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Adoption of variable rate fertiliser application in the Australian grains industry: status, issues and prospects

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Abstract Variable rate application of fertiliser (VR) is a practice underpinning a profitable grains industry in Australia. We updated the extent of VR adoption through a national survey ($n = 1\ 130$) covering all grain growing regions. Three smaller regional-based surveys ($n = 39$–102) collected detailed information on the nature and reasoning behind the use of various forms of the technology. We analysed the constraints to the adoption of each step using adoption theory. Surveys showed that 20% of grain growers have adopted some form of VR (varied from 11–35%), up significantly from <5% found 6 years earlier. Adopters are more than likely to have larger farms with a higher area in cropping. Many non-adopters were convinced of the agronomic and economic benefits of VR. A significant proportion of growers were managing within-field variability with manually-operated systems rather than more sophisticated VR technology, and have adopted some form of VR without yield maps, preferring to use soil tests, electro-magnetic induction or their own knowledge of soil and yield variation to define management. The rate of adoption is expected to continue to rise based on greater awareness of the benefits of the technology. The constraints to adoption were technical issues with equipment and

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software access to service provision and the incompatibility of equipment with existing farm operations.

Keywords Variable rate technology · Precision agriculture · Australia · Economics · Adoptions · Survey

Introduction

The implementation of precision agriculture (PA) involves the use of one or more of the following technologies: vehicle guidance for field operations, including controlled-traffic farming, yield monitoring, and variable rate (VR) application of agricultural chemicals, especially fertiliser. Overviews of the state of PA in Australia have been provided by Cook et al. (2000), McBratney et al. (2005), McBratney et al. (2005), Cook et al. (2006), Robertson et al. (2007) and Bramley (2009). Precision agriculture can underpin the maintenance of a profitable grains industry (Chen et al. 2009) through more cost-effective use of inputs (chemicals, fuel, labour, and machinery), increased yields, and increasing product value through selective harvesting.

Technologies used to implement VR, such as GPS positioning, yield monitors, and variable-rate applicators, have been available for more than a decade (Cook and Bramley 2001). Since a study in 2004, which showed only ~3% of grain growers were using some form of VR (Anon 2009), there is a need to update the extent of VR adoption with more information on the nature and reasoning behind the use of various forms. The advent of rising input costs (Chen et al. 2009), declining PA hardware costs, a national research and development program in Australia (Anon 2009) and a greater awareness of VR and associated adoption issues (Lamb et al. 2008), would suggest that the extent and nature of VR adoption ought to have changed.

We consider the nature of adoption for VR to be different to other PA technologies such as vehicle guidance. Adoption is not straight-forward and a high level of data management, interpretation, and judgement is required. The benefits of using PA technologies are not embodied in the technologies themselves and they therefore present a more complex and challenging adoption scenario. Unlike embodied technologies that can directly increase efficiency or productivity as soon as they are used (e.g. a new crop variety, herbicide or auto-steer/guidance as a PA-related example), on-going information, decisions, learning, and management are required to benefit from PA technologies such as yield mapping and variable rate controllers (other examples of non-embodied technologies are decision support software and crop/soil testing). For this reason, understanding the benefits and adoption of VR is likely to require strong emphasis on the farmer decision-making process and capacity.

A number of authors have speculated on the possible reasons for low/variable adoption of PA technology (Cook and Bramley 2001; Griffin and Lowenberg-DeBoer 2005; Robertson et al. 2007, 2009; Bramley 2009). There is an extensive body of literature on the diffusion and adoption of innovations in agriculture initiated by Rogers (2003). The five key attributes of an innovation (relative advantage, compatibility, complexity, trialability, and observability) can be used to explain a high proportion of the variance in the adoption patterns of innovations (Rogers 2003). Here we apply Roger's approach to the attributes of PA technology and VR and document some of our personal observations in interacting with farmers, advisors, and researchers working on PA. Such insights should have applicability outside Australia and indeed to production systems apart from grains.

This paper has three aims with the adoption of VR fertiliser by grain growers:

1. To quantify the current rate of adoption as it varies with region, farm and farmer characteristics,
2. To document what methods and associated technologies are being used to facilitate VR, e.g. yield mapping, soil mapping, geophysical surveys, remote sensing, vehicle guidance, etc.,
3. To identify and discuss the significant drivers and constraints to adoption of VR and related technologies.

In this paper we focus our analysis to the adoption of variable rate fertiliser management, as this is widely used in the Australian grains industry. While other inputs such as seed, lime and gypsum are varied in space across grain farms, by far the largest use of VR is for fertiliser application. The term "VR fertiliser" covers a range of approaches by farmers. These extend from zone × rate applications, practiced by farmers for a long time using observation and enhanced in more recent times by access to yield maps, through to systems in which management inputs are varied continuously in space through the use of prescription maps and variable rate controllers. "VR fertiliser" also covers sensor-based approaches, utilizing real-time sensors and feedback control to measure desired properties on-the-go, usually soil properties or crop characteristics, and immediately using this signal to control the variable-rate applicator.

Methods

Four sets of farmer surveys, one national, two in Western Australia (WA) and one in Victoria, were conducted to document the current state of adoption of PA and its component technologies (Table 1). The national study was used to indicate the proportion of grain growers using VR and yield mapping across different regions while the other studies were used to explore localised VR use and the drivers of adoption in greater detail.

