Lessons from nearly 20 years of Precision Agriculture research, development, and adoption as a guide to its appropriate application

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Abstract. Precision Agriculture (PA) is an all-encompassing term given to the use of a suite of technologies that promote improved management of agricultural production through recognition that the potential productivity of agricultural land can vary considerably, even over very short distances (a few m). It can be regarded as a means of increasing the chance that the right crop management strategies are implemented in the right place at the right time.

Numerous examples exist of the successful application of PA to various cropping systems around the world, in many cases supported by a burgeoning PA literature. However, the rate of adoption by growers of many crops remains low and, in some industries, is negligible. One such example is the Australian sugar industry, in spite of its relatively high rate of adoption of controlled traffic and the ready access that growers have to supporting infrastructure such as local GPS base stations. However, the Australian sugar industry is now seeking an informed basis from which to make decisions as to appropriate investment in PA, whether these be in terms of pragmatic application by growers, the level of involvement (if any) by millers, or with respect to research to facilitate such adoption. A part of acquiring this informed view of PA is to look at its application in other cropping systems. This review therefore examines PA research and application in a range of cropping systems 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.

It is concluded that sugarcane production is ideally suited to the adoption of PA. Like other broadacre systems, such as cereal production, the opportunity exists to target the management of inputs to production. However, the vertically integrated nature of the sugar industry and existence of a potentially significant crop quality imperative also present opportunities for targeted strategies such as selective harvesting, as used in the wine industry. Thus, to get the best result from adoption of PA, the sugar industry will need to consider it as a tool for optimising management of the production of sugar, as opposed to solely an avenue for improving the agronomic management of sugarcane. Several recommendations are made as to how this adoption might be supported.

Introduction

Land is variable. This is true, 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. 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, such as 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 Fig. 1 illustrates, this assumption is flawed.

The advent of so-called ‘Precision Agriculture’ (PA; e.g. Cook and Bramley 1998; Pierce and Nowak 1999; Robert 2002; 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 (Cox et al. 1997; Bramley and Quabba 2001), but a collapse in world sugar prices, among 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 is a response to renewed interest in PA within the Australian sugar industry and, in particular, a desire on the part of the industry 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 over 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 nine occasions, while the European Conference on Precision Agriculture has been held six times; aspects of PA are also regularly canvassed at more general agronomic 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 (Profitt et al. 2006) industries. Both of these publications have much to offer interested sugarcane growers and their advisors, and 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 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 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. Since the idea of PA as ‘information-intensive’ agriculture (Fountas et al. 2005, 2006) is a core underpinning principle, the use of controlled-traffic and GPS guidance systems is 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, which are now being extensively adopted in the Australian sugar industry (Davis et al. 2007), may play an integral part in the adoption of PA because such technologies can be useful in familiarising growers with the use of GPS in their production systems, and so may facilitate the adoption of yield mapping and targeted management.

**Background philosophy and enabling technologies**

Over 10 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; Taylor et al. 2007), 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 treated it as ‘noise’ (Cook and Bramley 1998) and so have tended to manage on the basis of homogeneity.

The philosophy behind the move towards more targeted management and the tools on which it depends have been discussed widely elsewhere (e.g. Cook and Bramley 1998; Pierce and Nowak 1999; McBratney et al. 2005b; Srinivasan 2006 and references therein). In summary, it is recognised that the inherent variability of land (topography, soil properties) leads to variation in its potential productivity. As a result, the input-output relationships driving the production system can vary, often over distances of only a few meters (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. Thus, the adoption of PA aims to increase the likelihood of farmers making a ‘correct decision’ (McBratney et al. 2005b) and thereby gaining a beneficial outcome through the targeting of inputs (Cook and Bramley 1998) or selectively harvesting outputs (Bramley et al. 2005b; Proffitt et al. 2006). Note that while ‘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. Good general descriptions of the relevant technologies required to support such strategies are provided in Leonard and Price (2006), Proffitt et al. (2006), and Stafford (2006), while more sugarcane-focused, albeit older, discussions are presented in Bramley et al. (1997).

