

## Precision Agriculture for improved environmental outcomes: Some Australian perspectives

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### Abstract

Precision Agriculture (PA) can be regarded as a means of increasing the chance that the inputs to production are applied in the right amounts in the right place at the right time. Intuitively, if farmers adopting PA are successful in achieving this objective, the likelihood of negative environmental impacts arising should be reduced. Conversely, where the likelihood of a negative environmental impact is shown to be high, the opportunity for reducing the amount of inputs used, and/or increasing their efficiency of use, should be apparent.

This paper explores these issues using examples from the Australian sugar and dairy industries. We conclude that the use of spatial data to better inform agricultural management can make a valuable contribution to reducing the risk of negative environmental impact whether applied in the implementation of PA (field and within-field scales) or at whole farm or regional scales. However, for the maximum environmental benefit to accrue through PA, the existing regional or whole-of-industry management guidelines need to be replaced by guidelines for site-specific management. This in turn will require a considerable enhancement to existing agronomic understanding.

*Keywords: Spatial variability, sugarcane production, intensive dairy farming, water quality, experimentation*

### Zusammenfassung

Precision Agriculture (PA) erhöht die Wahrscheinlichkeit landwirtschaftliche Produktionsmittel in richtiger Menge, am richtigen Ort und zur richtigen Zeit anzuwenden. Im Umkehrschluss kann davon ausgegangen werden, dass Landwirte die PA erfolgreich einsetzen und die oben genannten Ziele erreichen, negative Umwelteinflüsse aus landwirtschaftlichen Produktionsprozessen reduzieren können. Weiterhin kann angenommen werden, dass in Fällen in denen starke negative Umwelteinflüsse durch Landwirtschaft nachgewiesen sind, PA die Möglichkeit bietet den Einsatz von landwirtschaftlichen Betriebsmitteln zu reduzieren bzw. ihre Effizienz zu steigern.

Im folgenden Artikel wird diesen Fragen an Beispielen aus der Australischen Zucker- und Milchindustrie nachgegangen. Zusammenfassend kann festgestellt werden, dass die Verwendung räumlicher Daten im Zuge einer verbesserten landwirtschaftlichen Betriebsführung, entscheidend zu einer Verminderung des Risikos negativer Umwelteinflüsse beitragen kann, unabhängig davon, ob PA auf der Feldebene, Betriebsebene oder regionalen Ebene angewendet wird. Um den ökologischen Gewinn aus der Anwendung von PA zu maximieren, ist es jedoch notwendig existierende, herkömmliche Bewirtschaftungsrichtlinien durch Leitlinien für räumlich variable Landbewirtschaftung zu ersetzen. Dies wiederum setzt eine wesentliche Erweiterung des bestehenden landwirtschaftlichen Verständnisses voraus.

*Schlüsselworte: Räumliche Variabilität, Zuckerrohrproduktion, intensive Milchviehhaltung, Wasserqualität, Versuchsanstellung*

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## Introduction

Agriculture is increasingly under pressure to meet public demands for improved environmental performance, sustainability of practices, and accountability for the traceability, quality and safety of its products (Ancev et al., 2005). In Australia, as in Europe (e.g. Stoorvogel and Bouma, 2005), "improved environmental performance" is generally taken to infer minimisation of the impacts of agriculture on water bodies, whether these be groundwater, rivers and lakes, or the sea. An obvious question is: how might "improved environmental performance" be achieved and demonstrated?

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 variable. It involves the collection of data describing the performance of the production system (e.g. yield, quality) and its inherent characteristics (e.g. soil properties) at high spatial resolution, and the subsequent use of this data to assist with management decision making. As such, PA is also a response to the 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.

Because of the inherent variability of land (i.e. topography, soil properties), the input-output relationships (Cook and Bramley, 1998) driving agricultural production systems vary spatially, often over distances of only a few metres (McBratney and Pringle, 1999). PA seeks to promote a better understanding of these relationships and provide a means of targeting management in response to them in such a way that the likelihood of a beneficial outcome being achieved is increased, whether in respect of the better targeting of inputs (e.g. Cook and Bramley, 1998) or selective harvesting of outputs (e.g. Bramley et al., 2005b). Thus, PA may be regarded as a form of agriculture which "increases the number of correct decisions per unit area of land per unit time with associated net benefits" (McBratney et al., 2005).

Intuitively, if a producer makes a "correct decision" in regard to an input such as nitrogen fertilizer, its efficiency of use should be enhanced, with the consequence that the chance of the nitrogen being leached to groundwater or exported off-site via runoff is reduced. Some industries have been quick to use this idea as a basis for promoting both the adoption of PA, and in cases where there has been some adoption, the environmental credentials of the industry (e.g. Wrigley and Moore, 2006). However, experimentally-based demonstration of the ability of PA to contribute to improved environmental stewardship has proven difficult judging by a dearth of scientific literature on the subject. Not the least of reasons for this is the fact that agriculture is generally regarded as a diffuse source

of pollution rather than a point source. However, Wong et al. (2006) and Stoorvogel and Bouma (2005) present evidence from Western Australia and Holland of the potential contribution of PA to minimising the risk of NO<sub>3</sub> leaching. Here, we also focus on the environmental component of "net benefits" (McBratney et al., 2005) and provide an additional Australian perspective to the evaluation of the role for PA in protecting water bodies from the negative impacts of agriculture.

## Environmental management in Australia

Constitutionally, Australia is a Commonwealth of States. Land and water management in Australia is a responsibility of the State and Territory Governments, whilst the Federal Government plays an important role in helping to coordinate efforts and activities across state and territory borders. In both land and coastal domains, regional input into natural resource management (NRM) by local stakeholders is coordinated through Catchment Management Authorities (CMAs) and NRM Boards.

In coastal regions, the major focus of the Federal Department of the Environment, Water, Heritage and the Arts (DEWHA) is on achieving significant reductions in the discharge of pollutants to agreed water quality 'hotspots' through its Coastal Catchment Initiative (CCI) program. The CCI, together with the relevant jurisdictions (i.e. State and Territory Governments), identify and agree on coastal hotspots and promote competent water quality planning to improve and protect water quality. To this effect, the CCI has been funding the development and implementation of Water Quality Improvement Plans (WQIPs) for various coastal hotspots around Australia, including the Great Barrier Reef region (The State of Queensland & Commonwealth of Australia, 2003). A WQIP will identify the most cost-effective and timely projects for investment by all parties - including the Australian Government, State and Local Governments, and community and environment groups.

A WQIP includes three key components. First, it identifies the Environmental Values (EVs) of water bodies and the Water Quality Objectives (WQOs) that will protect these. Next, it estimates the sustainable target loads based on the WQOs, and compares these with the estimated current pollutant loads. Finally, it identifies management action targets, and associated management actions, that will result in progressive (quantified) reductions in the pollutant loads from both diffuse and point sources required to achieve sustainable loads.

The framework for setting EVs and WQOs is well established through the National Water Quality Management Strategy (ANZECC, 1994, 1998). Furthermore, in the State of Queensland, this framework is embedded in the *Environmental Protection (Water) Policy 1997* (State

of Queensland, 1997). The preferred uses and values of local water bodies are determined by identifying the EVs, which are categorised into aquatic ecosystems, primary industries, recreation and aesthetics, drinking water, industrial uses, and cultural and spiritual values. Based on the community's choices for EVs, and the water quality guidelines and standards to protect them (ANZECC, 2000), draft water WQOs are identified. These draft WQOs can be considered 'trigger values', that would indicate a potential environmental problem if exceeded, and 'trigger' a management response. Note that in Queensland, whilst it is possible for EVs to be scheduled under the Queensland *Environmental Protection Act*, WQIPs currently have no 'teeth'. That is, their effectiveness is essentially dependent on voluntary self-regulation by local industries. The threat nevertheless remains that Government will regulate perceived polluters if WQOs are either not met, or actions are not taken towards meeting them. This raises the question as to which actions individuals or industries might take in order to reduce the possibility of a WQO being exceeded.

### Precision Agriculture, sugarcane production and protection of the Great Barrier Reef

The Great Barrier Reef (GBR; Figure 1) contributes an estimated A\$6.9 billion per year to the Australian economy, principally through tourism activities (Access Economics, 2007). The economic contribution depends on the maintenance and enhancement of the environmental values of the GBR aquatic ecosystems. To protect the GBR, and its environmental values, from land based sources of pollution, the Australian and Queensland Governments jointly developed and launched the *Reef Water Quality Protection Plan* (the 'Reef Plan'; The State of Queensland & Commonwealth of Australia, 2003). The goal of the Reef Plan is 'to halt and reverse the decline in water quality entering the Reef within 10 years'. A key aspect of implementing the Reef Plan is the development and implementation of WQIPs for high risk coastal catchments. The primary concern of these WQIPs is the reduction of sediment, nutrient and pesticide loads in water entering the GBR.

Fifteen river catchments covering an area of approximately 375,000 km<sup>2</sup> drain into the GBR Marine Park (GBRMP) which itself covers around 350,000 km<sup>2</sup> and spans almost 2,000 km of coastline (Johnson et al., 2001). In areal terms, landuse within these catchments is dominated by extensive grazing of unimproved pastures in the more inland areas. However, in the coastal floodplains immediately adjacent to the GBRMP, intensive cropping, dominated by sugarcane production, is a major land use (Figure 1); further details are provided by Johnson et al. (2001). The close proximity of this intensive land use to the GBRMP coupled with high and strongly seasonal tropical

rainfall, raises the likelihood that land use signals may be evident in both fresh and marine waters, especially during peak flood events (Mitchell et al., 1997; Furnas and Mitchell, 2001; see also <http://www.clw.csiro.au/new/2007/sedimentplumes.html> - last accessed April, 2008). Again, this raises the question as to what actions individuals or industries might take in order to ensure that the WQOs of the WQIPs in the GBR region are met?