In the national survey (Table 1), 1 170 grain growers from across the major grain growing regions (Table 2; Fig. 1) were interviewed by phone in 2008 as part of a larger study of factors influencing adoption of cropping practices (Llewellyn and D'Emden 2010). The farms contacted in each region (Table 2) were randomly selected from a

Table 1 Summary of surveys to document adoption of variable rate technology by Australian grain growers

Region and date	Number of respondents	Aim of survey
National (2008)	1 170	Use of variable rate fertiliser and yield mapping, associated with explanatory variables of farm and farmer characteristics
Victoria (2008)	39	Use of zoning and variable rate, the criteria used for and confidence in zoning and differentially managing field
Western Australia (Liebe Group) (2006, 2009)	65	Use of VRT and nine associated PA technologies. Degree of awareness, collection of information, degree of on-farm evaluation/testing, scaling up the use across the farm, review and modification and any dis-adoption that had occurred
Western Australia (3 regions) (2007)	102	Awareness of variability and ways to manage it, methods for diagnosis of causes and location of low yielding zones, constraints to adoption of VRT

comprehensive commercial farmer database. Data were collected from a primary cropping decision maker on farms cropping greater than 200 ha in a typical season with the aim of achieving a representative sample of commercial grain growers from each region. For comparison, the average farm area operated on all Australian cropping farms in 2007–2008 was 2 989 ha and the average of the sample in this study was 2 570 ha (median 1 900 ha). Of all suitable households with a primary cropping decision maker contacted, 14% refused to complete the survey. Thirty-seven percent of all households first contacted led to contact with a primary cropping decision maker and a complete usable response. The remainder arranged a callback that was not required before the target number of complete responses for their region was reached.

Considering that PA use was likely to be low and in the early stages of diffusion in many regions, the 'adoption' criteria we employed focused on selected elements rather than measures of the extent or sophistication of use. Questions relating to PA adoption included "Do you have a crop yield map from any of your fields?" and "Do you apply variable fertilizer rates to identified zones within any of your cropping fields?" The latter question captures farmers who apply variable fertilizer rates to specified areas of fields with or without the use of GPS-based technology. Logit regressions, using the limited range of available farm, farmer, and information-related characteristics as explanatory variables were conducted. Variables included in the analyses to explain adoption of variable rate fertilizer, yield mapping, and the use of variable-rate fertilizer together with yield mapping technology were: arable area managed; average percent of arable area cropped over the past 3 years; use of a paid consultant for cropping advice (binary); membership in a local farmer group focused on cropping issues (binary); someone managing the farm with a university degree (binary); age (categorical), and region. The use of yield mapping was also used as an explanatory variable of variable rate fertilizer, recognizing the possibility of sequential adoption (Khanna 2001). Use of variable rate fertilizer was also used as an explanatory variable of yield mapping, recognizing the possibility that in some cases the sequence may involve initial application of variable-fertilizer rates within fields without GPS technology may later encourage greater collection of spatial information.

A second survey was used to examine the factors influencing adoption in the Victorian Mallee region (Table 1), which had the highest level nationally of VR fertiliser adoption (Table 2). Farmer participants in a farm planning program run by the Victorian State Government's Department of Primary Industries and Mallee Catchment Management Authority in two Victorian Mallee districts were surveyed at two workshops in April 2007 and February 2008. The questionnaire collected data on current use of zoning and VR, the criteria used by farmers for zoning fields and how zones were being differentially managed. The farmer sample of 39 can be considered reasonably representative of the districts (participants did not self-select to the workshop based on interest in precision agriculture) and the two districts are considered to be among the more cropping-intensive districts in the Victorian Mallee. Representativeness was based on the fact that average annual area of crop sown was 1 961 ha compared to 2 225 ha for the sample in the Victoria Mallee region for the national survey described above. The proportion of growers stating that they have a yield map was 38%, higher than the region-wide average of 24% (Table 2).

A third survey was conducted in Western Australia (WA) between 2006 and 2009 by a large community-based farmer group, known as the Liebe Group (www.liebegroup.asn.au) (Table 1). The group is based in the low to medium rainfall zones of the northern agricultural region of WA (see WA Northern region in Table 2), has a membership of 200 farmers and 120 farm businesses, with the "average" farm size of 4 700 ha with 70% of that area under cropping. A total of 65 growers (50 group members, 15 non-members) were

Table 2 Use of within-field variable rate fertiliser application and yield mapping by Australian grain growers, 2008–2009

State	Region (respondents)	Have at least one crop yield map (%)	Using variable rate fertiliser on identified field zones in at least one field (%)	Using variable rate fertiliser on identified field zones in at least one field AND have at least one crop yield map
New South Wales (NSW)	Central West (81)	19	20	6
	Northern (146)	28	19	9
	Southern (90)	26	17	10
	All (328)	25	18	8
Queensland	Southern (123)	26	14	2
South Australia (SA)	Central (60)	20	13	7
	Lower Eyre Peninsula (50)	32	20	10
	Mallee (90)	17	24	9
	Upper Eyre Peninsula (56)	20	32	5
	Western Eyre Peninsula (40)	8	15	3
	All (296)	19	21	7
Victoria	Loddon (66)	24	20	9
	Mallee (80)	24	35	18
	Wimmera (70)	23	11	4
	All (216)	24	23	11
Western Australia (WA)	Northern (61)	41	16	11
	Central (81)	40	22	9
	South west (66)	29	21	9
	All (208)	37	20	10
	All respondents (n = 1 170)	25	20	8

NB. Due to small sample size regional summary data for NSW Mallee is not presented

interviewed between October 2006 and May 2007 and then again between October 2008 and January 2009. The growers were asked about their use of VR and associated technologies. The survey also measured VR awareness, collection of information about VR, degree of on-farm evaluation/testing of VR, scaling up the use of the technology across the farm, review and modification and any scaling down or dis-adoption that had occurred. Questions distinguished between nine different variation management technologies associated with VR: yield monitoring, yield mapping, normalised difference vegetation index (NDVI) imagery, GPS technologies, GPS with auto-steer, soil testing, geophysical technologies (such as electro-magnetic induction and gamma radiometrics), aerial topography mapping and VR of fertiliser and chemicals (only measured in the final interview).