**Spatial v. temporal variation and the null hypothesis of PA**

A significant constraint to the adoption of PA in 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) that may have quite different fertiliser requirements. These sorts 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, 2007) analysed yield maps obtained from several vineyards over several vintages to demonstrate that the patterns of variation in wine grape 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 an 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 (Fig. 2; Cook and Bramley 1998) rather than a one-off action and therefore has its own temporal dimension. Note therefore, 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 wine grape 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) have 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.

**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 wine grapes (e.g. Bramley et al. 2005b; Proffitt et al. 2006), citrus (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 (Antuniasi 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 used in a range of crops (Gerhards and Christensen 2006), while PA approaches to disease management are also being explored (e.g. Heap and McKay 2005). The application of PA to the management of tobacco and olives (Blackmore et al. 2006), tomatoes (Lee et al. 1999; Zhang et al. 2005; Fig. 1b), apples (Praat et al. 2001), kiwifruit (Praat et al. 2007), and
sugarcane (Bramley et al. 1997; Bramley and Quabba 2001) has also been canvassed. 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 (2009), Proffitt et al. (2006), and Tisseyre et al. (2007). 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 farmers adopting PA.

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 ~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 were being yield monitored in the early 2000s (Griffin and Lowenberg-DeBoer 2005). 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. Godwin et al. 2003; Lowenberg-DeBoer 2003; Doerge 2005), in particular with respect to the maximisation of yield (Blackmore et al. 2006). In Europe, an important reason for interest in PA is its potential use as a tool for minimising any detrimental environmental effects of agricultural production (Lowenberg-DeBoer 2003; Stoorvogel and Bouma 2005; Blackmore et al. 2006), thereby demonstrating the sustainability of production systems, and also for product tracking (Praat et al. 2001; 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.

**Economic benefits from PA**

Early studies on the economics of PA (e.g. Swinton and Lowenberg-DeBoer 1998) were circumspect as to its profitability. A possible reason for this is that in some
cropping systems, even large deviations from the economically optimum agricultural decision can make little difference to the payoff (Pannell 2006). 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 with uniform application was £22/ha. Griffin and Lowenberg-DeBoer (2005) reported that of 210 published studies in which economic losses or gains of variable-rate nitrogen application compared with uniform application 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). However, such costs were considered in recent case studies of PA adoption by Australian grain growers (Robertson et al. 2009); benefits of $14–30/ha were identified. More generally, Lowenberg-DeBoer (2003) concluded that the use of variable rate application (VRA) is likely to be profitable for higher value crops (e.g. sugar beet), but will be break-even at best for bulk commodities (e.g. corn). Sugarcane, presumably, 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 responses to this are that since the crop has to be harvested, it may as well be yield mapped, as opposed to one in which industry is left to interpret research results from some sort of field study. 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 detailed analysis was estimated did not take the cost of image analysis into account. It should be noted that while the $25–30/ha that Australian grape growers 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 to the fact that maps of bare soil do not change greatly over time. They also offered the view that there are ‘relatively few reliable remote sensing analysis or consulting firms’. They were also critical of the frequent use of subscription-based marketing strategies in which several images per season had to be bought. Thus, Lowenberg-DeBoer (2003) described yield monitors as ‘the killer application of information technology for agriculture’.