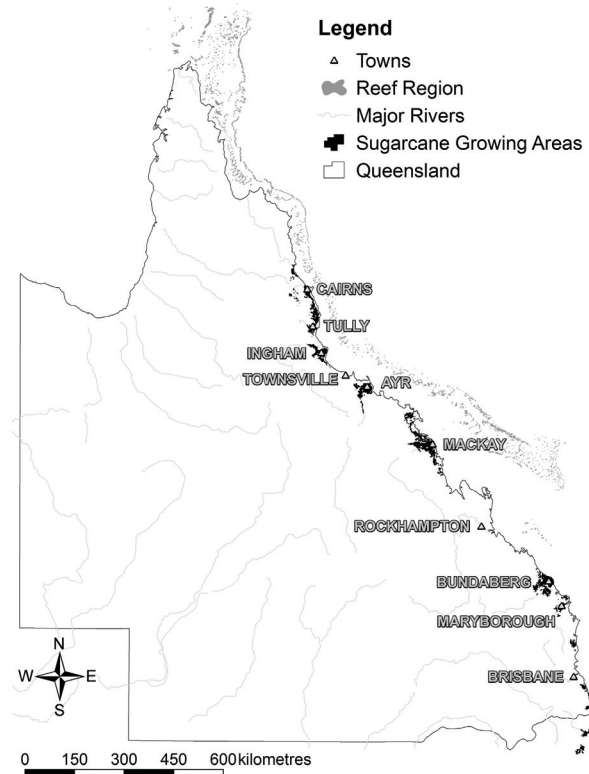


Figure 1:  
The Great Barrier Reef and Queensland Sugar Industry

In a study of land use impact on water quality in the lower Herbert River catchment, Bramley and Roth (2002) demonstrated that compared to grazing and forestry, sugarcane production had a significant impact on riverine water quality, as evidenced by higher concentrations of nitrogen (N), phosphorus (P) and total suspended solids (TSS) in stream-waters draining land under sugarcane. Notwithstanding that major rainfall events during this study tended to occur in coastal, rather than inland (i.e. grazed) regions, inclusion of sampling sites that were dominated by upper-catchment grazing did not alter the conclusion that land under sugarcane was the predominant source of pollutants. Thus, it was concluded that there was considerable room for improvement in the management of land under sugarcane with the aim of minimizing the off-site export of nutrients and sediments.

### *Improving management of sugarcane production at regional and industry scales*

Until recently, the management of fertilizers by Australian growers of sugarcane was based on recommendations (Calcino, 1994) that were applied ubiquitously throughout the cane-growing regions of Queensland with almost no account taken of either between or within region soil differences. Thus, in the case of P for example, the recommendations did not account for the likelihood that different soils under sugarcane production would have differing P sorption behaviour (Wood, 1988; Bramley et al., 2003) and therefore differing abilities to supply P to the crop (Moody and Bolland, 1999; Burkitt et al., 2002), or indeed, release it to the environment. Bramley et al. (2003) made use of the availability of an intensive (1:5,000) regional soil survey (Wood et al., 2003) coupled with indices of P sorption by both the soils surveyed, and by sediments derived from them (Edis et al., 2002), and of the susceptibility of the soils to runoff, to map spatial variation in the potential for P loss from Lower Herbert land under sugarcane. They also proposed an 'environmentally sound basis for P fertilizer management' based on integration of this potential for P loss with a knowledge of the P requirements of sugarcane and the index of soil P sorption.

From a philosophical point of view, the approach suggested by Bramley et al. (2003) is PA applied at regional scale. That is, spatial variation in soil P behaviour in the Herbert district formed the basis of targeted application of P to 'zones' delineated on the basis of soil type, rather than the standard P fertilizer recommendations of Calcino (1994). More recently, Schroeder et al. (2006) have followed a similar approach based on an understanding of soil properties to ensure that fertilizer management is better matched to both the crop demand for nutrients and the soil's ability to provide them. This approach, known as '6 easy steps' and using a series of regionally based, soil-specific sets of fertilizer recommendations, is currently being rolled out to the industry (e.g. Schroeder et al., 2007).

### *Improving management of sugarcane production at paddock and sub-paddock scales*

Notwithstanding the potential for initiatives such as the '6 easy steps' to elicit changes to the management of sugarcane production that are consistent with the Reef Water Quality Protection Plan (State of Queensland and Commonwealth of Australia, 2003) at regional scales, we were interested in assessing the potential of PA to provide further improvements to the environmental performance of

the sugar industry at the paddock scale<sup>1</sup>. This follows from the recent widespread adoption of GPS-guided controlled traffic and consequent industry interest in PA (Bramley, 2007), together with earlier exploratory work (Bramley et al., 1997, 1998; Bramley and Quabba, 2001) which suggests that within-paddock yield variation in sugarcane production systems is of a similar order of magnitude as for other crops (Cook et al., 2006; Figure 2).

Whilst the soil-specific fertilizer management strategy proposed by Schroeder et al. (2006) has attractions as a means of improving the efficiency of fertilizer use, its effective implementation is dependent on access to soil maps at appropriate scale. It also relies on the concept of soil types and their spatial arrangement rather than individual soil properties which may themselves vary considerably for any given soil type; Moody (1994) provides a nice illustration of this for Krasnozems which are common in the Australian wet tropics. For PA applications, it is reasonable to assume that soil data will be required at higher resolution than is conventionally available in regional maps of soil type (typically 1:50,000 or 1:100,000). Thorburn et al. (2003b, 2007a,b) have recently proposed a strategy for N fertilizer management for sugarcane based on the idea of maintaining nutrient balances through nutrient *replacement*. They proposed that the amount of N to be applied this year is based on that removed in the previous crop, plus an amount unavoidably lost to the environment, reasoning that these combined N losses are 1 kg N t<sup>-1</sup>. Thus, the N application to a sugarcane crop with the replacement strategy requires application of 1 kg N t<sup>-1</sup> of harvested sugarcane from the previous crop. They argue that in an overwhelming number of situations, the soil under cane will be in a 'quasi-steady state' with respect to its organic matter content because of the long history of sugarcane production, often as a monoculture (Garside et al., 1997). Obviously there will be short term changes in organic matter resulting, for example, from the annual addition of cane trash (10–20 t ha<sup>-1</sup>) to the soil during harvest (Robertson and Thorburn, 2007). But these changes around the steady state value represent short-term periods of net immobilisation or mineralisation of N. Thorburn et al. (2007a,b) have demonstrated that the strategy may deliver significant environmental benefits over conventional practice without compromising profitability.

Because this approach depends only on a knowledge of yield, it lends itself to application where yield mapping forms a part of the implementation of PA, especially where detailed knowledge of soil fertility parameters is sparse. The N Replacement strategy was developed and its implementation tested in paddock-scale field experiments

<sup>1</sup> Note that throughout this paper, the terms 'paddock' and 'block' are used to refer to a single field or farm management unit.

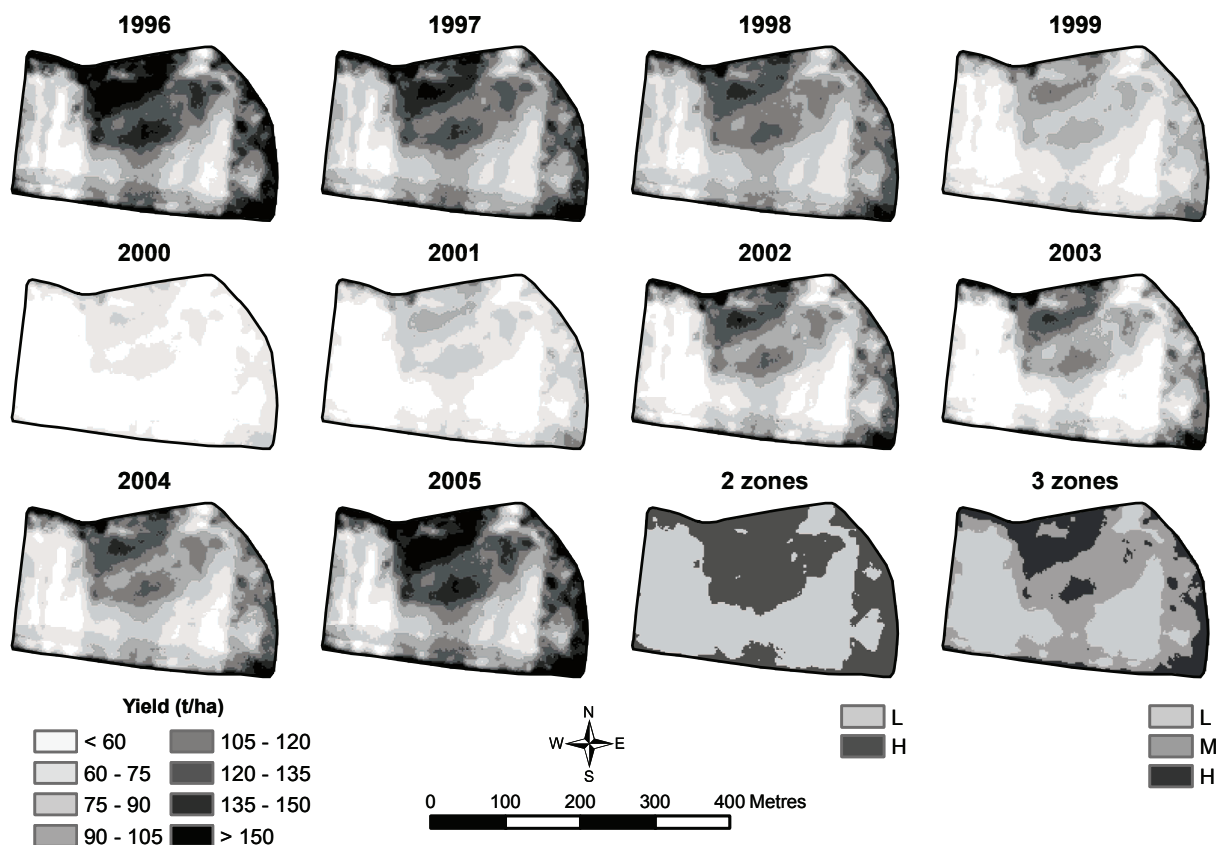


Figure 2: Estimated (and in 1998, actual) yield in a 6.7 ha Herbert River sugarcane paddock, 1996-2005

