technical solutions have enabled manufacturers to refine existing machinery and develop new machinery so that seed, fertiliser, agricultural chemicals, soil ameliorants, irrigation water and tillage can all now be applied variably within-field utilising more complex automated systems. The rate is changed on the basis of either a preset map (determined by the user from the integration of yield, soil and plant data) or information gathered by sensors as the machine moves through the field.

The greatest benefits of VRT will be seen in blocks with high variability in soil fertility, water management, weed growth or soil compaction. Instead of applying a single rate of input throughout an entire paddock, the input rate can be adjusted to match the potential yield of the management zone or to tackle infestations of weeds or pests.

The latest generation of implements are being developed with 'black box machine controllers' that enable the implement to operate as a self managed unit able to receive rate instructions and react immediately to deliver specific rates as directed by a cab mounted 'task computer'.

Variable irrigation control has been attempted using sprinklers on self-propelled irrigators, lateral move, centre pivot irrigators or trickle irrigation. These systems can be modified to apply varying amounts of water and liquid fertiliser (Perry *et al.*, 2003).



### **8.1.1 Sensor-based VRT**

Sensor-based VRT utilises real-time sensors to collect data, such as soil properties or crop characteristics, on-the-go. This information is processed and used to vary the amount of input applied. This technology does not rely on GPS or require data gathering and analysis to provide detailed maps or extensive decision making prior to application (Williams, 1997).

Sensor-based VRT can be utilised with or without precision farming practices with similar benefits. Sensor-based VRT tends to be highly specific, one piece of equipment will only apply pesticides and another will be needed to apply fertiliser. The specific nature of the equipment is driven by the different sensors needed and the different processing required by each input. At the current level of technology, sensor-based VRT is only available in complete units, so while it is simpler to purchase, each unit will only perform one function.

### **8.1.2 Map-based VRT**

Map-based VRT involves creating application maps that describe the varying amounts of input needed throughout the paddock. Application maps are produced from yield, topography, soil, nutrient or weed maps which have been 'ground-truthed' to give specific details of inputs required throughout a paddock. The application maps are interpreted by small computers called controllers that increase or decrease the amount of input according to the map.

Map-based VRT allows farmers to make decisions based on the detailed maps and knowledge of the paddocks before they are in the field. Map-based VRT gives farmers precise control over how much of a given input is applied to specific areas within any paddocks. However, it does involve collecting and processing certain amounts of data, greater amounts of data collected over longer periods of time can create more accurate maps.

Map-based VRT will require more components than sensor-based VRT. However, these components are available commercially and can be used for multiple inputs.

## **8.2 Prospective management options**

Considerable yield variability exists within cane growing systems. The question is what variables are controlling yield variation. These may include soil water status due to variation in the degree of subsoil sodicity and subsequent impacts on irrigation efficiency, soil chemical parameters such as acidity, crop nutrition or a combination of these (Bramley *et al.*, 1997). There is currently impetus for the industry to adopt management practices to address this yield variability.

### **8.2.1 New farming systems**

The Sugar Yield Decline Joint Venture (SYDJV) has been developing a new sugarcane cropping system which incorporates the three basic principles of minimum/zero tillage, controlled traffic, and legume breaks to the sugarcane monoculture. Research has demonstrated that these three basic principles can be combined and result in improvements in soil health, crop productivity, and water and nutrient use efficiency (Garside *et al.*, 2006, Bell *et al.*, 2003, 2006).

Growers have continued to adopt more sustainable farming practices that improve farm productivity while delivering improved environmental outcomes. While the total new cropping system program may not be suitable on all farms, growers are adopting components of the system and are finding benefits which encourage them to progress with more changes that are in line with the base concepts of reduced cultivation, control traffic and break cropping.

In conjunction with new cropping systems, the sugar industry has seen the application of variable rate application technology, which seeks to have more precise operations such as targeted fertiliser and chemical use in line with the requirements of areas within paddocks.