If the application of PA to sugarcane production is confined to agronomic, as opposed to environmental, issues, it seems likely, based on the Griffin and Lowenberg-DeBoer (2005) survey, that benefits will accrue to some producers but not others. Which category a particular grower falls into is likely to depend on both the ease with which the drivers of variation are identified, and the ease with which these can be beneficially managed on his/her farm. Key factors affecting both of these aspects will be the availability of appropriate diagnostic expertise and either the amount of ‘management time’ (Lowenberg-DeBoer 2003) that the grower can afford to spend in addressing them, or the $ investment that the grower is willing to make in getting someone else to do this for him/her. Perceptions as to the likely size of the benefit relative to the cost of addressing it will also be crucial and will be treated differently by each individual. In this connection, it is important for researchers to appreciate that farmers do not generally make decisions regarding changes in management practice on the basis of the level of statistical significance seen in agronomic experiments. More typically, the decision as to whether a new practice should be adopted is made on the basis of considerations such as the magnitude of the response (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? ’), among a whole raft of other possible considerations (e.g. Pannell et al. 2006). Intuition is a critical guide to decision making for most managers (McCown 2002; Fountas 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 yield v. quality imperative

As indicated above, the early adopters of PA in broadacre cereal systems have overwhelmingly used yield mapping, and sometimes other tools such as high-resolution soil survey (e.g. EM38) and elevation modelling, to inform the VRA of inputs to the production system. The most common use of VRA has been for nitrogen (N) fertiliser application (e.g. Godwin et al. 2003; Lowenberg-DeBoer 2003). In contrast, the early adopters of PV 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 focusing 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 that exists in the wine industry.

In contrast to growers of wine grapes, broadacre cereal producers do not generally have a strong ‘ownership’ of their crop once it leaves the farm gate because information flows within the cereal industry value chain are corrupted by disjunction between the interests of growers, bulk handlers, marketers and markets, and the effect of price pools. There is therefore a general lack of vertical integration of product and information flows. Exceptions may apply in the case of producers of high-grade durum wheat or barley, who may have specific relationships with particular producers of pasta or beer, but in the case of grain delivered to a bulk silo for subsequent export overseas, grower involvement in 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, even though Stewart et al. (2002) and Skerritt et al. (2002) have demonstrated the potential for targeted management of grain quality. Another has been the absence, until very recently, of a reliable grain 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).

Like the wine industry, but in marked contrast to the wheat industry, and especially the export-orientated Australian variant, the sugar industry is highly vertically integrated. Both sugarcane and wine grapes 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 wine grapes, 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 several 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 wine grapes 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 benefit from selective harvesting was worth over $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 content (ccs), 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. (1998a, 1998b, 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 from 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 their temporal stability, in addition to those for yield. In the case of wine grapes, it has been shown that while 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, while 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 the regional scale in the Tully district. They found no spatial relationship between yield and ccs, although spatial variation in both was temporally stable.

PA as an environmental management tool

PA lends itself to demonstrating the environmental credentials of crop production systems 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, while 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), among other conservation objectives (Delgado et al. 2005).

In general, the low-input systems that 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. (2006) have explored the use of PA to minimise the detrimental effects of N fertiliser use in the WA wheatbelt, while 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 used compared with 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). Indeed, a recent analysis of the possible contribution that targeted N fertiliser management industry (Wrigley and Moore 2006) suggests that PA may have much to offer in improving the environmental performance of the Australian sugar industry. In this work, targeted management of N was estimated to maintain profitability at the same time as markedly reducing the risk of N loss off-site. This work also highlighted a role for PA in identifying opportunities for more general improvements to sugarcane agronomy. Similar conclusions were drawn by Bongiovanni and Lowenberg-DeBoer (2004) in an analysis of maize production in Argentina, which showed 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 focused only on N (Bongiovanni and Lowenberg-DeBoer 2004).

PA 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 and references therein) and 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, militated against the Australian industry taking advantage of the early lessons. 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).

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). While 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 in terms of a crop quality imperative in addition to a focus on yield optimisation, as occurs in the wine industry (e.g. Bramley et al. 2005b).

A key driver of the early Australian interest in PA in sugarcane was the development of a cane yield monitor at the University of Southern Queensland (USQ; Cox et al. 1996, 1997; Harris and Cox 1997; henceforth referred to as the ‘USQ system’) 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 District 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 that prevailed at that time (Wood et al. 1997). These have since been markedly improved with due recognition given to inter-regional differences and soil variation at the intra-regional scale (Schroeder et al. 2005).