A fourth survey was conducted in 2009 in Western Australia, where a paper-based questionnaire was circulated to growers in the WA northern agricultural region, in the central wheatbelt (WA Central in Table 2) and in the Esperance region (WA South West in Table 2) (Table 1). Responses were voluntary and drawn from active participants in

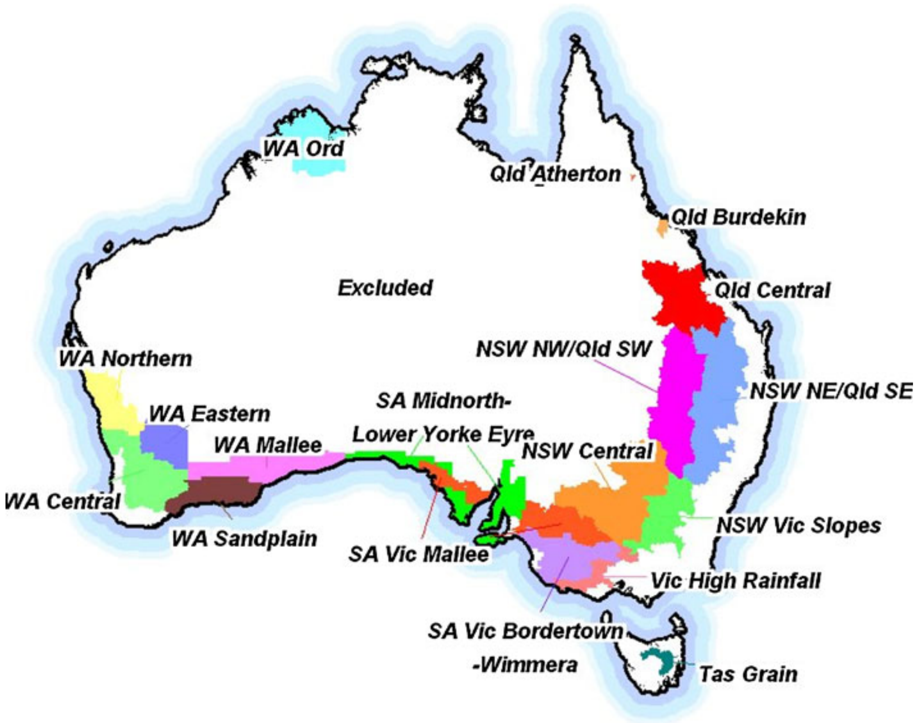

Fig. 1 Location of grain-growing regions in Australia used in the national survey of precision agriculture adoption

grower groups in these three regions. The survey was a relatively small one, sampling 102 growers, with the breakdown of Esperance (45), North (28) and Central (29). Questionnaire items were grouped into three categories addressing the questions of "Does variability exist on your farm and how could you manage it?", "What methods do you use for diagnosis of low yielding zones in fields and where to vary inputs?", and "What is holding you back in adopting PA?". For the purposes of defining "manageable variability" we followed the rule-of-thumb developed by Robertson et al. (2008) where a difference between zones in wheat yield potential of at least 1 t/ha would constitute enough to justify financially the use of variable rate application of fertiliser.

Results and discussion

In the national survey, 25% of respondents had at least one crop yield map (Table 2), varying from 8% in SA Western Eyre Peninsula to 41% in WA Northern. Nationally, 20% of farmers stated that they were using VR fertiliser on identified zones in at least one field. This varied between 11% in the Victorian Wimmera to 35% in the Victorian Mallee. Only 8% were using VR fertiliser on identified zones in at least one field and had at least one crop yield map (ranging from 3 to 18%) (Table 2). There was not a high correlation between having a yield map and using VR fertiliser on an identified zone. Fifty-nine percent of growers using VR fertiliser did not have a yield map.

Table 3 Factors significantly associated with use of yield mapping and use of variable fertiliser rates on identified zones by Australian grain growers based on logit regressions

	Yield mapping	Variable fertiliser rates	Variable rate and yield mapping
Higher cropping %	+*	+*	+**
Larger farm area	+***	+*	ns
Local farmer group membership	ns	ns	ns
Higher education	+***	ns	ns
Age	ns	ns	ns
Use cropping consultant	+***	ns	+**
Variable fertilizer rates	+***		
Yield mapping		+***	
Regions[a]	SA Western −*		Vic. Mallee +* WA Northern +*
Model significance (P)	<0.001	<0.001	<0.001

Results from national survey (Table 1)

ns, not significant; ±, direction of influence

[a] All regions were included in the analyses but only those with significant regional effects are shown here

* $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$

Regression results based on the national survey data indicated variables associated with adoption at this relatively early stage of the diffusion process (Table 3). The use of variable rate fertiliser was positively associated with larger area of land managed; higher proportion of land cropped (as opposed to areas of the farm used for grazing) and having a yield map. As measure of the impact of an explanatory variable on the estimated probability of adoption (with all other variables remaining unchanged) the odds ratio from the logit model showed that having a yield map was associated with the use of variable rate fertiliser being 2.3 times more likely.

Variables representing education and expert support were more important in explaining yield mapping than use of variable fertiliser rates, with a higher proportion of land cropped; use of a paid cropping consultant; higher education and the use of variable rate fertiliser all being significant (Table 3). The odds ratios showed that out of the latter three binary variables, consultant use was associated with the largest increase in the estimated probability of yield map adoption (2.5 times increase), followed by variable fertiliser use (2.3 times) and higher education (1.8). Consultant use was also found to be significantly associated with the joint use of variable-rate fertiliser with yield mapping (odds ratio of 2.0) (Table 3).