### 8.2.2 Ground preparation/compaction management

Variation in soil texture, structure and strength within a field may combine to produce significant spatial variability in the tillage required to achieve a suitable or optimum result. Generally, conventional tillage systems attempt to apply a uniform treatment to the soil irrespective of the spatial variation in soil tilth/structural condition that may occur. Schafer *et al.* (1985) discuss the concept of 'prescription tillage' as involving the combination of soil characteristics, the interaction of soil/machine operations and the eventual crop requirements into a suitable tillage operation. Therefore, prescribed tillage or site-specific tillage operations for a specific crop may be achieved by controlling the type of tillage implement and the depth of operation. This modifies the physical properties of soil only where the tillage is needed for crop growth and potentially offers significant savings in tillage energy.

Site-specific tillage can be implemented either with pre-tillage map technology or a real-time sensor. The pre-tillage map technology would be a two-step process in which a sensor such as a soil cone penetrometer or soil electrical conductivity would be used to develop maps showing soil characteristics (e.g. hardpan existence and depth). This map would then be used in the site-specific tillage equipment control system to control subsoiling location and depth. The real-time sensor would provide a one-step system to control subsoiling location and depth. A number of technologies are now available to allow tillage depth to be varied on-the-go according to soil profile or compaction status.

The use of GPS guidance systems to implement controlled traffic wheel tracks confines compaction to the wheel zone and maintains the soil in most of the paddock in an optimum state for plant development and growth. The use of this very precise guidance technology to implement controlled traffic systems also minimises the potential for skips and overlapping of crop production inputs during the application stage as is often a problem with conventional application equipment. Tullberg and Yule (2005) demonstrate that controlled traffic based farming systems are applicable to all cropping industries, including sugar. The key components for the sugar industry are matching all machinery including infield haulouts and transition to the new system.

### 8.2.3 Elevation profiling

The high-accuracy positioning receivers (RTK GPS) being used to provide locations in a field also measure elevation at the same time. Hence, in addition to assisted guidance systems there are a number of other applications in which this technology may be utilised. Most notably is the creation of field-scale digital elevation models (DEM). The term DEM may also be used interchangeably with the term digital terrain model (DTM) (Stewart *et al.*, 2005).



Field-scale DEM datasets can be recorded easily during routine guidance activities and then may be utilised in a number of ways for agricultural purposes. The DEM is useful because it provides information on the potential movement of water within a paddock, on areas at risk from frost, and on locations where changes in soil type or key attributes may occur. The DEM can also be used to calculate other topographical properties such as aspect, slope, water shedding and accumulation points, which in turn can indicate differences in clay content, soil depth or nutrient status. The DEM is also often used as a data layer in the process of directing soil sampling sites.

An opportunity for the sugar industry is the ability of a RTK GPS survey to generate a DEM capable of identifying areas within the field of localised waterlogging or water-shedding caused by poor laser-levelling or years of erosion. Such information will enable growers to prioritise their laser-levelling programmes according to need and should lead to the more efficient application of irrigation waters. Furthermore, yield patterns within the field may be linked back to localised micro-elevation.

#### **8.2.4 GPS guidance systems**

Guidance systems use GPS positioning technology to improve the accuracy and efficiency of a number of farming operations. When properly installed and operated, such benefits include: the ability to generate straighter rows with no wide or narrow middles, the establishment of controlled traffic lines to minimise compaction areas within fields, the operation of equipment at higher ground speeds with less operator fatigue, a reduction in the amount of overlapping of sprayers and fertiliser equipment beyond that of the current foam marker system and the ability to download data on application areas for future reference. When the GPS receiver is not being used for guidance, it may be used for other operations in the PA system including yield monitoring, crop scouting and variable-rate applications.

#### **8.2.5 Irrigation and water management**

The spatial factors that influence yield variability include genetic variation, field topography, soil hydraulic and nutritional properties, micro-climatic differences, pest and disease infestation; fertiliser uniformity and irrigation uniformity (Zhang *et al.*, 2002). Some of these factors also vary temporally within spatial management units. However, Sadler *et al.* (2000) speculate that water is the main input resource for precision management since yield is highly correlated with water application in water-limited situations. Similarly, Cox (1997) offered the view that up to 90% of in-field variation in crop production was soil-water related. Further evidence of this is given by the lack of correlation between yield and soil fertility for many crops; spatial variability of crop temperature (and hence, water stress) that is indicated by remote sensing images; and known spatial variability of soil properties, including water holding capacity. An important component of precision agriculture is thus focussed on optimal management of the spatial and temporal components of water and irrigation.