With a 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) subsequently completed two seasons of yield mapping in the Herbert River District, using a prototype USQ system and implementing some of the early lessons 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 (among other factors) left the Australian industry without the firm platform of research and technical support that experience in other industries suggests is key to adoption by other than the most innovative of growers.

The yield mapping undertaken by both Bramley and Quabba (2001) and Pivot demonstrated that, as has been commonly seen in other crops (e.g. Pringle et al. 2003), yield variation showed marked spatial structure. This strongly suggests that both zone-based and continuous variable rate management may have potential application in sugarcane production, as does the recent work of Bramley et al. (2008). Bramley and Quabba (2001) 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). Thus, it was no surprise that a significant proportion of a 6.7-ha cane block in the Herbert River District (Fig. 1c) was either operating at a loss or returning gross margins substantially below the goals of its owner (Fig. 3).

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 (McDonald and
Routley 1999). Markley et al. (2003) and Markley and Fitzpatrick (2004) further developed this work, a 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% were achieved using imagery obtained from these systems (J. Markley, Mackay Sugar, pers. comm.).

Other countries

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 et al. 2003). The approach taken 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. Importantly, the range of yield variation in Mauritius (60–150 t/ha) was similar to that seen in Australia (e.g. Fig. 1c) and in the US (36–134 t/ha; Johnson and Richard 2002), with higher yields thought to be associated with higher soil water-holding capacity (Jhoty et al. 2003).

Early work in Brazil was divided between development of a harvester-mounted yield monitor (Pagnano and Magalhães 2001; Cerri and Magalhães 2005), which was essentially the same as the USQ system; development of a weighing system for grab loaders used following hand-harvesting (Saraiva et al. 2000); and an approach similar to that used in the USA (Johnson and Richard 2002), based on the use of load cells on haul-out bins (Molin et al. 2004). These differing Brazilian approaches largely reflected the use of either mechanical or hand-harvesting. More recently, Magalhães and Cerri (2007) have published details of a new Brazilian yield monitoring system. This is a modification of the Cerri and Magalhães (2005) yield monitor and includes several 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 of a Cuban cane yield monitor (Hernandez et al. 2005) is also significant, especially given its commercial availability in 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. Automated control of forward speed and base cutter height is also available along with a guidance system that better synchronises the position of the haul-out bin relative to the harvester.

In spite of the development of a further variant of the USQ system in the US (Benjamin et al. 2001), published accounts of sugarcane yield mapping in the US employed a system that uses load cells on the ‘field transport wagon’ (Johnson and Richard 2002, 2005a, 2005b). In South Africa, the relative lack of mechanisation—a consequence of an abundance of cheap labour—meant that 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 South African focus was 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). Much of this work was 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).
Remote sensing has also been a major area of focus in Brazil (e.g. Galvão et al. 2005; Almeida et al. 2006). 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 given that a single 30-m pixel will reflect composite information about ~20 rows. Indeed, the question of what the desirable on-ground resolution of remotely sensed imagery should be for application to PA in sugarcane, and thus what platform should be used to acquire it, are matters worthy of further investigation. Note that several 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. 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 (Lamb 2000; Hall et al. 2002; Bramley et al. 2005b) that grape growers can purchase for approximately A$30/ha. 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; disease identification is another potential application. Based on experience in other industries (e.g. Lamb 2000) these latter potential uses for remote sensing seem feasible, although the use of DMSV to distinguish varieties or disease is an area that may require considerable further work since these are applications that might be expected to depend on hyperspectral methods (Apan et al. 2001; Markley and Fitzpatrick 2004; Galvão et al. 2005; Almeida et al. 2006). Whether 50 cm or a coarser resolution (which would be cheaper) is appropriate for sugarcane sensing is something worthy of further investigation. A resolution of 50 cm is used for viticulture to allow removal of non-vine (i.e. inter-row) signals, something that is unlikely to be an issue for sugarcane sensing assuming that this is done after, or close to, canopy closure. The question of what spatial resolution is desired will presumably therefore be largely determined by the size of the minimum area for which growers would consider targeted management to be feasible. However, Schmidt et al. (2004) note that selection of the most appropriate vegetation index for sugarcane is still a researchable issue, as is evaluation of the most appropriate time during the season for the acquisition of remote sensing data (cf. Lamb et al. 2004). Given the length of the harvesting season and the consequent effect this has on crop age, with cane of varying ages likely to appear in single images, this presents a potentially complex research issue. Overall, the fact that Almeida et al. (2006) were able to predict yield from Landsat with errors of around 5%—considerably less than the local mill—suggests that higher resolution instruments, where available and affordable, may have much to offer sugar industry adopters of PA.