In a few cases the location of farms in a particular region were shown to be significant in explaining adoption (Table 3). Two regions associated with an increased likelihood of adoption of variable rate fertiliser with yield mapping, Victorian Mallee and Western Australian Northern, are the subject of further research presented in this paper. Factors that were consistently not significant with adoption of either variable-rate fertilizer, yield mapping or both were the age of the farmer respondent and local farmer group membership.

In the Victorian survey, only 28% of growers varied both inputs/management of different parts of a field and had a yield map (data not shown). A majority (59%) of growers varying inputs/management within field did not have any yield maps, consistent with the

Table 4 Confidence of farmers (all and adopters/non-adopters of within field variable management) in ability to define and manage within-field zones

	Mean	Low confidence (≤5) (% growers)
Identifying zones	7.1	14
Non-adopters	6.0	45
Adopters	7.6	4
Managing zones	6.9	23
Non-adopters	7.4	64
Adopters	5.9	12

Scale of 1 (Not confident at all) to 10 (Extremely confident). Results from Victoria survey (Table 1)

results of the national survey. All but two of the growers varying inputs/management within field were varying fertiliser (93%). Other inputs being varied within field were seeding rates (19%), herbicide/weed control (11%), crop type (7%), and cultivation/fallow practice (7%).

Growers typically have a reasonable level of confidence in their ability to define management zones in their fields and are slightly less confident in their ability to manage those zones (decisions on fertiliser, seeding rate, etc.) (Table 4). Non-adopters were much less likely to be confident in defining and managing different zones than adopters.

Lack of profitability of variable rate management was not commonly cited as a constraint to adoption (Table 5). Not having suitable machinery and the cost of acquiring it was seen as a difficulty with zone management by 44% of all growers (Table 5), including 30% of those already using VR. The demands and uncertainty associated with zoning and management were seen as major difficulties, even in this Mallee environment, where upland areas ("dunes") can easily be distinguished from valleys ("swales") that can often greatly assist with zonal identification and understanding. Those varying inputs were most commonly basing their input management decisions on past experience and knowledge of yield history, together with soil type knowledge (Table 5). When asked what information they thought would help them to (more) confidently define management zones, growers most commonly cited yield maps (53%) and soil type/soil testing (53%) followed by electromagnetic mapping (50%) and elevation/contours (17%).

Table 5 Main methods used for defining zones (% of adopters), main reasons for not using variable management (% of non-adopters) and the main perceived difficulties associated with using zone management (% of all growers)

How do you choose variable inputs/management	%	Reason for not varying	%	Main difficulties with zone management	%
Soil type	26	Don't have equipment	64	Don't have machinery/cost of equipment	44
Soil tests	22	Don't have knowledge	14	Complexity/uncertainty/information demands of zone management decisions	38
Experience/yield history	39	Cost	7	Zone identification decision and confidence	32
Yield maps	9	Not profitable	7	Aversion to technology/computers	12
Elevation	9			Consumes time	9
Agronomist	9			Lack of profitability of VR	6

Results from Victoria survey (Table 1)

The Victorian Mallee has one of the highest proportions of growers using some form of within-field variable fertiliser management (Table 2). However, it is clear that the region is still in the early stages of implementing PA and VR management. At the time of the survey, most zoning and subsequent management was based on relatively simple soil type observation and experience, without the use of specialised PA technology such as yield mapping and VR controllers. This can be seen as an entry point to variable input management.

Very few growers in this region believed that variable input management would not be profitable given the distinct within-field differences in soil types. It is evident that many growers wanted to progress to more advanced spatial management involving mapping and investment in variable rate machinery. Time, together with R&D and services that focused on improving confidence in zoning and zonal management, without greatly increasing management demands, is likely to lead to more extensive use in the future.

In the Liebe Group survey in Western Australia (Table 1), of the nine activities investigated, awareness amongst respondents was high (over 90%), except for geophysical technologies (gamma radiometrics and electro-magnetics; data not shown). Technologies that have high adoption rates (greater than 50% of respondents using on a regular basis) include soil testing, GPS, yield monitoring and GPS with auto-steer (Table 6) and are in line with the experience in Europe (Reichardt et al. 2009). The percentage of farmers adopting variable-rate technology was only assessed once (in 2008/2009) and was 14% (consistent with the 16% figure for WA Northern in Table 2) with a further 31% saying they were actively researching VRT. About two-thirds of farmers were yield monitoring but only around 50% were converting their yield data to yield maps (Table 6). Anecdotal evidence suggests that these growers were paying attention to yield variation by observing the yield monitor in operation at harvest time, albeit without taking the next step to converting the data to a map. Growers stated that they used variation management (both within and between fields) for varying fertiliser and lime applications, followed by the management of seeding rates, culling poor performing areas within a field and for crop species choice, and that soil testing and yield mapping were the most important technologies to support this.

The most highly used practice for managing variation was soil testing with 97% of respondents using the practice on an on-going basis (Table 6). One-half of respondents were utilising soil testing for both within- and between-field variation management, while 37% were using it for between-field management only (data not shown). Eleven percent of respondents were using soil testing for within field management alone. Soil testing is supported by large fertiliser companies, who provide sampling guidelines in addition to

Table 6 Percentage of respondents who have adopted variation management strategies and technologies in the Liebe Group (Western Australia) survey (Table 1)

Variation management strategies	% Growers who have adopted	
	2006	2009
Soil testing	97	97
GPS	71	78
Aerial topography mapping	70	32
Yield monitoring	65	68
GPS with autosteer	46	66
Yield mapping	45	47
Variable rate technology	–[a]	14

[a] Not asked in 2006

chemical analysis and interpretation of results. Soil testing is a relatively straight-forward technology to adopt, with an actionable response implied from the information that is derived.