The current situation in irrigated cropping systems has been reviewed recently by several authors. A scoping study on opportunities for improved irrigation application systems by Schimdt (2005) summarises the current technologies, technology and adoption gaps and research opportunities for precision irrigation systems in a range of regions and cropping systems across Australia. Misra *et al.* (2005) highlighted the importance of accurate measuring and monitoring for precision irrigation and outlined in detail a range of measurement technologies that have been developed. Inman-Bamber and Attard (2005) have reviewed many software tools that are available to improve the precision of irrigation and water management and have outlined the technology, benefits, applications, limitations, barriers to adoption and promotion and further development needs. Raine *et al.* (2005) outlined future opportunities for adaptive irrigation control systems to manipulate irrigation inputs

in real time to optimise the quality or quantity of crop produced. The basic components of an adaptive control system are the ability to variably control the application of pertinent input variables (e.g. water and nutrients), sensory measurement of the crop response and decision support systems linking the sensed output with the variable application control.

### **8.2.6 Fertiliser management**

Variable-rate application of fertiliser at a block scale has generated a significant amount of interest among growers and service providers within the sugar industry. Fertiliser can be distributed by various means, most of which can be adapted with varying degrees of success to variable rate control. All systems suffer from an inherent problem of having no effective means of directly measuring the relatively small mass flow of the dry product and so systems rely on some surrogate measure (usually feed mechanism rotational speed or hopper opening size).

A range of map-based variable rate controllers are commercially available. These controllers feed the rates of input to the piece of equipment that varies the rate of input application. While the technology to implement variable rate fertiliser application is available and in use by some parts of the industry, this issue opens up a wide field of debate between those who say that we still need to know more about factors at block or farm level and those who believe that more might be explained by yield maps themselves. The situation is limited by the knowledge of fertiliser requirements and the development and interpretation of suitable prescription maps.

### **8.2.7 Soil amelioration**

Another agronomic input that may be more judiciously applied by using a site-specific strategy is gypsum for soil structural problems caused by sodic soil. Gypsum could be applied on the basis of sodicity maps, yield maps or on-the-go soil sensors.

Within the sugar industry the variable rate application of soil ameliorants such as gypsum is considered feasible and worthwhile. In attempting to manage the sodicity problem on his farm, Cox and a local contractor developed variable rate technology for gypsum spreading (C4ES, 2004). Cox (1997) also believed that variable application of lime might be similarly worthwhile on acid soils.

### **8.2.8 Pest and weed management**

Although still at an evolving stage of development, the site-specific management of weeds holds clear potential to reduce herbicide use within the industry. Whilst commercial equipment is available and in use in other industries (i.e. grain, cotton), we are not aware of any practical uses of the fully automated variable rate technology within the Australian sugar industry.





### 8.3 Road ahead

Concepts that are currently being developed are most likely to lead to innovations that will be used in the medium term due to the time required to develop and diffuse agricultural technologies. Figure 9 shows a timeline with some of the innovations that may be adopted for agricultural cropping operations over the next 15 years. The technologies illustrated are based on existing technologies and do not consider the potential for new technologies that may be developed.