In addition to examining variation in the yield of cane, Johnson and Richard (2002) also examined variation in ‘theoretically recoverable sugar’ (TRS) levels (51–104 kg/t) within a single 3.3-ha block which, when coupled to variation in cane yield, enabled variation in the yield of sugar (2.64–14.57 t/ha) to be assessed. Subsequently, Johnson and Richard (2005a) 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 sulfur status and brix %, while at another, the strongest correlation (–0.54) was between organic matter % and pol %. No analysis of the spatial association 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 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 VRA of lime. The results showed promise in terms of reducing the cost of liming, through application to only 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 property variation on sugarcane yields in a 38-ha block in Florida. Yield variation (43–101 t/ha) was shown to be related to soil Ca and Mg status, P buffering, and the depth to water table. While not specifically a PA study, this work, and very similar research undertaken in Brazil (Corá and Marques 2000; Corá et al. 2001), nevertheless lends weight to the idea that the identification of soil-based zones and subsequent application of differential management strategies has merit on sugarcane farms. 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.

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

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). Meanwhile, a study in which 5 US cornbelt fields were intensively sampled on a 15-m 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 (Boureennane 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, e.g. in maize grown in the 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 wine grapes (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, Robert (2002) described PA as ‘a challenge for crop nutrition management’. 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. At the outset, and apparently without robust scientific justification, grid-based soil sampling was chosen 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). 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 the fertility-driven US one.

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). Grid-based sampling in the US typically involves 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 an intensity as low as one sample per 2.5–5.5 ha is appropriate for the delineation of 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 the application of PA to broadacre crop production, 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 uses 75-m grids (approx. equivalent to 2 samples/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/ha) to one per 1.6 ha (i.e. 0.6/ha) with zone-based sampling and sampling based on local soil maps (1:120 000). While 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 analyses, 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 Meirvenne (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. On the other hand, it is important to note that, in Australia, the adoption of soil testing by farmers has been low compared with other countries such as the USA (Peverill 1993). This is because growers do not see soil fertility as the most important variable governing fertiliser application. Furthermore, 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 at spatial resolutions that are consistent with PA and in a manner that is sufficiently cost effective for the relative importance that growers attach to soil fertility to be enhanced?

In terms of soil sampling, the merits of a directed sampling approach based on electromagnetic (EM) soil survey at high spatial resolution were demonstrated by Bramley (2003b) and Bramley and Janik (2005) for a vineyard situation. In this particular example, the same number of soil samples was 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, while 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 a 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), and 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).
merits of a new soil test are nearly always assessed by comparison with the existing test, which may itself be far from optimal. As McKenzie et al. (2003) conclude, the aim of characterising spatial variation in soil properties is best satisfied by ‘measuring more less well’. With 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 with laboratory-based alternatives. In the opinion of this author, until such time as a range of on-the-go sensors are available with a capability for 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 laboratory-based spectroscopy methods will probably offer the best way forward for agricultural industries such as sugar. McKenzie et al. (2003) and Adamchuck and Viscarra-Rossell (2009) provide reviews of the potential benefits and opportunities of rapid soil measurement. A summary of the currently available technologies is given in Table 1.

