

SRA Research Project Final Report



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Cover page

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Executive Summary:

Strong sugar industry interest in Precision Agriculture (PA) has developed during the 2000s on the back of considerable progress with PA in other Australian agricultural sectors (grains and wine in particular), attempts in the Herbert (HCPSL and partners), and more recently in other districts, to develop a regional harvest management and yield mapping capability, and increased support for initiatives deemed of value in minimising possible impacts of sugarcane production on the Great Barrier Reef, including the provision of grants to growers for the purchase of GPS guidance systems and variable rate controllers for fertilizer spreaders. Against this background, the then Sugar Research and Development Corporation commissioned the reviews contained in SRDC Technical report 3/2007. A subsequent workshop held to mark the delivery of these reviews identified a number of PA-related R+D priorities which collectively could be characterised as being aimed at properly positioning the sugar industry for appropriate PA adoption, supported by access to the necessary technology, skills, methodological protocols and case studies. This project emerged from that process. Its intended focus, was to be based around core field sites in the Bundaberg, Burdekin and Herbert districts which were established with the intent of both PA research and demonstration.

Initial trials identified significant shortcomings with all three of the yield monitoring options being used commercially at the time. In particular, there were gross inconsistencies in the patterns of yield variation identified by the three sensors, all three were significantly compromised by the nature of the harvest (harvester speed, presentation of the crop, logging interval), and their calibration against mill tonnages was highly subject to the vagaries of the consignment process. Accordingly, and in the absence of robust yield monitoring, reduced focus was placed on case studies with attention turned instead to development and assessment of robust approaches to yield monitoring and mapping. Significant progress has been made in this area with a key finding being that rather than the mode of yield sensing *per se.* being critical to yield monitor performance, the post-processing of sensor data, calibration of these data against tonnages recorded at the mill, associated issues of consignment, the stability of sensor calibration and minimisation of sensor 'noise' are critical to the industry having access to a robust yield monitoring and mapping capability.

From this work, we have developed protocols for yield sensor data manipulation and subsequent mapping, with the other identified issues relating to yield mapping remaining the focus of ongoing work. In addition, we have also:

- Demonstrated the value of high resolution soil survey (VERIS, EM38) and elevation modelling in understanding drivers of within block yield variation; Gamma radiometry has also been explored;
- Highlighted the utility of remotely sensed imagery, in concert with DPI021, for understanding temporal stability in patterns of variation in crop performance given scarce yield data;
- Highlighted the impact of within-block CCS variation on paddock gross margins and the consequent need for an on-the-go (i.e. high resolution) CCS sensing capability to complement yield monitoring; within-block CCS variation accounts for around 20-25% of the within-block variation in income;

- Demonstrated the inaccuracy of existing solid fertilizer application systems, raising questions about the merit of retro-fitting spreaders with variable rate controllers;
- Explained the pathway to PA adoption through our case studies, PEC videos, numerous technical workshops, conferences and regional grower meetings;
- Through our Burdekin case study, demonstrated significant financial benefits which may accrue through targeting management within-block (savings of \$330/ha through this example of variable rate gypsum application by comparison with uniform application);
- Generated a measure of industry interest in PA through a substantial industry-wide grower survey of attitudes to PA and identified areas of grower interest in future RDE; and
- Made recommendations for future priority RDE activities to enable the sugar industry to capture the benefits from PA to their fullest extent.

Background

Precision Agriculture (PA) is not new; the first yield map published in the scientific literature, derived from a yield monitor and GPS, was produced from a canola crop in Germany almost 25 years ago (Haneklaus *et al.*, 1991; Schnug *et al.*, 1991); the biennial 12th International Conference on PA has just been held in Sacramento, USA. In Australia, PA symposia have been convened by the University of Sydney and/or the grower-driven PA group SPAA-Precision Agriculture Australia (SPAA; <http://www.spaa.com.au/>) since 1997 (see http://sydney.edu.au/agriculture/pal/research_symposia/archive_of_proceedings.shtml for an archive of these), with the 17th such symposium being held in early September this year.

A sugar industry PA workshop was also held in 1997 (Bramley *et al.*, 1997), inspired by early sugar industry interest in PA in the mid-1990s when Graeme Cox and Harry Harris (USQ) developed a prototype sugarcane yield monitor. This was subsequently used in preliminary research on a Herbert River farm, and commercially by Davco farming (Burdekin) who funded part of its development; alas, it was never commercialised in spite of evaluation by equipment manufacturers such as Case-IH and the then fertilizer company, Pivot, who were looking to develop PA services. The collapse of the sugar price at the end of the 1990s helped to ensure no further work with PA occurred in Australia beyond the on-going use of selected technologies by Davco.

Following a resurgence in industry fortunes during the mid 2000s, strong sugar industry interest in PA emerged. This occurred on the back of

- considerable progress with PA in other Australian agricultural sectors (grains and wine in particular);
- attempts in the Herbert (HCPSL and partners) to develop a regional harvest management and yield mapping capability supported by a local GPS network; and
- increased support for initiatives deemed of value in minimising possible impacts of sugarcane production on the Great Barrier Reef, including the provision of grants to growers for the purchase of GPS guidance systems and variable rate controllers for fertilizer spreaders.