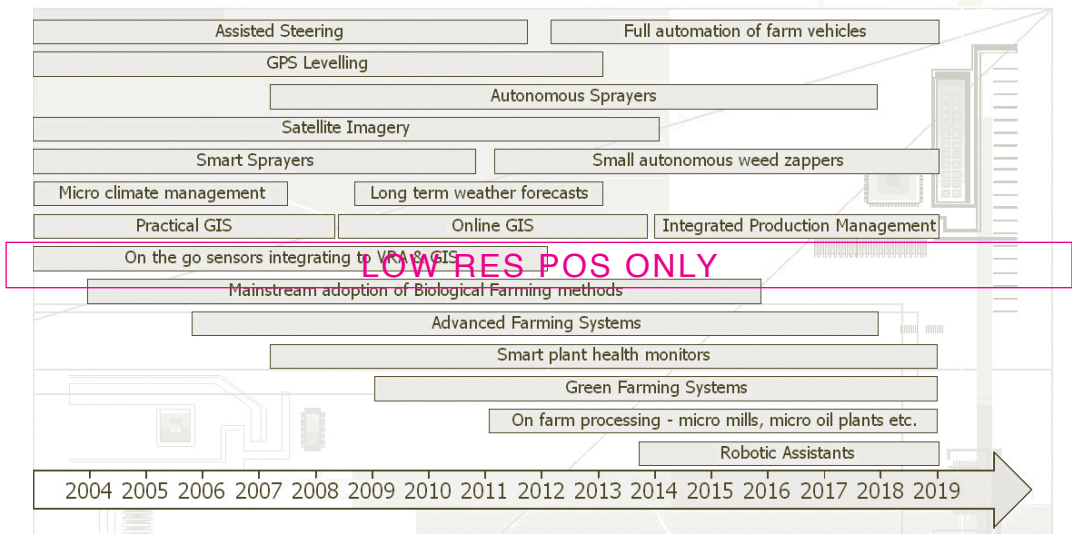


Figure 9. Potential new technologies, showing estimated timeframes to commoditisation

## 9. Recommendations to Growers

PA enabling technologies have been strengthened in recent years with accurate spatial referencing using DGPS, soil (moisture, nutrients) and crop monitoring capabilities, development of variable rate technology for spatially variable application, harvester monitoring capabilities and GIS interface systems.

Many cane growers and harvesting operators will benefit from the use of some parts of the PA suite of technologies. For example, implementation of new farming systems through GPS for machinery guidance, the testing of new varieties using yield data or harvester tracking and monitoring will be adopted.

However, PA may not be for everyone, at least not straight away. The first step is recognising whether significant variability in yield and profit is occurring whether the scale is within a paddock or across the farm, and whether the yield zones are stable or unstable between years (seasons) and different crops. This can generally be achieved from grower's own knowledge of blocks and from mill data from individual blocks.

The next step should be to identify the underlying causes of yield variability. These could include soil depth, soil type (water-holding capacity, nutrients), topography (elevation), acidity, subsurface salinity or compaction, presence of soil pests and diseases, or the influence of past management (old fencelines, previous crop type). This step may require soil or disease testing, aerial photographs, or contour data. There is little point in trying to manage spatial variability in a block that suffers from waterlogging or compaction. Sorting out these more important problems, for example with laser leveling, controlled traffic or minimum tillage systems, will reduce the variability seen within the block.

Where there are several likely causes, it is important to get a sense of their relative impact on yield and profit. By the end of this step, growers should know what the main underlying causes of yield variability are, and whether it is practical to do anything about them, either by direct amelioration (ripping, correcting nutrient deficiency, liming, gypsum) or by changing management (variety change, reducing fertiliser inputs on non-responsive areas and increasing them where there is a good yield response).

Dealing with spatial variability is not always a cane grower's first or immediate priority. Growers first need to make sure that they have addressed the basic components of their cropping system (crop type and varieties, rotations, nutrition, disease, weed and pest control) and have these working satisfactorily, before dealing with spatial variation. In other words, make sure the basics are right before considering PA.



The next step should ask the question 'Does it matter?' In other words, knowing that variation exists and the scale of variation in yield (step 1) and the underlying causes and possible solutions (step 2), is it worth doing anything about it. In this step the cost of enabling technologies (GPS, remote sensing etc), grower/adviser experience or crop modelling can be evaluated to help assess the likely impact on yield under different management systems and seasonal conditions. The impediments to adoption of PA should also be assessed (i.e. current level of understanding and management, technology gaps or cost etc.). Growers can then determine whether it is economically feasible or sensible to tackle yield variability using PA, and if so what its relative priority should be in the farm or cropping budget.