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

The predominant means of acquiring information about soil variation at high spatial resolution involves EM measurement 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. Williams and Baker 1982; Williams and Hoey 1987; Rhoades 1992), and have also been used to assist with practical agronomic decision making for several years (e.g. Evans 1998), including in the Australian 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 by Corwin and Plant (2005 and references therein), while Gebbers and Lück (2005) provide a useful comparison of the various EM sensing technologies currently being used in Europe.

Fundamentally, EM survey measures the bulk electrical conductivity (EM38) or resistivity (VERIS) of the soil over a defined depth range. An excellent explanation of which soil properties are reflected by EM instruments and a hierarchy of their importance to the EM signal are given by McBratney et al. (2005a), along with an attempt, using some first principals of soil science, to make interpretative use of the numbers recorded by EM instruments. In saline soils, the effects of salinity and its variability will dominate the EM signal (e.g. Bramley 2003a). 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 (e.g. Bramley 2003b) to be identified. However, because the EM signal may potentially reflect a range of properties, it is not possible to make a priori assumptions about the nature of the information that an EM survey will provide. Thus, if the aim of the survey is to infer variation in specific soil properties, EM 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. However, this does not mean that the sugar industry needs to spend time and money in evaluating the utility of EM methods. The recent work of Kingston et al. (2005) is a good example of this sort of wasted research effort; EM survey is a mature science and the sugar industry should feel able to use it with confidence.

As indicated, elevation is commonly found to be a valuable data layer in understanding variability in crop production. Similar utility is to be expected in the sugar industry where production is

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

Capacitance probe and other similar technologies for in situ assessment of soil moisture have deliberately been excluded from this list. Several such technologies are readily commercially available.

<table>
<thead>
<tr>
<th>Method</th>
<th>Laboratory/field/on-the-go</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-infrared reflectance</td>
<td>Laboratory/field?</td>
<td>Correlative technique. Good characterisation of mineral and organic surface properties and some bulk physical properties; less effective for measurement of plant nutrient availability</td>
</tr>
<tr>
<td>Near-infrared reflectance</td>
<td>Laboratory/field/on-the-go?</td>
<td>As above. A tyne-mounted sensor has been developed by Japanese researchers. Unclear how wide a range of soils this would work in</td>
</tr>
<tr>
<td>Visible/near-visible reflectance</td>
<td>On-the-go via remote or proximal sensing</td>
<td>Remote sensing is unlikely to yield information from deeper than 2 mm into the soil profile</td>
</tr>
<tr>
<td>Ion-exchange resins</td>
<td>Laboratory or field (in situ)</td>
<td>In situ method. Has advantage of accounting for both surface chemistry and diffusive limitations to nutrient availability</td>
</tr>
<tr>
<td>ISFET</td>
<td>Field/on-the-go</td>
<td>Potentially highly effective for real-time sensing</td>
</tr>
<tr>
<td>Electromagnetic induction</td>
<td>Field/on-the-go</td>
<td>Widely used as an indicator of soil variability. Ground-truthing to soil properties of interest is essential</td>
</tr>
<tr>
<td>Resistivity</td>
<td>On-the-go</td>
<td>As above. Two commercially available systems Highly material dependent. Potentialy useful for identifying variation in soil moisture content</td>
</tr>
<tr>
<td>Ground-penetrating radar</td>
<td>Field/on-the-go/airborne</td>
<td>Detects natural decay of isotopes of K, U, and Th. Most useful for sensing variation in clay mineralogy</td>
</tr>
<tr>
<td>γ-radiometrics</td>
<td>Field/on-the-go/airborne</td>
<td>Load sensor easily mounted on a standard tractor 3-point linkage</td>
</tr>
<tr>
<td>Draught resistance</td>
<td>On-the-go</td>
<td></td>
</tr>
</tbody>
</table>
rain-fed and where laser-levelling has not been used. In irrigated areas, and in others where land planing or ‘laser-levelling’ has been used, access to elevation data pre-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). Access to elevation data may also assist in distinguishing between management-induced and inherent soil variation.