A stand-out result was the adoption of GPS guidance with auto-steer increasing from 46% in the initial interview to 66% in the final interview (Table 6). The result was driven by the lower cost of the technology, the higher price of inputs (such as fertiliser), and reduction in stress and fatigue when operating machines for extended periods of time.

There were no growers using NDVI imagery and geophysical technologies on a regular basis on either sampling occasion and little interest in researching them (10–15%, data not shown). Early adopters in the Liebe Group region had limited success with the application of these two technologies, which resulted in the technologies having little perceived relevance. 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. While this comment is relevant to real-time use of imagery to make decisions, it does not explain why the retrospective use of historical NDVI images to define management zones, as described by Adams and Maling (2005), has not been adopted more widely.

The Western Australia survey conducted in three regions (Table 1) confirms that the respondents had a high degree of awareness of manageable variability on their farms and the gains from managing the impact of this on profitability (Table 7). More than 80% of the farmers were varying inputs between fields and one-half to two-thirds said they vary inputs *within* fields (Table 7). Growers were using manually-based approaches to varying fertiliser, lime, gypsum and seed by management zone, without necessarily using prescription maps and variable rate controllers. Hence, many farmers were managing within-field variability, even though they did not describe it as "variable rate technology". This result was somewhat surprising and needs to be confirmed by a larger sample of the grower population.

The results in Table 8 suggest that most farmers believe they know if and where they have a yield limiting problem simply by observation, with some help from soil testing and yield maps. The analysis of Oliver et al. (2010) suggests that this pragmatic approach is well founded. Table 8 also confirms the results of the national survey above that yield mapping is not seen by growers as a necessary precursor for management of variability. However, it was the most relied upon of the formal spatial data layers, more than electromagnetic induction or NDVI.

The most commonly cited factors as constraints to further PA use were technical and data complexity issues, and not a lack of conviction about agronomic benefits. This result may be specific to a group where the majority were VRT adopters.

Table 7 Percent of responses as "yes" to items addressing the question of "Does variability exist on your farm and how could you manage it?" in Western Australia survey (Table 1)

	Esperance	North	Central	Average
Does the yield vary in ANY field by more than 1 t/ha?	84	89	88	87
Are low yielding parts of your farm reducing profitability?	84	96	100	92
Do you vary inputs between fields for the same crop?	78	100	88	87
Do you vary inputs to different parts of a field?	44	75	63	58
Could varying inputs (within the field) make your cropping program more profitable?	100	100	100	100

Table 8 Breakdown of methods for diagnosis of low yielding zones in fields and where to vary inputs in Western Australia survey (Table 1)

	Esperance	North	Central	Average
Diagnosis				
Farmers observation	64	57	88	69
Soil test	31	93	62	57
Yield maps	29	36	25	30
Agronomists	11	14	13	12
NDVI imagery	11	11	0	8
Variation of inputs				
Farmers knowledge	33	33	58	40
Yield maps	27	27	20	25
Soil surveys	13	13	33	19
EM surveys	18	18	–	13
Agronomists	4	4	20	9
NDVI imagery	4	4	–	3

Values are percentage of respondents citing that method

In summary, a number of conclusions can be drawn when looking across the results from the four surveys. The surveys confirm that there is a widespread and rapidly growing use of GPS technologies on farms, particularly guidance. There was also a wide appreciation of spatial variation and the benefits of managing it, primarily through varying inputs (fertiliser, lime, pesticides, and seed). Significantly, the perceived lack of agronomic and economic benefits of VR were *not* being cited as a constraint to adoption. Many growers were collecting information about, and considering adoption of, VR.

The adoption of VR at national level stands at or around 20% (although it is significantly higher in some regions), which is significantly up from survey results from 5 years ago (<5%). Adopters were more than likely to have a paid consultant (although the survey did not explore if the growers used the consultant for PA services) and larger farms with a higher cropping percent. Higher education became significant only for adoption of yield mapping. This is a similar result to that of Larson et al. (2008) who found that education status and emphasis on cotton production on the farm was related to the use of remotely sensed imagery in cotton production in the USA. Daberkow and McBride (2003) concluded that simple efforts to raise awareness of PA technology in the US were not likely to increase adoption. This appears likely to be the case with VR in Australia, with one indication being the high proportion of growers with yield maps not choosing to apply variable rate fertiliser.

The regions shown to be most commonly associated with VR were low rainfall/low input regions and tended to be those where substantial, readily identifiable soil differences exist (e.g. dune-swale land systems). These are likely to be regions where zone-specific fertiliser response can be most readily understood (Bullock et al. 2002).

Although many growers would not define it as VR, over a third of growers in some regions said they were managing within-field variability most often through manually-operated systems. Interestingly, many growers were adopting some form of VR fertiliser without first collecting yield maps. This suggests that many growers were using a low-technology approach (i.e. without yield mapping) with their tacit understanding to applying and evaluating variable fertiliser to identified zones. Yield monitoring was more common than yield mapping, but more than 30% of farmers with yield monitors were not converting these to yield maps. Although it is possible that some value from yield monitoring was being extracted through 'live' observation of the monitor at harvest time, the result most likely reflected that many yield monitors were acquired by farmers independent of any motivation to adopt PA (e.g. via new harvester purchase).

For farmers pursuing PA and VR, their own experience and soil test results were commonly being used to diagnose and devise management regimes for field zones. Further use of spatial data was used if uncertainty around management needed clarification. It appears yield maps were an important, but not critical, source of data. While conventional wisdom suggests that several years of yield maps are required for robust zone delineation, many farmers were following alternative sources of information such as electro-magnetic induction (EM38; e.g. Whitbread et al. 2008) or other knowledge of soil variation derived largely from their own experiences as a basis for zoning a field. Nonetheless, non-adopters had less confidence in basing decisions on zone definition and management options, even in landscapes where soil type delineation was clearly observable.