The next step is implementation (and at what scale) and monitoring the outcome. At present application of PA within the sugar industry is considered at a number of scales from regional level through to block scale. Monitoring the outcome should occur as part of a continuous learning process of change.

Future directions for PA will be dependent on external factors such as the continued development of technology, the conditions of world markets or the insistence of buyers on product standards - all of which are beyond the control of cane growers. In the end, the adoption of precision agriculture will depend on the economic benefits offered, which will, in turn, depend on the degree of variability present in the field, and the opportunity to manage that variability.

## 10. Priorities for Precision Agricultural Research

Precision farming is a systems approach to managing soils and crops to reduce decision uncertainty through better understanding and management of spatial and temporal variability.

Figure 1 provides a schematic of the PA system. A review of the technologies associated with each component of this system outlined in Figure 1 suggests a range of skills are required for implementation of a successful PA system. Collectively, the sugar industry has the skill base required viz. engineering technology, agronomic, soil science, GIS and information technology to facilitate adoption.

However, much of the research conducted to date has occurred across a number of scales to develop strategies for crop management within the sugar industry. Researchers and growers have collected huge amounts of information, but assessing the quality of this information, transforming it into meaningful management decisions, evaluating potential benefits and risks, and coordinating has proven to be a difficult task with respect to PA.

For example, many growers have shown an interest in GPS as they can see that it works in principle. Much of the development and adoption of GPS has been driven by growers who are motivated to adopt a new farming system incorporating the principles of controlled traffic, minimum tillage and rotation crops. This has opened up a range of opportunities including reduced driver fatigue, precise tillage, planting and fertiliser placement, minimising overlaps, efficiency gains and staff management. Growers in most cases have individually purchased GPS systems incorporating base station and rovers. Networked RTK GPS is a completely different approach to calculating and communicating base station information to the mobile unit (i.e. tractor). This approach offers an opportunity to the sugar industry with the potential to rapidly increase the number of users through a reduction in the cost of the technology. Community network based GPS are already being implemented within Queensland, with networks being established in the Maryborough, Isis, Bundaberg and Herbert River areas. This area along with developments in integrated communication technology and networking (i.e. wireless networks, broadband internet etc.) should continue to be one area of focus for PA research and development.

For sugar cane farming, the full benefits of PA are severely constrained by the lack of an accurate and reliable spatial yield monitoring solution. Within the industry a number of attempts have been made to monitor yield variation across a block, ranging from discrete yield monitoring systems based on mass measurement systems to the current focus of monitoring chopper pressure, feed train roller displacement and elevator power. An independent evaluation of the commercially available mass flow sensors should be undertaken. Depending on the outcome of this evaluation priority research may be needed into the development of a reliable and accurate mass flow sensor. Accurate yield monitoring will close the PA cycle to enable the use of precision farming tools and analyses that allow spatially based farming management and associated variable rate applications. It will also allow improved understanding of what factors are controlling yield, prescribing treatments and determining optimum management units. This should be a high priority for PA research.



A major opportunity for the sugar industry is to significantly increase industry profitability without increasing capital investment by reducing field losses of cane and juice during mechanical harvesting. Harvester performance monitoring systems are now available to the industry, however the priority for further research should be in the interrogation of the information collected and the development and interpretation of practical and meaningful real-time performance feedback indicators.

The APSIM-Sugarcane model has evolved and emerged as one of the more powerful modelling tools currently available to the sugar industry. It has been used in a number of studies for improving water and nitrogen management by more quantitative prediction of crop yield, water and nitrogen needs during the growing season. Climate forecasting has been shown to be a tool available to the industry to improve competitiveness and profitability, through enhanced decision making and forward planning. Further research should be aimed at building on social science and economic capacity to increase awareness about the capability of the technology and for the industry to understand the strengths, limitations and associated risks of the technologies so they can be better positioned to use the technology appropriately. Decision support tools that combine GIS and results derived from crop modelling and seasonal climate forecasting systems should also be developed to provide objective assessments of management alternatives for specific crops and locations.