**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. 2005), the obvious question is: why is it so?

A key issue among many farmers, and broadacre cereal growers in particular, is a perceived lack of benefit. Since there is more evidence to the contrary than there is in support of this view (Griffin and Lowenberg-DeBoer 2005; Robertson et al. 2009), this perception among farmers may reflect a need for an enhanced extension effort from researchers, service providers, and equipment manufacturers aimed at demonstrating what is needed (time, money, and effort) for benefits to accrue. On the other hand, 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 or even non-existent for others. Whatever, PA researchers and extension staff must recognise that a majority of farmers are not ‘profit maximisers’; other factors affect their decision making. As this is a generic issue, more extension of PA in terms of its potential for enhancing profitability may not lead to increases in adoption.

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 with 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). While 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 $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 grain 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. $2500/year) is viewed by many Australian farmers, even in high value crops like wine grapes, as expensive and a disincentive to its use. The commodity-specific nature of some technologies (i.e. you cannot 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 2 presents a simple schematic of PA. Yet careful consideration of the various technologies identified in Fig. 2 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. So how might a farmer obtain 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 among independent agronomic advisors, partly due to their skill base and, in particular, conservatism among 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 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 among agronomic researchers. Indeed, it is striking that, in spite of a growing understanding of the sort of spatial variability shown in Fig. 1, and its implications for agronomic experimentation (Adams and Cook 1997, 2000; Cook and Bramley 2000; Bramley et al. 2005a), 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, while 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 subregions of a single paddock ranged from <30 to >200 kg N/ha, while 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. It is therefore of little surprise that perceived lack of agronomic relationships should be a reason
contributing to poor rates of PA adoption. Note, however, the cyclical nature of PA (Fig. 2) and consequent opportunity to use data collected at time $A$ in a predictive sense to guide decision making at time $B$.

Given the relative lack of support among 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. Indeed, the adoption of PA could be described as a ‘discontinuous technology change’ (Traffiler and Tscharke 2007) given that for many, it ‘breaks with existing technological experience’ and/or will ‘destroy acknowledged paradigms’ as illustrated by the nutrient management examples of Cook and Bramley (2000), Bramley and Janik (2005), and Doerge (2005). In this connection, Lowenberg-DeBoer (2003) notes that while the unwillingness of farmers to commit ‘management time’ to PA may present an opportunity for consultants and other service providers, this same unwillingness of farmers to undertake their own computer analysis and decision making may be a key impediment to adoption. Robert (2002) makes a similar suggestion which is strongly supported by the results of a farmer survey conducted by Fountas et al. (2005) in the US and Denmark. Wong et al. (2005) have also suggested that a perception that PA-derived knowledge should replace existing farmer knowledge has also been a disincentive to adoption among Western Australian wheat farmers, 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. Douthwaite et al. (2001) make a similar point about agricultural innovation more generally. Clearly, adoption of such methods in the sugar industry, along with those relating to the collection, processing, analysis, and management/storage of data, will be dependent on appropriate effort being put into PA capacity building among cane growers, consultants, and researchers.

Opportunities and research requirements for PA in the Australian sugar industry

Despite the evidence from grains and wine grapes 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 by potential adopters of PA 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—sugarcane is 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 generally 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 affect it. Desirably, the first 3 should be tackled together, with economic evaluations of the answers obtained conducted as and when results become available. As a part of this work, and arguably as a precursor to it, an issue that requires immediate attention in the sugar industry is assessment of the relative merits of the various sugarcane yield monitoring systems, and provision of guidance on the robust calibration of chopper pressure sensor-based yield monitors. For gravimetric-based sensors such as the USQ system and its numerous international variants, 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 e.g. Bramley and Williams 2001). In the case of yield monitors based on the sensing of hydraulic pressure in the choppers, it is not clear on what basis chopper pressure, and the other indices measured, are converted to yield. A key question relates to the form of the relationship between pressure and yield. Assumption of linearity based on yield monitor and mill 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 for harvester tracking purposes, with all of these potentially convertible to yield monitors through addition of off-the-shelf pressure sensors at a cost of around $800 (J. Markley, Mackay Sugar, pers. comm.). For operators to have confidence in such pressure sensor-based systems, and an understanding of their level of accuracy, clear instructions on their calibration are needed, along with development of an appropriate protocol for converting the data to yield maps. In the latter regard, modification of the protocol developed for wine grapes (Bramley and Williams 2001) would be a useful starting point.