In two regional surveys the most commonly cited constraint to adoption was technical (both equipment and software) and data complexity issues. This is confirmed by unpublished results from a sample of 104 growers from New South Wales, Victoria and South Australia surveyed by a grower organisation that promotes the use of PA (SPAA-Precision Agriculture Australia) (personal communication) in March 2010. The sample population had a higher rate of adoption of VR (30–40%) and yield mapping (80%) than in the national survey. However, for this group, with a high percentage of VR technology adopters, the main constraints cited covered a range of hardware and software difficulties.

Application of adoption theory to variable rate technology

In this section we apply the theory of Rogers (2003) and the five key attributes of an innovation (relative advantage, compatibility, complexity, trialability, and observability) to the attributes of VRT in order to reveal possible reasons for low/variable levels of adoption.

Relative advantage

Relative advantage is the degree to which an innovation is perceived as being better than the idea it supersedes (Rogers 2003). Relative advantage is often associated with some improvement in a measure of economic profitability but can also include related aspects such as risk. In Australia, sceptics of VR fertiliser point to the lack of evidence of relative advantage (Robertson et al. 2007), which has led to considerable effort to quantify the economic benefits of VR fertiliser in a range of situations. The aim of this work was not to derive normative estimates of the economic benefits, but to highlight the key determinants of relative advantage and derive rules of thumb for use by advisors.

Published Australian studies of economic analysis of VR fertiliser in broadacre grain production include experimental comparisons, case studies of farmers who have adopted the technology, and economic modelling based on both representative and actual farms and fields (Brennan et al. 2007; Robertson et al. 2007; Robertson et al. 2008; Robertson et al. 2009). The benefits range from close to zero to around AUD50/ha.

All of these methods have drawbacks. Experimental comparisons suffer from the limitation that they have a backward-looking or ex-post perspective—i.e. analysed after environmental conditions, including weather, have been fully revealed—which do not account for the reality of a farmer's forward-looking or ex-ante perspective with imperfect information (Anselin et al. 2004). This point is illustrated well by the example given by

Robertson et al. (2007), where the advantage of VR over two seasons and two fields differed from 0 to AUD81/ha depending on whether the long-term optimum rate or the optimum rate for each season for each zone was used in the comparison with the base case of uniform management. The issue of seasonal conditions interacting with the performance and management of zones under VR interferes with the observability and trialability of VR.

Case studies with farmers that aim to document the change in profit with VR *ex-post* also suffer from limitations. In nearly all cases there is no valid base case of uniform management with which to compare performance under VR. In the study of Robertson et al. (2009), where the whole-farm benefits of the adoption of VR on six farms were analysed, the available data included yield and fertiliser rates in management zones in a series of fields over a number of seasons. To deal with this limitation of no baseline they elected to estimate what the yield *would have been* in each management zone, based on yield performance under VR and some estimates from the farmers. Clearly, this approach is not ideal. However it is difficult to imagine farmers maintaining large commercial areas of uniformly managed fields just so a valid comparison could be made with VR. An additional issue is the fact that farmers modify the definition of management zones over time as they learn. Alternative approaches based on whole-of-block experimentation may assist with this constraint (Panten et al. 2010). We will return to the issue of on-farm trialling below.

In response to the limitations of ex-post analysis of trials and farm case studies, a number of researchers have resorted to economic modelling to quantify the benefits of VR (Brennan et al. 2007; Robertson et al. 2009; Havlin and Heiniger 2009). While modelled results suffer from the lack of grounding in reality that farmers and advisors wish to see in any test, it has the advantage of being able to vary systematically the separate and interacting effects of the shape of the input–output response function (which may be a function of season, background resources, and the particular inputs and outputs being examined), zone areas, prices, and costs.

Despite the acknowledged limitations of the various methods to quantify relative advantage, there is a reasonable degree of convergence in the estimates of average increase in grain crop gross margin that occurs with the adoption of VRT with estimates ranging from less than AUD5/ha up to an upper limit of around AUD50/ha. Based on the increasing rate of adoption of VR documented by the surveys above, a benefit of AUD5–50/ha represents enough relative advantage for many adopters of VR.

The question of profitability must also be examined in terms of a return on investment, particularly where up-front investment in equipment, data and services is a pre-requisite to adoption. While there is a perception that adoption of VR requires a large up-front investment, we have documented a number of farmers who have incrementally adopted VR without the use of variable rate controllers, guidance, or a history of yield mapping (Robertson et al. 2009). Moreover, we have also shown that VR is able to recoup a modest investment in equipment over a moderately-sized cropping area with realistic assumptions about increases in gross margin (Robertson et al. 2007).

While in a narrow sense, relative advantage is best quantified in profitability terms, surveys and informal observations of farmers have revealed that there are a number of significant intangible benefits to VR technologies that can be difficult to quantify in monetary terms. In the case studies described by Robertson et al. (2009), intangible benefits listed by farmers were: the ability to conduct on-farm trials, increased knowledge of field variability, and increased confidence in decision making.

Compatibility

Compatibility is the extent to which an innovation is consistent with existing knowledge and practices within a given farming system. Innovations that are more compatible with the current system may be viewed as less uncertain to the potential adopter and are more likely to be adopted. Compatibility is closely related to the concept of relative advantage in that they both are viewed in the context of current practices. Farmers will be wary of radical innovations that differ significantly from those with which they are familiar and comfortable.

We would argue that the main compatibility issues relevant to the adoption of PA relate to the complexity of the technology and management of the data generated. The computer skills, attention and desk time that data management required (Griffin and Lowenberg-DeBoer 2005) is often not compatible with the field work focus of many farmers.