conducted in most sugarcane growing regions in Australia (Thorburn et al., 2007a,b; Webster et al., 2008). However, at that scale there are considerable yield differences (Figure 2). So the fact that the N Replacement system gives similar yields compared with higher N applications (Thorburn et al., 2007a,b; Webster et al., 2008) suggests both that high yielding parts of the block are being adequately fertilised and that lower yielding parts of the block are being over fertilised. Thus, application of the N Replacement concept at smaller spatial scales, as can be achieved through yield mapping and variable rate fertilizer application, may allow N applications to be reduced in some parts of a block.

Here, we assess what potential additional benefits might accrue through integration of the N Replacement strategy with variable rate fertilizer application – a technology that might be expected to be used by a farmer adopting PA. Such an approach requires access to yield maps for previous years. Our analysis is based on a single yield map obtained in 1998 from a 6.7 ha block of cane from the Herbert River district (Bramley and Quabba, 2001); the cane in this block was 1<sup>st</sup> ratoon in 1998. Because we only had access to yield maps for this block for a single year (1998),

we had to simulate yield maps for other years (Table 1).

The 1998 yield map was interpolated using a procedure based on that developed for winegrape yield mapping (Bramley and Williams, 2001) and a normalised ( $\mu=0$ ,  $\sigma=1$ ) version of this map was produced. Knowing the mean district cane yields (Table 1), and ignoring the tendency for yields to decline gradually through the ratooning cycle, estimates of the mean yield in our block of interest were made for the period 1996-2005 using simple linear scaling of the 1998 mean yield against the known annual district mean yields. Annual rainfall data were accessed for the 1996-2005 period from Australian Bureau of Meteorology records. We used these to modify the range of variation present in the simulated yield maps based on the assumption that within-paddock variation was likely to be greater in dry, compared to wet years. A random number generator was used to generate estimates of the coefficient of variation (CV) in kriged yield data (i.e. in the simulated yield maps) between values of 20 and 40 %. These were ranked and assigned to individual years in order of annual rainfall. Thus, the simulated yield map for 2003, the driest year (Table 1), was assigned the highest randomly generated CV (38 %), whilst the wettest year (2000) was

assigned the lowest CV (22 %). Knowing the mean estimated block yields for each year, the standard deviation of mapped yield was calculated from these CVs and the normalised 1998 yield map then back-transformed to give simulated maps for the ten year period of interest. The results are shown in Figure 2. Also shown in Figure 2 are the results of clustering the yield maps for the 10 year study period into so-called management zones using *k*-means clustering (Cuppitt and Whelan, 2001); 2 and 3 zone solutions are shown.

Table 1:

Estimation of yield and N inputs in a Herbert River sugarcane paddock, 1996-2005<sup>A</sup>

Year	Mean district cane yield (t/ha) <sup>B</sup>	N applied (kg/ha) <sup>C</sup>	Annual rainfall (Sep-Aug) (mm)	Estimated mean block yield (t/ha)	Estimated CV % (kriged data) <sup>D</sup>	Estimated $\sigma$ (kriged data) (t/ha)
1996	97.6	213	1208	111.3	32	35.62
1997	92.0	198	2082	104.8	27	28.31
1998	86.1	209	2846	<b>98.6</b>	<b>23.4</b>	<b>23.11</b>
1999	69.2	204	2556	78.9	24	18.95
2000	48.0	183	3457	54.7	22	12.04
2001	58.2	201	2409	66.4	26	17.25
2002	77.3	205	1161	88.1	34	29.97
2003	71.1	191	949	81.1	38	30.81
2004	81.6	155	1648	93.0	28	26.03
2005	97.3	153	1533	110.9	31	34.38
Mean		190				

<sup>A</sup>1998 data in bold are actual, not estimated, values  
<sup>B</sup>Calculated from sugar mill records  
<sup>C</sup>Data provided by Incitec-Pivot  
<sup>D</sup>CV denotes coefficient of variation

From fertilizer usage statistics obtained from a major supplier of fertilizer to the sugar industry for the 1996-2005 period, 'standard practice' was assumed to be uniform application of N at a rate of 190 kg N ha<sup>-1</sup> y<sup>-1</sup> – the mean rate used in the Herbert River district over the 10 year study period. The maps shown in Figure 2 were then used to estimate the potential loss of N to the environment, and its spatial variability within the block. Four other possible fertilizer strategies were also evaluated. First, the N Replacement strategy of Thorburn et al. (2007a,b) was evaluated assuming that N was applied uniformly at a rate of 1 kg t<sup>-1</sup> mean yield achieved in the previous year (Nrep), and that 0.9 kg N t<sup>-1</sup> yield achieved this year is removed in the crop (Thorburn et al., 2007a,b). Second, a modified version of the Nrep strategy was evaluated with the paddock divided into the 2 management zones identified from the 2 cluster *k*-means clustering shown in Figure 2

(Zone based). Third, the Nrep strategy was modified on the basis that N use efficiency by sugarcane is potentially better than demonstrated at a paddock-scale by Thorburn et al. (2007a,b) because N concentrations in sugarcane (Thorburn et al. 2007b) are lower than that originally assumed by Thorburn et al. (2003b) in developing the strategy. Thus, the third strategy (eff) involved N application at rates of 0.7 or 0.8 kg N ha<sup>-1</sup> t<sup>-1</sup> yield in the previous year to the higher and lower yielding zones with crop removal adjusted to 0.6 kg N t<sup>-1</sup> yield achieved this year. Aside from assuming a more efficient use of N, this strategy also recognises that one consequence of the poorer performing parts of the paddock being lower yielding is that they are also areas of lower N uptake by the crop, relative to the amount applied, and thus are potentially larger contributors of N to the environment. Finally, we simulated the Nrep strategy when implemented using continuous variable rate fertilizer technology (1998 only). To make this more realistic in relation to typical spreading equipment, a fertilizer application map was simulated from the 1997 yield map (2 m pixels) by locally averaging to 10 m pixels. All calculated N application rates were rounded up to the nearest 5 kg N ha<sup>-1</sup>.

In addition to evaluating the effects of these different strategies on the potential for N loss to the environment, their impact on farm income was also estimated. The cost of fertilizer was assumed to be A\$1 kg<sup>-1</sup> N, based on a urea price of A\$460 t<sup>-1</sup>. Harvesting costs were assumed to be A\$6.50 t<sup>-1</sup>, and the sugar price was set at A\$340 t<sup>-1</sup> (equivalent to US\$0.12 lb<sup>-1</sup>); for sake of simplicity, these costs were assumed to be constant for the 10 year study period. It was also assumed that the sugar content of harvested cane (ccs) was invariant in both space and time and was set at 12. The work of Kingston and Hyde (1995) shows this assumption to be incorrect but, in the absence of information about spatial variation in ccs or its relation to spatial variation in yield and in the interests of simplicity, we assumed constant ccs. Using this information and the maps shown in Figure 2, partial gross margins for the various fertilizer strategies evaluated were estimated as gross income from sales of cane, less the costs of fertilizer and harvesting.

The results of this analysis are shown in Figures 3-6 and Table 2. Figure 3 shows the implications for potential N loss to the environment of 'standard practice' and the various strategies based on N Replacement, except continuous variable rate, for 1998 only. As can be seen, application of an industry standard uniform rate of N in 1998 was estimated to result in a much larger N surplus – and thus, potential for N loss to the environment – than the other strategies (Figure 3). When the results are collated for 9 harvest seasons (1997-2005), it can be seen that much of the paddock may potentially leak approximately 1000 kg N over 9 years under the standard practice, whereas each

of the strategies based on N Replacement result in at least some parts of the block where there is no leakage at all (Figure 4). Note however, that because the Nrep strategies depend on calculation of mean paddock yield, irrespective of whether this is partitioned into zones, the Nrep and Zone based strategies yield almost identical results (Table 2) and so Figures 3 and 4 essentially illustrate the effects of the different strategies on spatial variation in N use efficiency. This shows that N surpluses derived following application of any other nutrient management scheme would scale in proportion to the application rates. As the data in Table 1 suggest, 'standard practice' in our analysis results in application of approximately twice as much N as would be applied on the basis of a requirement of 1 kg N t<sup>-1</sup> cane. It also represents application of more N than in the industry recommendations of Calcino (1994); had these been followed (approximately 20 % less N applied), the results presented in Figure 3 and 4 suggest that proportional reduction in N surplus would have resulted. Whatever, the results presented in Figures 3 and 4 strongly suggest that not only is 'standard practice' based on flawed agronomy, but that the N Replacement strategy of Thorburn et al. (2007a,b) almost certainly assumes a higher requirement of sugarcane for N than is in fact the case; indeed, Thorburn et al. (2007b) present field data in support of this view. Thus, application of N following the 'eff' strategy results in further reductions in potential N loss (Figures 4 and 5) but importantly, does not impact on the financial performance of the paddock (Table 2). Also apparent from Figures 4 and 5 is that a lack of perfect knowledge about inter-annual variation in yield potential, driven primarily by variation in climate, results in the possibility of N being in deficit in parts of the paddock in some years.