Remote sensing provides, at relatively low cost, a great deal of fundamental information relating spectral reflectance and thermal remittance properties of soils and crops to their agronomic and biophysical characteristics at scales that may range from small patches within a field to large regions. Research has highlighted the potential for remote sensing in yield forecasting, improving crop production and detecting outbreaks of disease. Continued research and development into higher resolution and hyperspectral sensors will open up many new possibilities for crop and farm management. The major opportunity is the need for further practical research in the sugar industry with lessons learnt from other industries (i.e. viticulture, grains, cotton etc.). In addition, broader agronomic application of remote sensing with respect to pest and disease monitoring and integration with crop modeling activities should be investigated.

The technology to implement site-specific management is now available. Variable rates of inputs can be implemented by simple, manually controlled systems or by fully automated variable rate controllers. The technology will vary according to the situation and the type of VRT to be implemented. Technologies range in complexity and features; most can be adapted to existing equipment and therefore do not require the expense of purchasing new equipment. It is possible to adapt machinery by adding different gearbox and clutch systems, but this will vary from one piece of equipment to another. With VRT capable machinery, it is necessary that the controllers have the correct 'drivers', software programs for that specific equipment. New equipment such as fertiliser applicators and sprayers can be purchased from several companies. Improving irrigation application uniformity may be one of the most important management improvements to come from precision agriculture. Variable irrigation control has been attempted using sprinklers on self-propelled irrigators, lateral move irrigators, centre pivot irrigators or trickle irrigation. Improved optimisation and management of furrow irrigation from a field rather than a furrow perspective should be investigated.

## *Investing in Sugarcane Industry Innovation*

To date most emphasis has been on proving reliability of the hardware rather than actually using geo-positioning to vary product rates. This is largely due to the lack of a sound basis for making site specific rate decisions. Therefore the question for site-specific management and implementation of VRT is what variables are controlling yield variation. This may range from soil water status due to variation in the degree of subsoil sodicity and subsequent impacts on irrigation efficiency, soil chemical parameters such as acidity, crop nutrition or a combination of these. The priority for the industry should be the development of accurate and reliable prescription maps. Therefore it is up to soil and crop scientists along with agricultural engineers to develop simple and robust methodologies and technologies for growers so that the full potential of PA can be exploited. They must conduct rigorous evaluation studies at multiple sites with standardised methodologies, including utilising PA technologies for gaining a better understanding of crop yield determinants.

Proof of economic and environmental benefits must be demonstrated. The widespread use of empirical rules and algorithms must gradually be replaced with more in-depth understanding of cause-effect relationships that determine crop productivity and soil and environmental quality at scales that are manageable through PA.

Technology gaps, adoption/commercialisation gaps and research opportunities identified for PA for sugarcane production and harvesting are summarised in Table 2.



**Table 2. Technology gaps, adoption/commercialisation gaps and research opportunities identified for PA for sugarcane production and harvesting**