A move into VR technologies can potentially mean the purchase of new machinery, configuring and operating a GPS, adoption of new methods for fertilising and yield monitoring, and handling large amounts of data. The time and attention required to set up and operate variable-rate machinery often conflicts with the urgency of sowing a cropping program in a timely manner. If the technology fails, specialist assistance may be difficult to source. Given this, it is not surprising that Robertson et al. (2009) observed that early adopters of VR technologies were all highly literate in the use of computers, GPS technology, and variable-rate controllers, routinely soil tested, and kept good farm records. All adopters invested considerable time in setting up their system in the beginning (with considerable teething problems in some cases), but on-going labour demands were minimal. Some did not use a consultant, while others placed heavy reliance on consultants for zone delineation, yield-map processing, and variable rate map production. This suggests to us that such adopters would not see VR as being incompatible with their familiarity with technology.

Complexity

Complexity is the 'degree to which an innovation is perceived as relatively difficult to understand and use (Rogers 2003). Unlike simple innovations, adopting a complex innovation is likely to involve change to several components of the farming system and its management. The degree of an innovation's complexity was negatively related to its likely rate of adoption. Some of the issues around complexity have been covered above under "Compatibility".

One of the ways to deal with the demands of implementing a complex innovation is through the use of expert support. Application of PA systems by farmers can be hindered by a lack of technical support and training to implement PA systems (Cook et al. 2000 in Australia; Reichardt and Jurgens 2009 in Germany). This includes the need for PA equipment suppliers to provide back-up support to users as a consequence of equipment incompatibility. Reasons for incompatibility from manufacturers include protection of intellectual property and the expense of R&D to make components compatible with specific brands. Manufacturers are beginning to address this in their service delivery using combinations of 24 h phone support, field technicians, training local dealers and customers, and the use of 'virtual mechanics' in which farmers can get access to hands-on-assistance in real-time via internet or mobile phone. There is also a need for consultants to help growers capture, interpret, and devise management actions based on the large amounts of information generated by PA tools. Some of this need is a consequence of a lack of farmer confidence in using computer-based technologies. It is noteworthy that our survey results indicate that adopters of VR are more than likely to use a paid consultant. It is, however, our assessment that there is too little capacity amongst the current pool of farm consultants to provide PA services to Australian grain growers, something that does not seem to have improved since being identified as a significant adoption constraint by Cook et al. (2000).

It is a truism that VR can involve relatively complex technologies and anecdotes abound of the frustrations that farmers have experienced in setting up and operating the technology. Survey results show that some farmers have adopted VR using a less complex pathway. This has often involved adopting variable-rate approaches, but not adopting high-precision, high information-intensive components. Ironically, PA sometimes suffers from the problem of generating too much information (yield maps, application maps, geophysics, remote sensing) which prevents its efficient conversion to knowledge that can help farmers make decisions. The over-abundance of data can result in an over-emphasis on precision, particularly in the definition of the boundaries of management zones. One example of this is in the precise location of zone management boundaries. Emphasising this problem is misleading because in our experience the boundaries of zones are usually adjusted by farmers in line with logistical considerations. Cook and Bramley (2001) advocated incremental adoption of PA, a strategy which would tend to mitigate against the adopter being swamped by too much data.

It is our contention that there has been excessive emphasis on the collection of data to delineate management zones precisely, and often insufficient emphasis on understanding the agronomic basis and economic potential of the variability. Oliver et al. (2010) showed that integrating farmer knowledge with other spatial data may be able to reduce cost of data collection and analysis and also improve communication between researchers and farmers. The use of spatial data can add value to the decision-making process, but fine-scale spatial detail can be distracting to the broad spatial patterns that are the key influences. Adams et al. (2000) reached similar conclusions when examining the value of detailed soil testing to aid site-specific nitrogen management. However, when one considers VR in terms of a continuum of application rates (rather than single rates applied to a few zones within a field) there would be a clearer case for the need for fine-scale data.

While farmer knowledge can go some way towards diagnosis of causes (Oliver et al. 2010), other methods (see review by Robertson et al. 2007) are under development such as some geophysical techniques (Wong et al. 2008), temporal dynamics of remotely sensed NDVI (Adams and Maling 2005; Robertson et al. 2007), and temporal dynamics of multiple yield maps (Lawes et al. 2009). Because causes of variation are context specific, no one method is universally applicable. It is interesting that in the two WA-based surveys above there was little uptake or current interest in technologies such as geophysics and EM. However, we are aware of some grain-growing (specifically the WA, SA, and Victoria Mallee) where EM has particular application and indeed is being more widely adopted for VR.

The flatness of the payoff response function for most agricultural inputs (Pannell 2004) means that precision is unnecessary when trying to optimise inputs at the top of the input-profit response curve. Oliver and Robertson (2009) showed in a study of VR that some imprecision (e.g. an estimate to within 500 kg/ha of the actual yield) results in little loss in profit due to the flat payoff response function. On the other hand, precision may help in identifying the input-responsive zones where VR will pay.

Trialability

Trialability is the extent to which an innovation can be implemented on a limited basis to facilitate learning about its value.

Varying fertiliser rates on different soils is readily trialable, although seasonal variability can make conclusions from single year results difficult (Wong and Asseng 2006; Brennan et al. 2007; Oliver and Robertson 2009). Variable rate is divisible in the sense that it can be trialled at a sub-field, field, and farm-scale, and does not require investment in PA equipment, although trialling approaches are easier if yield monitoring is available to take full advantage of the spatial pattern and resulting insights in trial results (see below). The availability of PA technology has raised potential new opportunities to gain insights from on-farm trials with variable input treatments.