In the meantime, Fig. 3 provides strong evidence that under uniform management, some parts of sugarcane fields may operate at a loss. Note that the map shown in Fig. 3 was produced at a time when the world sugar price was about US$12c/lb. It subsequently fell to around US$5c/lb before recovering to its present level (approx. US$13.5c/lb in August 2008). 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...
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 (Bramley and Janik 2005). 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 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. (2005a), Bishop and Lark (2006), and Panten et al. (2008), traditional forms of experimentation based on classical ‘Fisherian’ statistics (i.e. analysis of variance or ANOVA) ignore the kind of spatial variability shown in Fig. 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 affected by the underlying spatial variation, which is not random. Figure 4 illustrates the problems posed for traditional plot-based experiments by underlying variability. 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 Figs 1–4 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 suboptimal, 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, while Bramley et al. (2005a) and Panten et al. (2008) have demonstrated the implementation of this approach to vineyard management. An important difference between this approach and the more traditional plot-based experiments is that it promotes a move away from the idea that treatment A might be better than treatment B, and instead recognises that whereas treatment A may deliver greatest benefit in some areas of a paddock, treatment B may do so in others. Thus, Panten et al. (2008) have highlighted the application of a geostatistically based method (Bishop and Lark 2006) for analysing the results of whole-of-block experiments, noting its value in demonstrating that both the response to treatments and the significance of differences between treatments may be spatially variable. Given that cane is grown as a row crop, this viticultural research may usefully inform application 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 is a potential application 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

Fig. 4. Possible locations for a classical agronomic experiment (a) in the absence of knowledge of underlying variation, and (b) using one of the same designs but where information about underlying variation is available; in this case, a yield map (Bramley et al. 2005a).
doubtless be other aspects of sugarcane agronomy which could be advanced through the whole-of-block approach.

Conclusions and recommendations for future work

Precision Agriculture can be considered just as applicable to sugarcane production as to other crop production systems. However, and based on the foregoing discussion, several key tasks in RDE will be required to enable its implementation in the Australian sugar industry. It is expected that most of these will apply in other sugar industries in other countries. 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 of the utility of remote sensing for in-field management is needed. As a part of this, the most appropriate and cost-effective spatial resolution and the optimal time of image acquisition need to be determined, along with evaluation of the merits of airborne compared with satellite-based remote sensing platforms.

3. Case studies highlighting the utility (and shortcomings) of the various tools of PA in delineating management zones within sugarcane blocks are needed 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. Opportunities for variable management of irrigation water could 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 on the relative merits of putting effort into removing variation as opposed to managing in response to it, or indeed, of seeking other (non-PA) means of deriving economic benefit. Of course, because many farmers are not profit maximisers, putting appropriate boundaries around the latter may be problematic.

4. Evaluation of the utility of whole-of-block approaches for sugarcane agronomic experimentation and the development of site-specific management strategies and site-specific criteria for interpretation of soil test data would be valuable and provide a robust basis for refining agronomic practice.

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. 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. The case for development of companion sensors for other attributes of cane quality, including key sugar impurities, based on appropriate economic modelling, needs to be established. Such a study would sensibly include input from millers and sugar refiners.

7. Evaluation 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.

In addition, there would be much value in initiating field-based research aimed at demonstrating the contribution that PA can make to improved environmental stewardship (Bramley et al. 2008). While 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 that cannot be overstated.

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