Technology gaps	Adoption/commercialisation gaps and opportunities	Research/development opportunities
	<ul style="list-style-type: none"> <li>■ Standardisation of PA technologies.</li> <li>■ Quantifying economic and environmental benefits of PA technologies and system implementation.</li> </ul>	<ul style="list-style-type: none"> <li>■ Facilitate capacity building of PA skills through appropriate training of committed industry people.</li> <li>■ Pre-emptive evaluation of emerging technologies.</li> <li>■ Foster the development of industry user groups on PA systems and facilitate the up-skilling of industry personnel in new technology – to allow growers access to up-to-date independent information.</li> </ul>
<p><b>Spatial referencing</b> Networked GPS</p> <p>Remote sensing</p>	<ul style="list-style-type: none"> <li>■ GPS networks have the potential to rapidly increase the number of users through a reduction in the cost of the technology.</li> <li>■ Improved relationships between technology suppliers, growers and researchers need to be developed.</li> <li>■ A program to rapidly up-skill personnel in new technology – to allow growers access to up-to-date independent information.</li> <li>■ Remotely sensed research trial data is insufficient to persuade growers to change systems. The major opportunity is the need for practical research with lessons learnt from other industries.</li> </ul>	<ul style="list-style-type: none"> <li>■ Facilitate cooperative based framework for GPS adoption.</li> <li>■ Industry/regional evaluation of systems for integrated communication networking and development of on-farm systems using currently available technology.</li> <li>■ Practical research on higher resolution and hyperspectral sensors.</li> <li>■ Research broader agronomic application of remote sensing with respect to pest and disease monitoring and integration with crop modelling activities.</li> </ul>
<p><b>Production environment monitoring</b></p> <p>The implementation of PA is severely constrained by the lack of an accurate and reliable spatial yield monitoring solutions. An appropriate mass flow sensor for sugarcane needs to be developed. Alternative systems need to be investigated.</p> <p>Standardisation of harvester performance monitoring and feedback management technology.</p>	<ul style="list-style-type: none"> <li>■ The basic technology is available for yield monitoring of sugar cane with the exception of a proven mass flow sensor.</li> <li>■ Improved and robust methodologies for the production of yield maps.</li> <li>■ Improved linkages and integration between researchers and growers to develop practical yield monitoring and mapping management outputs.</li> <li>■ An examination of the EM, VERIS and other similar soil sensing systems for providing surrogate data for the creation of high-resolution maps of soil properties such as texture, cation-exchange capacity and soil moisture for PA.</li> <li>■ The hardware for monitoring harvester performance is now available. Any number of performance parameters can be measured. The limitation for widespread adoption as opposed to a research tool is the lack of suitable design/evaluation software.</li> <li>■ An examination of image analysis for providing yield variation data.</li> </ul>	<ul style="list-style-type: none"> <li>■ Research is needed into the development of a reliable and accurate mass flow sensor.</li> <li>■ Independent evaluation of commercially available mass flow sensors should be undertaken.</li> <li>■ Information from yield maps needs to be translated into spatially based farming management impact, variable rate applications and economic return.</li> <li>■ Developing practical and meaningful real time performance feedback measures, specifically in relation to harvesting best practice.</li> <li>■ Build on social science and economic capacity to increase awareness on the strengths and limitations of crop and climate modelling.</li> <li>■ Development and interpretation of key performance indicators for real time harvester performance monitoring.</li> </ul>

**Table 2. Technology gaps, adoption/commercialisation gaps and research opportunities identified for PA for sugarcane production and harvesting (cont'd)**

Technology gaps	Adoption/commercialisation gaps and opportunities	Research/development opportunities
<p><b>Attribute mapping</b> Spatial farm productivity information</p>	<ul style="list-style-type: none"> <li>Through its operational framework, large resources of base mapping data about the crop are collected. This information is predominantly used by mills for their business of crop estimation and harvest planning. However this information could be further exploited and utilised for farm productivity management and practice change.</li> <li>The advent of Web-based GIS offers growers the potential to effectively map their property and send data to a consultant with the specialised technology and within hours be able to access a GIS map of their property. This makes available this technology without the costs, or time and energy in learning to use specialised farm mapping software.</li> </ul>	<ul style="list-style-type: none"> <li>Facilitate collation of data into a central node for warehousing and presentation.</li> </ul>
<p><b>Decision support</b></p>	<ul style="list-style-type: none"> <li>Spatial variability within the field needs to be quantified to ascertain whether differential treatment within the field is warranted.</li> <li>Need to fully understand causes of yield variation.</li> <li>Prescribing treatments.</li> <li>Determining optimum management units.</li> </ul>	<ul style="list-style-type: none"> <li>Integration of crop models into a GIS environment to permit their use at the within-field scale will prove invaluable in the future.</li> <li>Improved understanding of yield variation with respect to treatment prescription.</li> </ul>
<p><b>Differential action</b> Weed management – ‘on-the-go’ sensing technology for distinguishing weeds from sugarcane plants</p>	<ul style="list-style-type: none"> <li>Emphasis has been on proving reliability of development of hardware rather than actually using geoposition to vary product rates.</li> <li>Focus needs to be the development of accurate and reliable prescription maps. Therefore simple and robust methodologies must be developed.</li> <li>Current precision spray technology cannot distinguish weeds from sugarcane.</li> <li>Targeting specific weeds has the potential to revolutionise weed management by maximising production and reducing herbicide usage while reinforcing minimum tillage concepts. Giving direct environmental benefits.</li> </ul>	<ul style="list-style-type: none"> <li>Improved understanding of what variables are controlling yield.</li> <li>Variable rate application linked to real time information on crop/soil moisture status.</li> <li>Variable rate application linked to real time information on weed infestation status.</li> </ul>
<p><b>Irrigation</b> Water meters should be essential components of any irrigation systems but are not widely used owing to cost/accuracy. Surface irrigation evaluation requires extensive/time consuming data acquisition and evaluation. This needs to be automated/streamlined.</p>	<ul style="list-style-type: none"> <li>Workshops are often more effective where a ‘credible’ outsider is used to give advice and guidance.</li> <li>Utilising optimisation tools such as irrimate.</li> <li>There is a need for better training of designers and suppliers who rely on standard specifications and equipment packages.</li> </ul>	<ul style="list-style-type: none"> <li>Improved optimisation and management of field rather than furrow.</li> <li>Improved management of higher technology pressurised systems.</li> </ul>