Against this background, the then Sugar Research and Development Corporation (SRDC) decided to have another look at PA and commissioned CSIRO and USQ/NCEA to produce the reviews contained in SRDC Technical report 3/2007. A workshop held to mark the delivery of these reviews identified a number of PA-related R+D priorities which collectively could be characterised as being aimed at properly positioning the sugar industry for appropriate PA adoption, supported by access to the necessary technology, skills, methodological protocols and case studies. Thus, SRDC project CSE022 was funded to address these priorities, a 6-year multi-agency project (USQ, BSES and led by CSIRO).

Figure 1 provides a schematic representation of PA as a continuous cyclical process comprising *observation* of crop performance and other biophysical characteristics of the farming system (e.g. soil properties, topography) at high spatial resolution, integration, *evaluation and interpretation* of these data, drawing on a range of methods of spatial analysis, leading to the implementation of a targeted management plan as an alternative to the conventional practice in which uniform application of management is treated as the optimal approach by default.

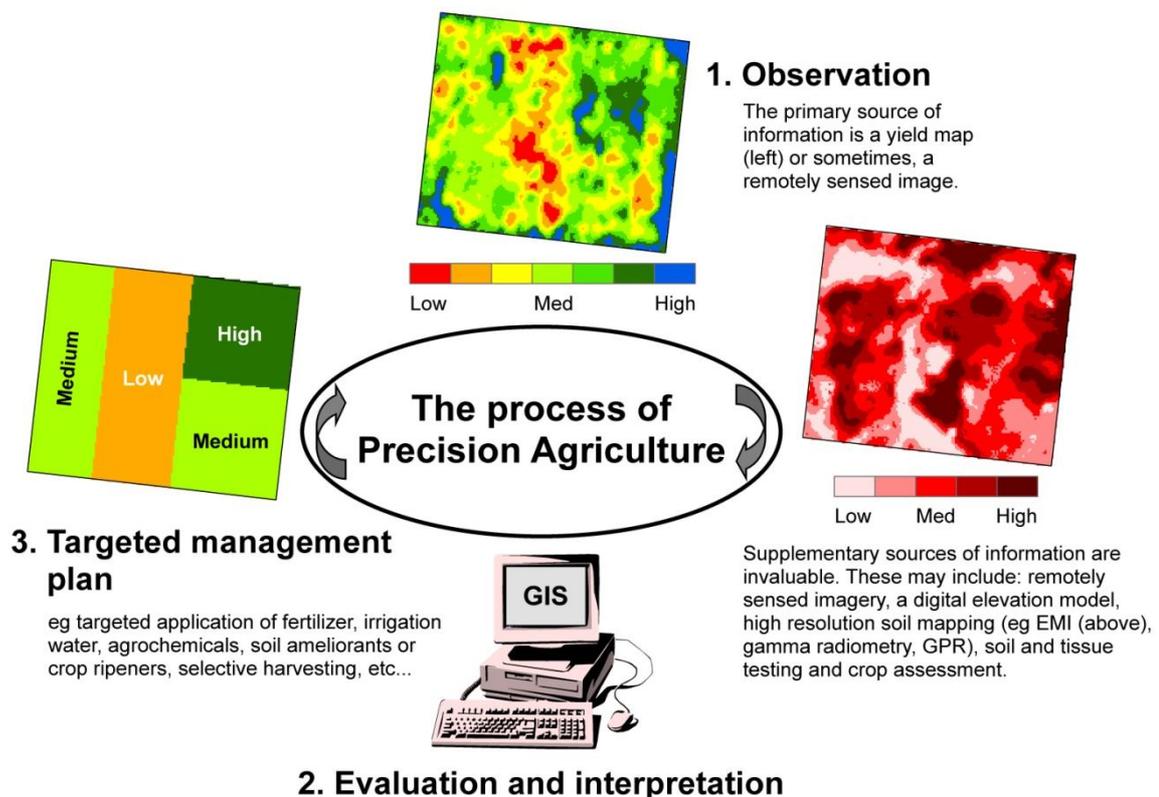


Figure 1. The process of Precision Agriculture - a framework for the conduct of CSE022.

During the conduct of this project, our research delivery and focus has been framed against Figure 1 and organized in four inter-connected 'streams' relating to:

1. Yield monitoring and other forms of sugarcane sensing (i.e. *observation*);
2. Data integration and case studies (i.e. *evaluation and interpretation*);
3. Agronomic management and variable rate application (i.e. opportunities for *targeted management*); and
4. Communication, adoption and capacity building.

Accordingly, in this report, we have organised the presentation in terms of these four streams as sub-sections under the various reporting headings specified by SRA. Our approach has been to report *briefly*, drawing on our previous Milestone reports and publications as appendices for the provision of further information for those interested in greater detail. Our intent in using this structure is to arrive at a report that is a useful resource rather than simply a record of the completion of contracted work. Readers wanting particular detail on a specific issue are encouraged to go straight to the list of appendices.