Figure 6 presents the results of the variable rate strategy and also considers the effect of fertilizer price on the analysis, given that fertilizer N has doubled in price in Australia over the 12 months to June 2008. As can be seen, neither

change in fertilizer price, nor an increase in the efficiency of N use have marked effects on partial gross margins or potential N surplus when the variable rate N Replacement strategy is followed. On the other hand, comparison of Figures 3 and 6 suggests that the variable rate strategy may result in a more uniform efficiency of N use over the paddock as whole; the long term agronomic implications of this are unclear.

Whilst this analysis is somewhat simplistic, it nevertheless sends some messages to the sugar industry that warrant more robust evaluation. First, it seems clear that PA may have a positive contribution to make to minimising off-farm losses of N without reducing the profitability of cane production. Indeed, Table 2 suggests that PA delivers a 'win-win' in that being kind to the environment is also profitable. However, it is equally apparent that PA will deliver little, if any benefit, if it is not combined with good agronomy. Thus, the fact that Thorburn et al. (2007a,b) found that the N Replacement strategy did not lead to loss of yield suggests that sugarcane can do well at less than 1 kg N t<sup>-1</sup>; yields obtained at low rates of N (up to 150 kg N ha<sup>-1</sup> less than conventional practice) also support this view (Thorburn et al. (2003a; 2007b). However, PA offers the significant benefit through yield mapping of enabling identification of the inherently higher and lower yielding areas and therefore those where N use efficiency can be expected to be higher or lower.

In spite of early identification of the potential for adoption of PA by canegrowers (Bramley et al., 1997, 1998; Bramley and Quabba, 2001), it has only been more recently and largely due to widespread adoption of GPS-guided controlled traffic that the Australian industry has once again shown interest in PA (Bramley, 2007). This analysis suggests that PA does indeed offer the basis for minimising the opportunity for N to be lost off-site, and thus of providing the benefits that, hitherto, the industry has assumed to accrue (Wrigley and Moore, 2006).

Table 2:

Summary of implications for profitability and environmental performance of selected N fertilizer management strategies in a Herbert River sugarcane paddock, 1996-2005

	Standard Practice		N Replacement (Nrep)		Nrep – Zonal @ 1kg N/t		Nrep – Zonal @ 0.7 or 0.8 kg N/t		Variable Rate @ 0.7 or 0.8 kg N/t	
	1998	1997-05	1998	1997-05	1998	1997-05	1998	1997-05	1998	1997-05
N applied (kg)	1,273	11,457	704	5327	725	5368	547	4071	502	nd
N surplus (kg)	680	6,792	108	644	129	678	10	-168	104	nd
Gross margin (\$)	11,065	85,620	11,601	91,602	11,616	91,734	11,794	93,031	11,164	nd
Value of N surplus (\$)	680	6,792	108	771	129	786	10	236	104	nd

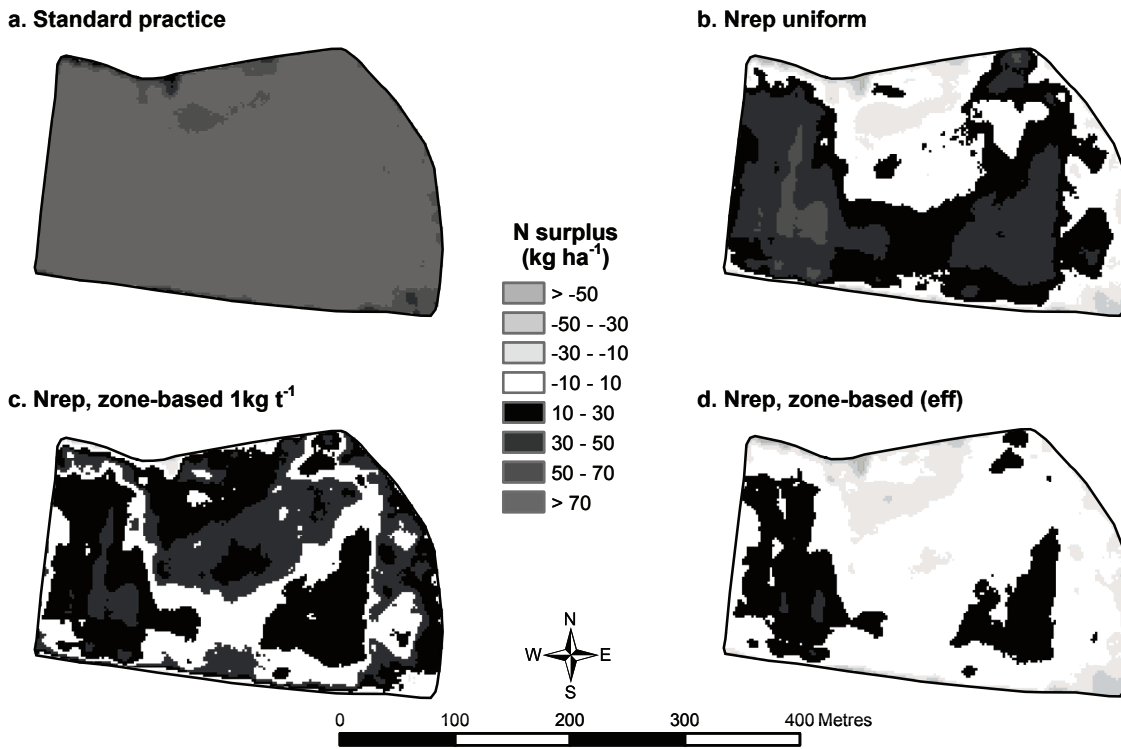


Figure 3:

Estimated potential N surplus derived from a 6.7 ha Herbert River cane paddock in 1998 when under various fertilizer management strategies. Three strategies simulated assuming N offtake by the crop of 0.9 kg N t<sup>-1</sup> were (a) uniform application of 190 kg N ha<sup>-1</sup>; (b), uniform application of N following the replacement strategy of Thorburn et al. (2007a,b); and (c) zone-based differential application of N based on the strategy of Thorburn et al. (2007a,b). Also shown in (d) is the N surplus when the N requirement and offtake was assumed to be 0.7 and 0.6 kg N t<sup>-1</sup> in the high yielding zone, but 0.8 and 0.6 kg N t<sup>-1</sup> in the low yielding zone

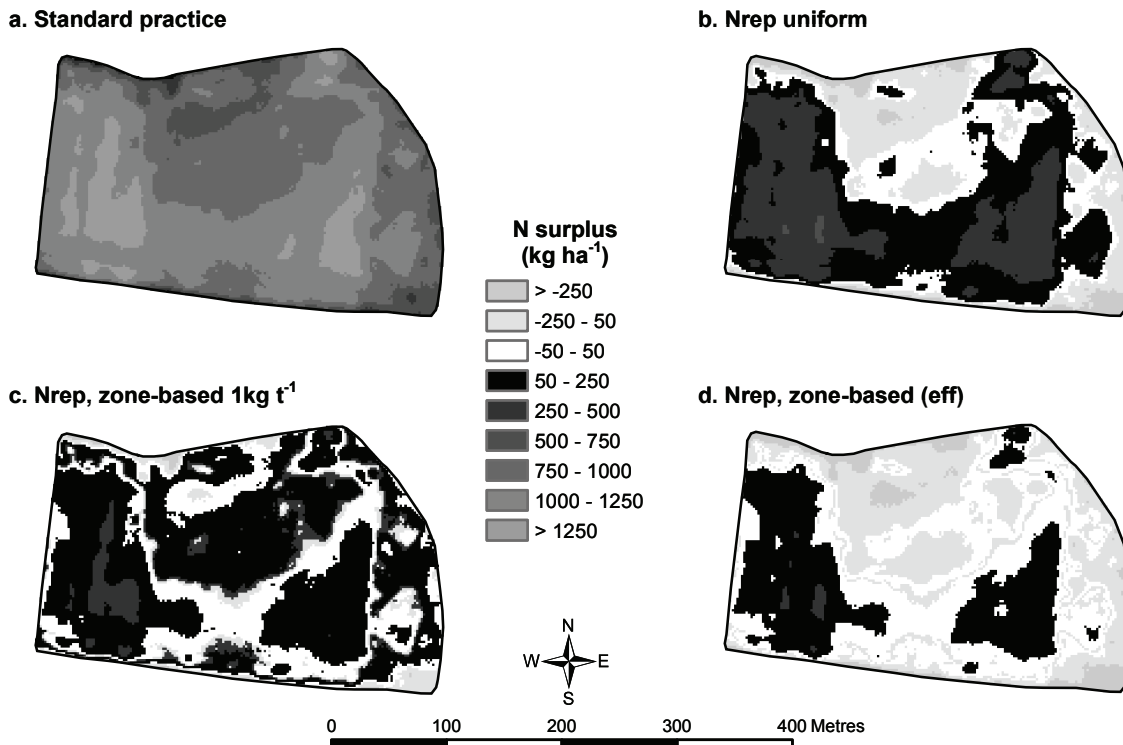


Figure 4:

Estimated N surplus from a 6.7 ha sugarcane paddock over a nine year period (1996-2005). The legend is as per Figure 3



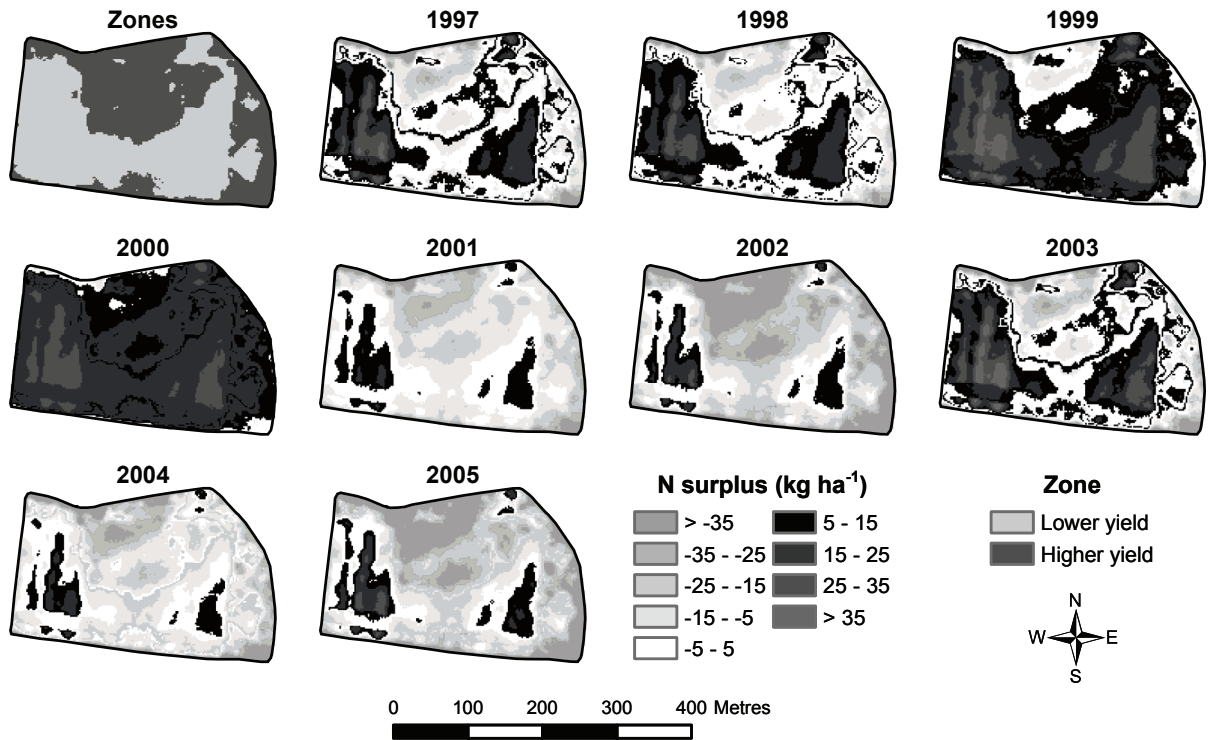


Figure 5.  
 Estimated N surplus over 9 years under a zonal N management strategy assuming N use efficiency of 0.6 kg N t<sup>-1</sup>

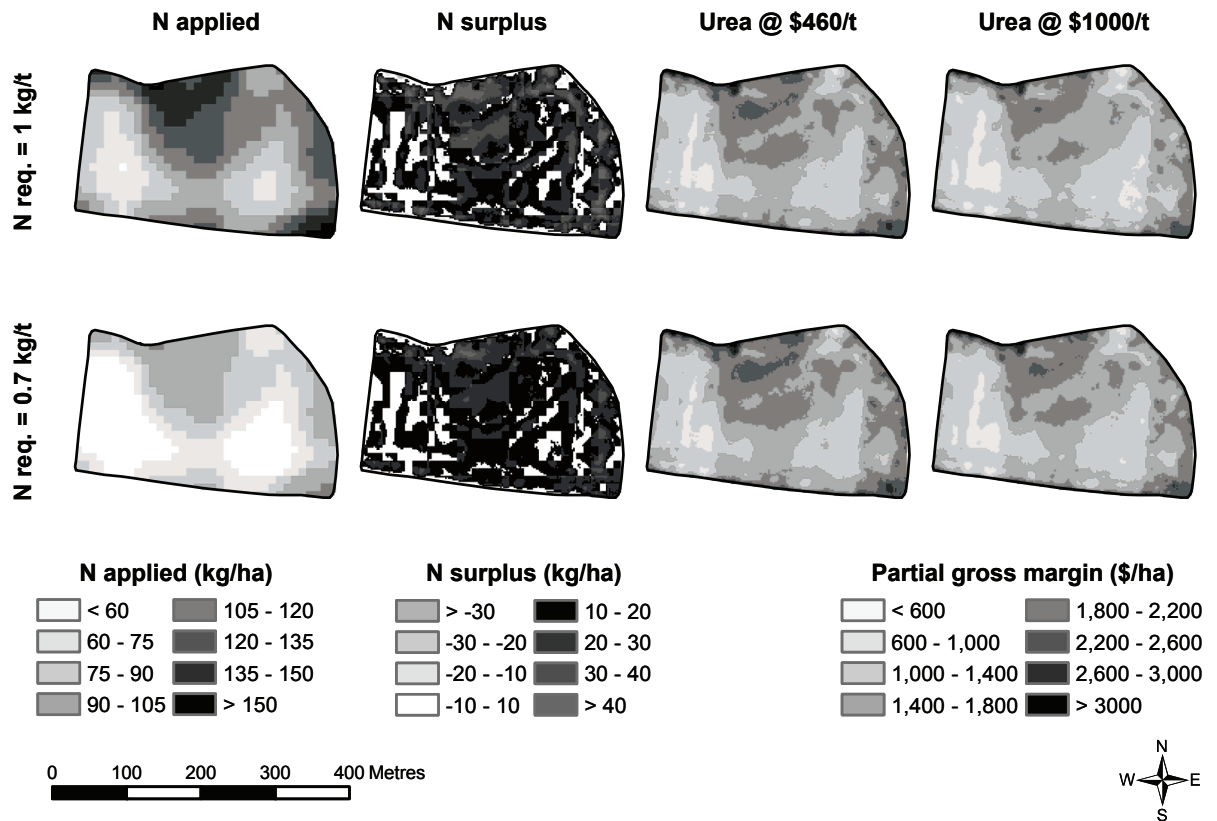


Figure 6:  
 N surplus following variable rate application in 1998 and the effect of fertilizer price on the partial gross margin from N use

**Best practice is dependent on access to spatial data – a second example from the dairy industry**

Intensive dairying is a major land use in the Gippsland region of Victoria (Figure 7), supplying milk and dairy products to much of Australia. However, in a somewhat similar situation to that confronting the sugar industry in Queensland, the region is bounded at its most downstream end by the Gippsland Lakes, a significant area of wetland of major ecological significance. As with the GBR, there are concerns that agriculture in the region may negatively impact on the lakes.

Ellinbank is a 180 ha research dairy farm operated by the Victorian Department of Primary Industries; approximately 150 ha is under dryland dairy pasture. Best management practice with respect to all facets of dairy production is considered to be implemented here. The farm is fenced into small (< 2 ha) paddocks, and these paddocks are cell-grazed using temporary electric fencing. Effluent is applied strategically and conservatively to approximately 10 ha of the farm, and irrigation is used only on fodder crops. The farm runs approximately 400 milking cows, with an average stock density of 2.7 cows / ha.

Following concern at the potential for nutrient loss from intensive dairy farms, the Farm Nutrient Loss Index (FNLI; Melland et al., 2007) was developed as an educational tool to help farmers understand about nutrient budgeting and loss. Whilst FNLI may achieve its original educational objectives, its implementation as a management aid is limited by the fact that, because it is a paddock-based assessment tool, it does not accommodate spatial continuities and so does not permit interaction between paddocks, which is critical to the management of dairy systems given the movement of stock. Recently, Hill (2008) has addressed this issue by implementing a modified version of FNLI in a GIS following the schema shown in Figure 8. Her objective was to facilitate examination of the *risk* of nutrient loss in agricultural landscapes, using inherent biophysical factors combined with dynamic management factors to determine nutrient loss *likelihood*. Here, we illustrate this with regards to fertilizer N and the risk of it being lost via surface runoff.