In contrast to trialling different input rates, it is not always possible to trial 'indivisible' variable rate machinery and hardware prior to the decision to purchase. However, from evidence presented in this paper, many growers are taking a stepwise approach to VR adoption meaning that components required for VR are rarely purchased as a complete package. This allows some degree of trialability as each component (e.g. GPS, yield mapping, variable rate seeding equipment) is sequentially acquired (Cook and Bramley 2001). The stepwise approach to adoption also means that a transformative change to the crop's value chain (such as advocated by Bramley 2009) may be more difficult to achieve.

Trialling, where rates of inputs are applied to selected sub-regions of a field, in conjunction with broad-scale adoption is a feasible approach to observe the benefits of VRT. Broad-scale adoption without trialling suffers from the lack of a baseline for comparison and any substantiation of benefits requires assumptions and modelling (see "Relative advantage" above). In the early days, researchers also focused on the wealth of information available and developed experimental designs that could be used by farmers to evaluate a treatment. Whilst robust, these designs were sometimes not adopted by the industry either because they did not fit in with conventional farming operations and/or because the analysis of results was perceived as difficult. Alternative approaches have now been developed that can be integrated into conventional farming operations and which employ analytical methodologies which are more accessible.

Observability

Observability is the extent to which the outcomes of an agricultural innovation are visible to others (Rogers 2003). Clearly, innovations that are more readily observed allow for a greater flow of information to other potential adopters (farmers, advisors and financiers) about the performance of the innovation. In the case of VR fertiliser, observability by others is typically low, whether or not fertiliser rates are being varied by soil type. Observation by others of increased profitability is also often problematic. However, problems related to low observability are readily overcome by group-based efforts around on-farm trialling. However, as previously raised, the major constraints to adoption of VRT are unlikely to be related to observation and subsequent awareness of the innovation's local existence. The ability to observe and forecast the relative advantage of using variable rate treatments in an environment of very high seasonal variability and uncertainty is likely to be much more critical. Seasonal influences can interact with responses and potentially undermine the confidence that VR can reliably deliver benefits.

Synthesis and implications for R, D & E

It is difficult to be definitive in the assessment of the relative importance of relative advantage, compatibility, complexity, trialability, and observability in influencing adoption of variable-rate technology. Our assessment is that while relative advantage may be clear for the particular situation being considered, for many growers the complexity of PA technology and lack of service provision means that the computer and data demands are often incompatible with their farm operation. This notwithstanding, rates of adoption of VR technologies have increased in the last 5 years, particularly those applications that involve less computer and data demands. If the experience with GPS/guidance is any indication, the rate of adoption will continue to rise based on farmers' greater awareness of the benefits of VRT and the modified systems for managing variability that seem to already be in place. We believe that the insights gained here on the adoption of VR fertiliser will apply to other uses of VR.

Uncertainty around benefits can be reduced if simple on-farm trialling can be developed and used widely over a range of seasons. Moreover, systems for rapid and unambiguous diagnosis of causes of variation (a requirement for soundly-based agronomy too), which complement farmer knowledge will assist in reducing uncertainty around the most appropriate type of management response required. Systems for easier collection and interpretation of yield maps will assist but will not be critical.

A striking aspect of our surveys is that they indicate that many of the constraints to the adoption of VR are the same as those that were identified several years ago, both in Australia (Cook et al. 2000; Cook and Bramley 2001) and elsewhere (Griffin and Lowenberg-DeBoer 2005). The results also reflect a lack of recognition of the opportunity to introduce a process control philosophy to agricultural production (Cook and Bramley 2001) and a general failure in the Australian grains industries to recognise that system redesign, especially in the broader context of the whole value chain (e.g. Bramley 2009), may yield significant benefits to both growers and processors. It could therefore be argued that in addition to the immediate constraints faced by growers in adopting elements of PA (the subject of this paper), a lack of industry leadership in driving the change which would encourage PA adoption is also a limiting factor. Meanwhile, at the time of writing, only two Australian universities offer a specific course in PA as a part of their undergraduate degree in agriculture. As a consequence, the short-term prospects for the present dearth of advisor support for PA being addressed do not seem encouraging.

With respect to the immediate constraints to the adoption of VR by growers, the implications of our results for research, development and extension are three-fold:

1. Development of the capacity of the grains industry to market, deploy and service PA equipment, and provide services. This should include targeting of training and education of consultants, their presence being a factor in early adoption. Emphasis should be on pragmatic systems that simplify complexity and are flexible. Documenting case studies that illustrate the multiple pathways to adoption will assist, particularly those that de-emphasise "high-tech" approaches.
2. Further development of rapid and cheap methods for diagnosis of the *causes* of yield variation, particularly those that account for seasonal effects. With the exception of methods for on-the-go sensing of soil constraints to crop growth, new methods for sensing and recording variation *per se* are probably not needed.
3. Development of simple approaches for on-farm trialling, including the interpretation of results.

Conclusions

Our study has shown that the rate of adoption of VR in 2008–2009 has increased significantly to 20% nationally from the low levels recorded in 2002. We see no reason for the rate not to continue to rise based on a number of factors: (1) the on-going rise in input costs for grain production placing greater emphasis on efficiency of input use; (2) an increasing awareness and appreciation of the agronomic and economic benefits of VR; (3) the active evaluation and perception of potential value by many current non-adopters; (4) many adopters using a stepwise approach to adopting precision agriculture and VR technologies; and (5) the greater availability and affordability of equipment.

While there is a greater appreciation by growers in general for the benefits of VR, uncertainty around the relative advantage of VR in specific field and seasonal situations remains a constraint and undermines confidence for non-adopters. Overcoming these constraints will be assisted both by developing adoptable on-farm trialling approaches, and techniques to complement farmer and advisor knowledge that rapidly and unambiguously diagnose causes of variation. This should reduce uncertainty around the most appropriate type of management response required.

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