## 11. Recommended Areas of Investment for SRDC

As the concept of PA is only embryonic in the sugarcane farming systems context, there are many potential areas of investigation that could significantly improve the profitability and long-term sustainability of the industry. Research needs to be undertaken to tackle some key technology gaps (e.g. yield monitoring); agronomic questions relating to site-specific yield variation, especially weed control and irrigation management; harvester performance; and building capacity with industry personnel in PA technology.

Finally, we urge the industry to consider the following research objectives to expand on the current understanding and management of spatial variability in Australian cane growing and harvesting systems:

- Investigations into the development of a robust, reliable, calibratable and accurate yield monitor and robust methodologies for the production of maps of yield.
- The provision of associated support services or tools for making use of the data collected by yield monitors to allow the development of accurate and reliable prescription maps.
- Investigations into the variable rate application of herbicides. This recommendation has significant environmental and economic considerations, demonstrating that best management practice is being employed for the coastal ecosystems in which the majority of sugarcane is grown. In addition, it may prolong the registered use life of key chemicals within the industry.
- An examination of variable rate irrigation technology for the industry.
- An exploration of remote sensing technologies (satellite and/or airborne) to aid in site-specific cane management particularly for the early detection of pest or disease outbreaks or water stress.
- An examination of the EM, VERIS and other similar soil sensing systems for providing surrogate data for the creation of high-resolution maps of soil properties such as texture, cation-exchange capacity and soil moisture.
- An examination of harvester performance data and the development of practical and meaningful real-time performance feedback measures for integration with PA programs.
- A program, possibly in combination with other industries, needs to be developed to rapidly up-skill personnel in new technology so that growers can obtain independent and up-to-date information.
- Pre-emptive evaluation of emerging technologies in other industries in Australia and overseas.
- Facilitate capacity building of PA skills viz. data acquisition, management and analysis through appropriate training of committed industry research personnel.
- Foster the development of industry PA user groups and facilitate the up-skilling of growers and consultants in PA. Allowing growers access to up-to-date independent information and to prevent other growers making the same mistakes as early adopters will be one of the keys to successful adoption of PA.

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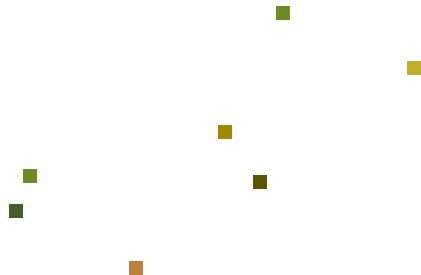












**Australian Government**  
**Sugar Research and Development Corporation**

Telephone: 07 3210 0495  
Facsimile: 07 3210 0506

Web: [www.srdc.gov.au](http://www.srdc.gov.au) Email: [srdc@srdc.gov.au](mailto:srdc@srdc.gov.au)  
PO Box 12050, Brisbane George Street Q 4003, Australia