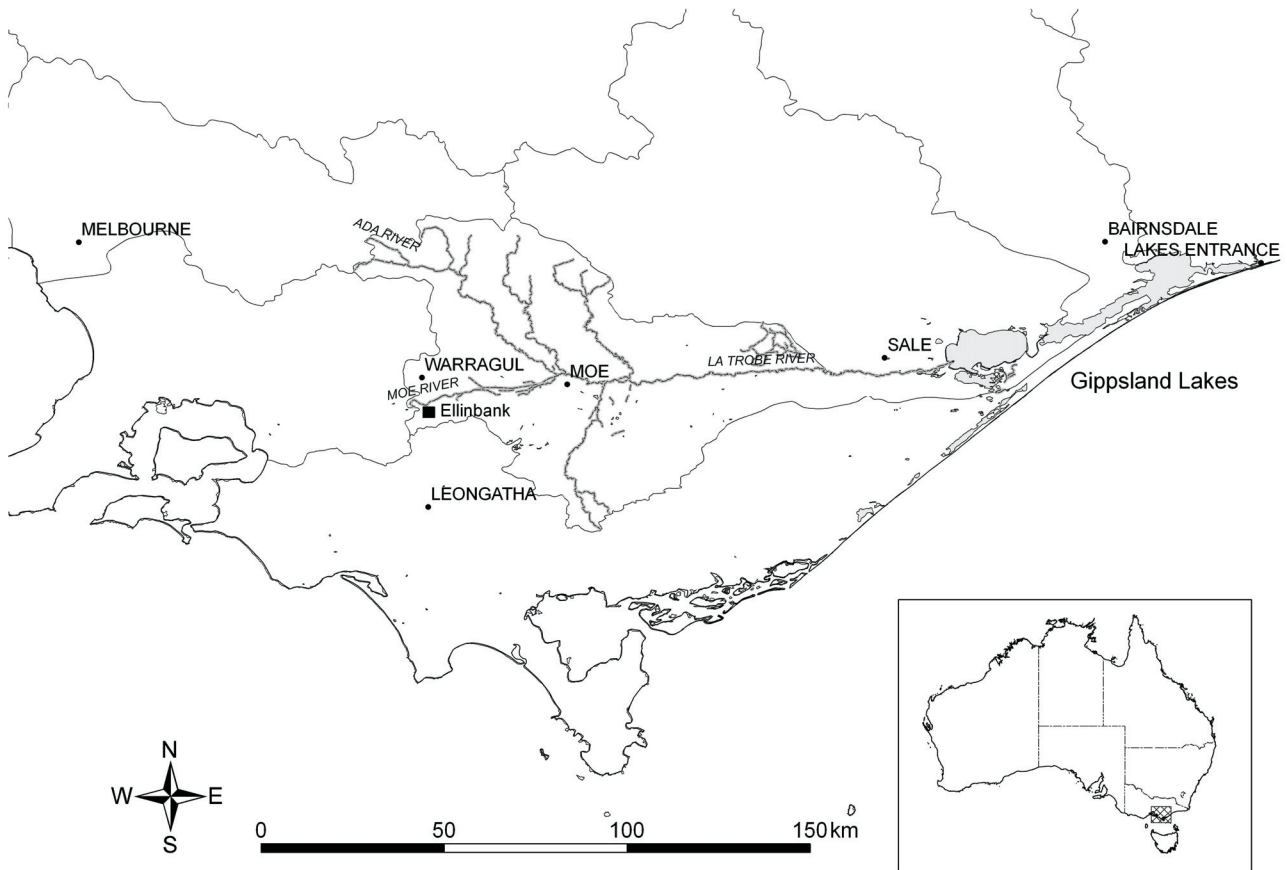


Figure 7:  
The Gippsland region of Victoria

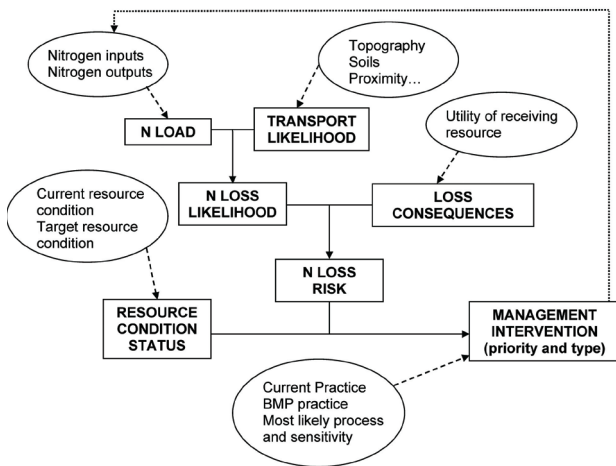


Figure 8:  
Schema used for assessing the risk of N loss from dairy farms and identifying opportunities for improvements to management (Hill, 2008)

*Risk* may be defined as the integration of *likelihood* and *consequence* (Standards Australia/Standards New Zealand, 2006). Generally, this integration takes the form of a simple multiplication of the likelihood and consequences factors.

The *likelihood* of nitrogen loss by runoff is a function of both nitrogen availability and the likelihood that runoff will occur. Fundamental to the work of Hill (2008) has been retention of a focus on nutrient budgeting to provide an estimate of the amount of nitrogen available for loss. Thus, and using the Ellinbank dairy farm as the focus of study, per paddock inputs of N (Figure 9c), were estimated from detailed farm records of fertilizer inputs (Figure 9a), fixation by legumes, imported feed and application of dairy shed effluent. Similarly, per paddock outputs of N (Figure 9d) were estimated knowing the amount of milk produced (Figure 9b), the liveweight gain of the cattle, and from estimates of the amounts of N exported in manure and urine (Eckard et al., 2007) and through farm records of exported feed or plant material (hay, silage, etc); further details are provided by Hill (2008). The difference between the maps shown in Figures 9c and 9d gives the amount of N that is potentially available annually for loss to the environment, otherwise termed the 'N load' (Figure 10a). The N load can then be combined with the likelihood of loss. Hill (2008) determined the likelihood of nutrient loss occurring on the basis that soil properties and landscape position control losses through various transport pathways,

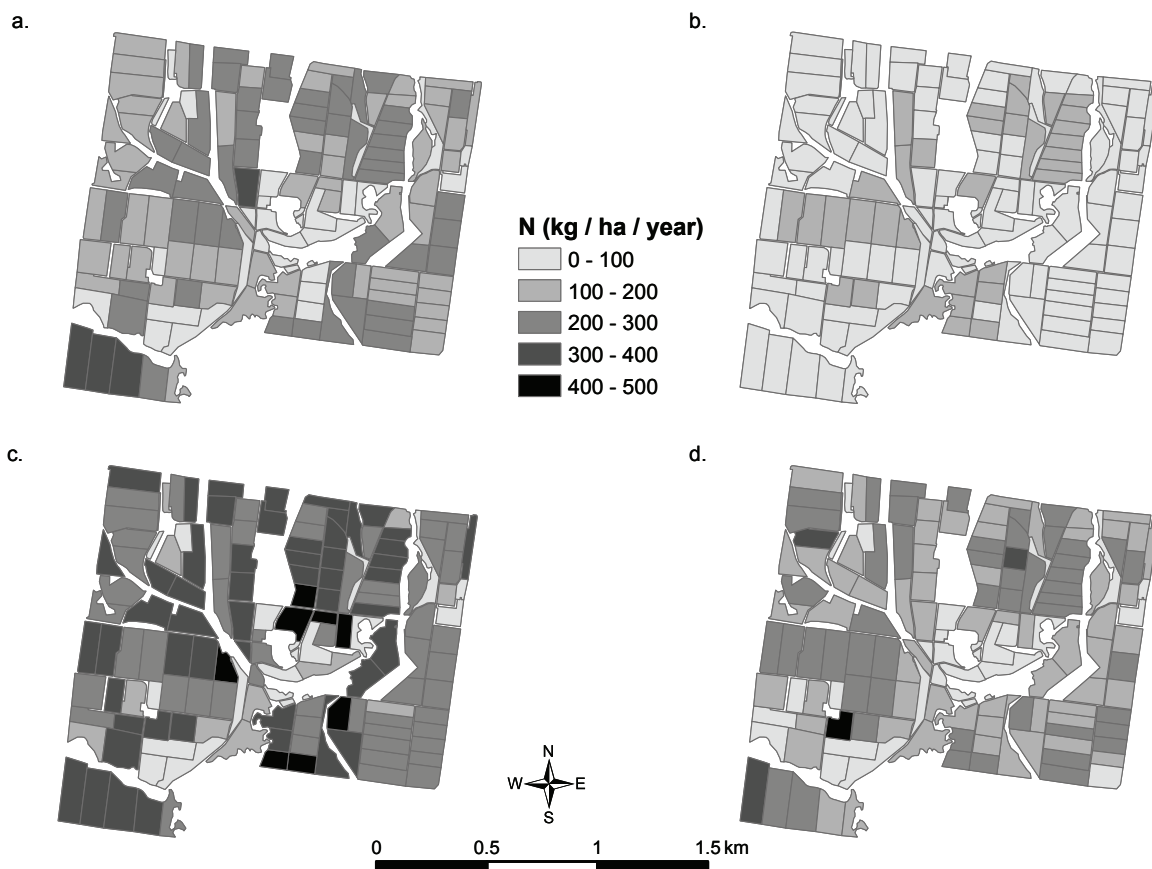


Figure 9:  
Nitrogen budgeting at Ellinbank dairy farm. (a) Fertilizer inputs, (b) exports in milk, (c) total inputs, and (d) total exports

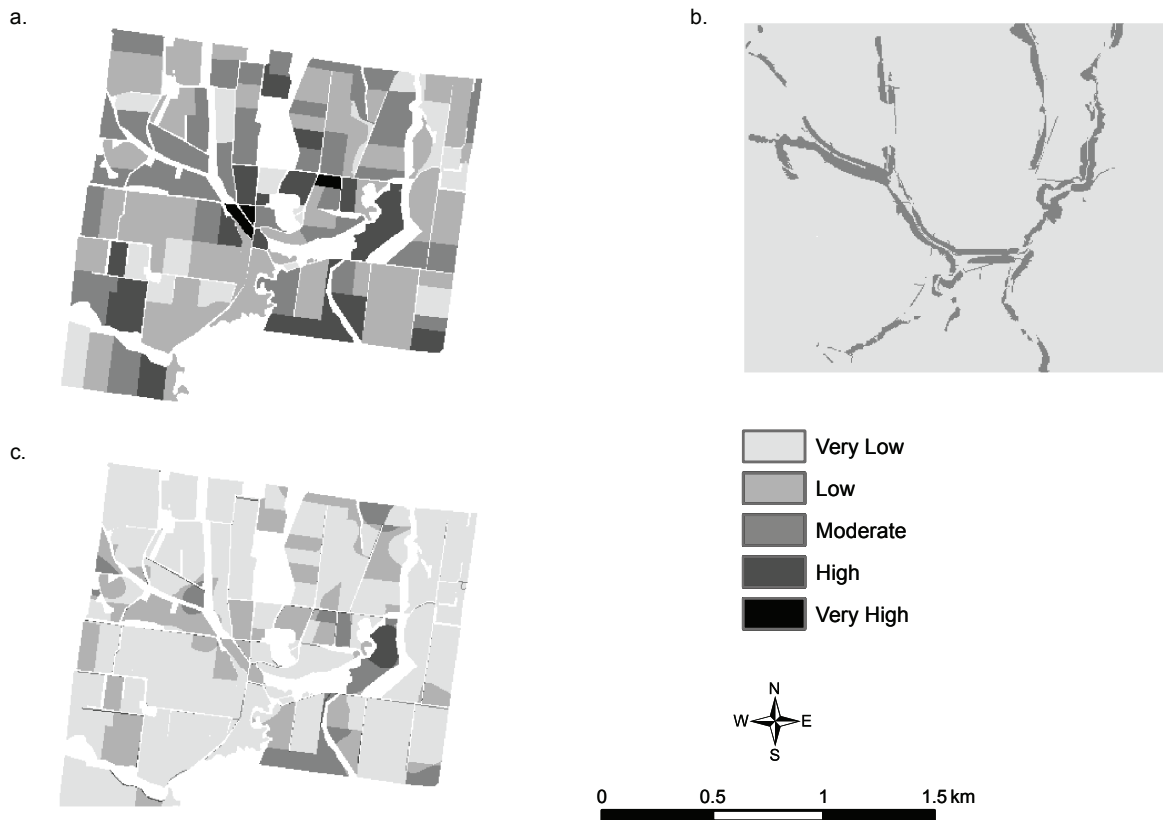


Figure 10:

Likelihood of N loss via runoff at Ellinbank. Integration of (a) the N load (obtained from the difference between N inputs (Figure 9c) and outputs (Figure 9d)) with (b) the likelihood of runoff occurrence (derived from soil and landscape properties) enables estimation of (c) the likelihood of N loss via runoff

including runoff, leaching / deep drainage, waterlogging, subsurface lateral flow and gaseous emission of nitrous oxide from soils. The soil and landscape properties considered important in controlling these processes were the soil profile type, the degree and dominant shape of slopes, the presence of runoff modifying features, proximity to receiving waterways and depth to groundwater.

Soil water movement in FNLI is derived from allocation of soil profile classes based on modal soils (Melland et al., 2007). However, in a 1:100,000 soil survey (Sargeant and Imhof, 2006), only 2 dominant landforms were identified for the entire Ellinbank property; one (Warragul) dominated by acidic red ferrosols, and another (Yarragon) dominated by clay loams over medium clays. However, the experience of the farm manager suggested a greater range of soil variation exists when considered at the farm scale. A finer level of detail was therefore considered appropriate for further analysis. A feature of advances in soil survey methodologies and, in particular, the digital storage and interpolation of soil property data (e.g. McBratney et al., 2003), is the ability to examine spatial variation in individual soil properties relevant to a particular purpose, as op-

posed to mapping soils as 'types' according to a classification system. Bramley et al. (2003) used such an approach in quantifying the risk of P loss from the Lower Herbert (see above). Thus, following a property-specific soil survey involving the collection of 104 cores, and with access to a digital elevation model derived from 20 m contour data, Hill (2008) was able to map spatial variation in N loss likelihood for the range of possible loss pathways for the Ellinbank property. Recall that, here we focus on loss by runoff only (Figure 10a). Thus, the N load and the runoff likelihood maps layers (Figures 10a and b) were combined using a multiplicative approach, to create an N loss likelihood layer (Figure 10c).

The *consequences* of N loss are based on flow pathways (on and off-farm), and the utility of the water body that receives water via these pathways. The utility of the resource determines the resource condition targets, and hence the consequences of pollution of the water body. Thus for example, N lost via the La Trobe River to the Gippsland Lakes is deemed far more serious than accession to the farm dam, which is used only for stock watering. Because most water at Ellinbank drains off-farm, the majority of the

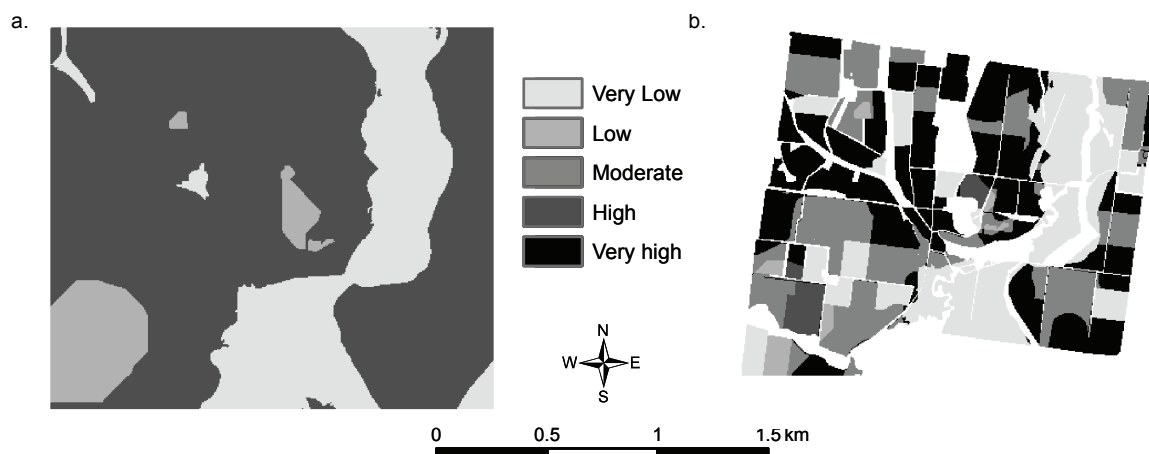


Figure 11: Risk of N loss via runoff at Ellinbank. Integration of (a) the consequences of N loss with the likelihood of N loss via runoff (Figure 10c) enables estimation of (b) the risk of N loss via runoff

property fell into a 'high' category with respect to N loss consequence, with areas of low consequence being those where runoff is into farm dams rather than the broader catchment (Figure 11a).

Integration of the maps shown in Figures 10c (*likelihood*) and 11a (*consequences*) using a multiplicative approach enabled Hill (2008) to map the *risk* of N pollution via runoff for the Ellinbank property (Figure 11b). Two features of Figure 11b are immediately apparent. First, pollution risk, when considered at farm scale, is highly spatially variable – as was the case with the paddock scale sugarcane example. Second, even though it is regarded as a 'best practice' farm, this analysis suggests that Ellinbank poses a significant risk with respect to offsite pollution arising from N, with the majority of the property having a pollution risk towards the high end of Hill's (2008) range.

Like the sugar example, this study provides a number of lessons for farmers and catchment managers. First, whilst this example is not Precision Agriculture (PA) *sensu stricto*, it highlights the value of spatial information. Second, this kind of analysis provides value and understanding with respect to the source of N surpluses and demonstrates that they are not uniformly derived, even though the analysis used a spatial resolution conditioned largely by the size of the component paddocks. However, as with the sugar example, this analysis demonstrates that access to spatial data and a PA approach will not deliver benefit by itself; there is also a need for significant improvements in agronomic management – in this case, presumably with respect to the management of fertilizers and dairy shed effluent in particular. Indeed, given that promotion of the production of milk is the whole point of using N fertilizer in dairy systems, a striking feature of Figure 9 is the low N use efficiency implied by the difference between N applied

(Figure 9a) and N exported in product (i.e. milk; Figure 9b). Thus, possible next steps towards true best practice might include a stronger move towards PA in terms of recording pasture production and milk yield on the basis of stocked areas rather than paddocks, the use of finer resolution spatial data, and more targeted management of paddocks and nutrients applied to them for both production and environmental goals. Such a strategy could lead to intensification of some areas but quarantining of others. It could also be informed by refinements to the loss risk assessment methodology incorporating temporal, in addition to spatial data, so that in addition to identifying where high risk of loss occurs, farm managers can also be aware of when the risks of N loss are greatest.

### A basis for more targeted management

A common feature of both our sugarcane and dairy examples is the demonstration that uniform management strategies, which in effect manage for the average condition, are a poor strategy from both a production and environmental perspective. Another is that they highlight the opportunity (and the need) for significant improvements to agronomic understanding. In this respect, they are consistent with the previous demonstrations that both generalised fertilizer recommendations (Cook and Bramley, 2000) and soil and plant test interpretation criteria (Bramley and Janik, 2005) derived from trials conducted over wide biogeographical regions may provide poor advice with respect to the management of specific locations. Indeed, this shortcoming is a principal reason for interest in PA and the use of variable rate fertilizer technology. However, as our sugar example indicates, access to a means of better targeting fertilizer does not deliver the benefit by

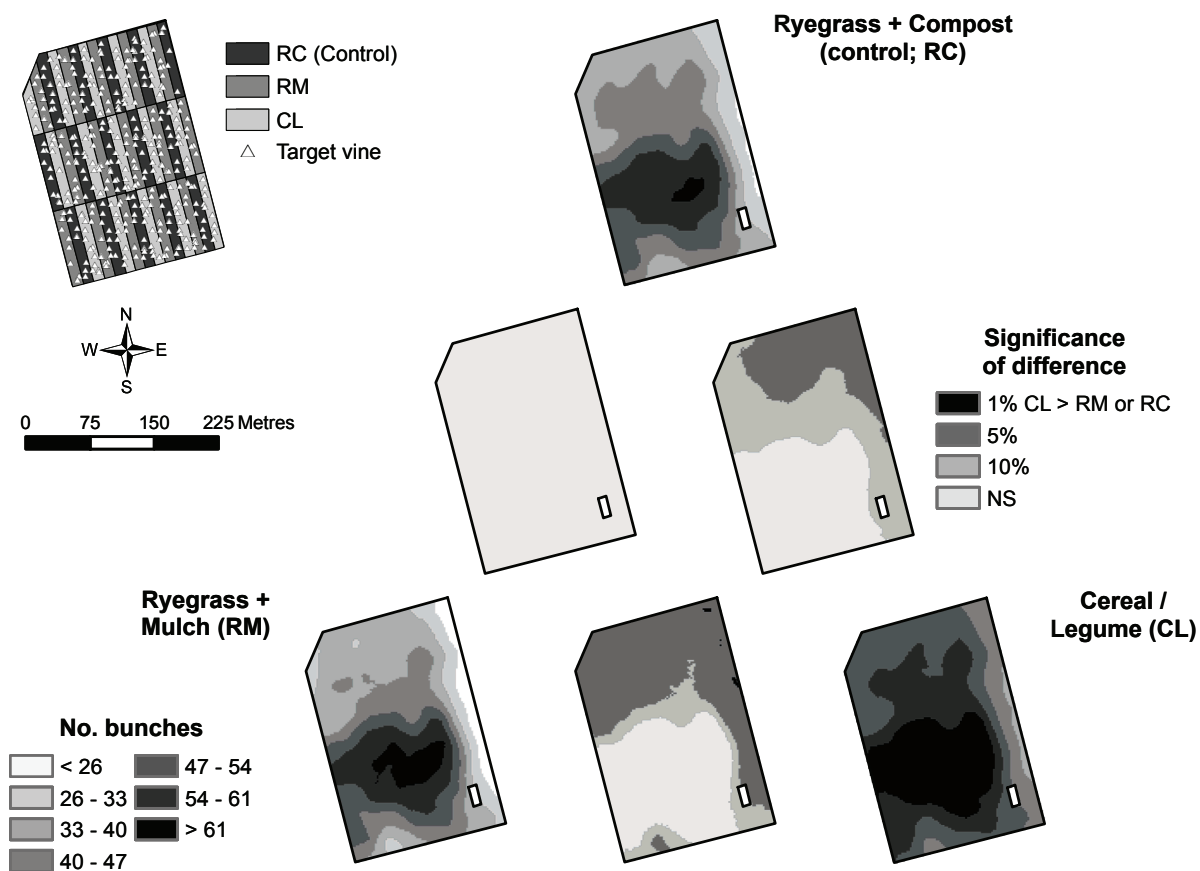


Figure 12:

A whole of block experiment conducted in South Australia (Panten and Bramley, 2007) in which a highly replicated design (top left) was applied in 2004 over an entire 4.8 ha vineyard to assess the merits of 3 mid-row management strategies. The method of Bishop and Lark (2006) was used to analyse treatment effects. Treatment specific responses, in this case assessed in terms of the number of bunches per m of row measured for 378 target vines at vintage in 2006, are shown in the maps in the corners of the triangle, with the significance of the difference between these shown in the maps positioned between them; the same legends apply to each bunch number or difference map. Whilst there is no significant difference between the RM and RC treatments, the benefits delivered by the CL treatment are markedly spatially variable

itself; it only satisfies the objective of putting the right amount in the right place at the right time if the right amount, place and time are known. This then raises questions as to how the farmer and/or their agronomic advisor should acquire this essential knowledge?

An obvious response to this question is that they should conduct some experiments on their own properties. However, if an experiment were to be conducted with the aim of guiding management of the sugarcane paddock or dairy farm discussed above, where ought it to be located? Should a trial be implemented in the lower yielding areas to the east or west of the sugarcane paddock, in the average yielding area in the centre or perhaps in the higher yielding northern part? Perhaps the delineation of zones might help, in which case should the trial be placed in the lower or higher yielding zone, in both or perhaps across the boundary between the two? In which of the Ellinbank paddocks ought an experiment to be located in such a

way that it informs management of the whole farm? Irrespective of the answers to these questions, on what basis should the results obtained be translated to locations beyond the experimental area? This question is relevant whether other parts of the same properties, other sugarcane or dairy farms in the Herbert or Gippsland districts or other farms even further afield are of interest. Such questions were the basis for early work with broadacre cereals (Adams and Cook, 1997; Cook et al., 1999) which explored the idea of conducting experiments with highly replicated designs over whole management units. More recently, Bramley et al. (2005a) and Panten and Bramley (2007) have explored the power of this approach in vineyards.

In the experiment reported by Panten and Bramley (2007), a new approach to the analysis of "landscape scale" experiments (Bishop and Lark, 2006) was used. This is based on the assumption that the observed responses (e.g.

yields) to a set of different treatments may be regarded as realizations of spatially auto-correlated and cross-correlated random variables. Thus, through the combined use of linear models of co-regionalisation and co-kriging (Webster and Oliver, 2001) the treatment responses to different treatments can be estimated for any part of the experimental site using the data pertaining to both. This allows the estimation of contrasts between different treatments measured at different locations over regions of different size and shape (Bishop and Lark, 2006). Figure 12 illustrates the application and merit of this approach to a vineyard experiment aimed at identifying the best of 3 alternate mid-row management strategies for enhancing vine vigour in an organically managed vineyard in South Australia (Panten and Bramley, 2007). As can be seen, rather than restricting the experiment to an array of small plots in one part of the block, as in the classical 'white peg' approach to agronomic experimentation, the experiment is applied over the whole management unit. Analysis of the results using the method of Bishop and Lark (2006) then enables the manager to see that the response to treatments is spatially variable. Critically, and in contrast to the traditional plot-based approach to agronomic experimentation which seeks to find out whether treatment A is significantly better than treatment B, this approach recognises that whilst treatment A may be better in some parts of a paddock, treatment B may be significantly better in others. Thus, a key element of both PA and the use of this experimental approach is that spatially explicit use of both A and B is feasible and appropriate. Another benefit of this approach is that by matching treatment response to a suitable covariate, perhaps plant available water or an index of soil fertility in this example, extrapolation of treatment response to other vineyards or properties beyond becomes much more feasible than is likely to be possible for a small, plot based experiment. In the latter case, the range of variation in the covariate may be insufficient for the development of a robust basis for extrapolation (Bramley et al., 2005a).

### Conclusions and future directions

An often-heard remark at sugar industry 'shed' meetings during the 1990s was "You can't be green when you're in the red!" It is therefore significant that of 210 published studies of PA – largely focussed on the US grains industry - in which economic losses or benefits were reported, 68 % reported benefits from some sort of PA technology (Griffin and Lowenberg-DeBoer, 2005); there are several examples of the profitable application of Precision Viticulture (Bramley et al., 2005b). If the definition of "profit" is extended from a purely financial viewpoint to one which also encompasses environmental performance,

or even more generally, demonstration that a correct decision demonstrating net benefit (McBratney et al., 2005) has been made, then the case studies presented here are strongly supportive of the view that PA is profitable. They also suggest that when collected at appropriate scales, the use of spatial data in agriculture can make a useful contribution to improved environmental stewardship. However, it is clear that the size of this contribution will be dependent on improvements to agronomy at the farm and paddock scale. In other words, it must be clearly understood that site specific management requires development of appropriate agronomic expertise on a site specific basis. By default, this means that the interpretation of soil tests and development of fertilizer strategies, for example, will need to be done on a site specific basis. Thus, whilst PA promotes a new approach to experimentation, its successful application may also depend on it.

These conclusions raise important questions for agronomic researchers, research managers and policy makers. One key question is that, if it is accepted that sub-optimal agronomy is a major problem contributing to the off-site impacts of agriculture, how will the strong perception amongst funders of agricultural research that "we have already done that" be countered? With respect to policy makers, especially in subsidised agricultural economies, a second key question to consider is whether subsidisation provides a disincentive for farmers to be as good at farming as they possibly can be? Ought adoption of at least some elements of PA be a legislative requirement or otherwise supported by policy? If such issues can be addressed, then we suggest that Precision Agriculture has a lot to offer the quest for improved environmental outcomes.

### Acknowledgments

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