Objectives:

As stated in the original proposal, this project had the following objectives:

- Coordinate and integrate an evaluation of PA technologies (i.e. yield monitoring and mapping) in collaboration with leading farmers, with emphasis on economics, case studies, communication and extension led by the key farmers;
- Provide the appropriate specialist integrative and interpretive skills to complement existing research and developing PA technologies
- Provide input into investigations aimed at 'ground-truthing' apparent variability within specific blocks of sugarcane.
- Develop standardised data collection, management and analysis protocols.
- Improve capabilities of EOs and to provide technical support via links to appropriate specialists.

As agreed between the project team and SRDC in March 2010, whereas the project commenced on the basis that the three yield monitoring variants that were being commercially used at project commencement were fit for purpose, early results indicated that this was not, in fact, the case. This necessitated a refocussing of the project with a view to placing much greater emphasis on yield monitoring and mapping than had been anticipated (see Appendix 15) which had follow-on consequences such as an inability to progress economic evaluation of PA to the extent intended or to develop experimental methods in support of agronomic fine-tuning. This refocussing was endorsed through the mid-project review conducted by SRDC in September 2010. In addition, significant re-organisation of the industry extension delivery model during the life of the project (changes within BSES followed by the merger of BSES and SRDC) had a significant impact on the project's abilities to deliver against the final objective. With these caveats, the project has succeeded with significant delivery against the agreed Objectives and has enabled the sugar

industry to take a much more knowledge-based approach to the adoption of Precision Agriculture than was occurring without it. The following outlines how.

Methodology:

1. Yield monitoring and other forms of sugarcane sensing

1a. Yield monitoring

Considerable time and effort has been invested in yield monitoring during the term of this project. In the early phases of the project, it was around understanding the commercially available units and assessing their ability to monitor yield. This work has been reported on in numerous milestone reports and research papers. The evaluation of the early commercially available yield monitors is detailed in papers attached as Appendices 17 and 18.

In undertaking this evaluation, issues were identified with the current equipment. To rectify these issues, the early work of Cox was revisited to confirm that all sensing concepts performed well under ideal conditions. A prototype research (as opposed to commercial) yield monitor system incorporating DGPS and a multichannel logger with the ability to take in the many and varied sensing techniques was developed (see details in Appendices 21 and 26). This system has been used over 4 seasons and across 3 locations. This same equipment will continue to be used in the new project “Product and profit – Delivering precision to users of Precision Agriculture in the Australian Sugar Industry”- preliminary number RB001.

1b. Yield mapping.

Our initial approach to yield map production was to implement methods that have been tried and tested in other cropping industries. Given similarities between the dimensions of a typical cane block and an Australian vineyard, and mindful of issues of GPS accuracy, our mapping protocol was essentially the same as that used in viticulture, but with special focus placed on data pre-cleaning and calibration against the Mill (Bramley and Jensen, 2013; Appendix 31). Thus, all maps were interpolated onto a 2m grid derived from survey of the block boundary with dGPS. Recent refinements to the calibration and mapping of yield sensor data are described in Appendix 32 and Appendix 33.

1c. CCS sensing

Since there is no sensor available in either commercial or prototype format, all sugar sensing done as part of this project was reliant on hand sampling during harvest followed by lab analysis. The sampling strategy used was based on a regular grid with modifications made to ensure something that was both safe and feasible, given that sampling had to be conducted in close proximity to an operating harvester, and that captured short-range variation. See Bramley et al. (2012; Appendix 30). This work was conducted at our Bundaberg site in 2011 and 2012 and the Burdekin site in 2012 and 2013.

Although not directly funded as a part of this project, a PhD student (Nazmi Mat Nawi) conducted research that ran in parallel with this work including accessing material from the Bundaberg site. He investigated potential ways of assessing sugarcane CCS that might have application to on-the-go harvester sensing. This work, and the methods use in it are described in the 5 journal papers that were published during his studies:

- Nawi NM, Chen G, Jensen T. 2014. In-field measurement and sampling technologies for monitoring quality in the sugarcane industry: a review . Precision Agriculture. (In Press)
- Nawi NM, Jensen T, Chen G. 2014. Application of spectroscopic method to predict sugar content of sugarcane internodes. Journal of Tropical Agriculture and Food Science 41, 211-220.
- Nawi NM, Chen G, Jensen T, Mehdizadeh SA. 2013. Prediction and classification of sugar content of sugarcane based on skin scanning using visible and shortwave near infrared. Biosystems Engineering 115, 154-161.
- Nawi NM, Chen G, Jensen, T. 2013. Visible and shortwave near infrared spectroscopy for predicting sugar content of sugarcane based on a cross-sectional scanning method. Journal of Near Infrared Spectroscopy 21, 289-297.
- Nawi NM, Jensen T, Chen G. 2012. The application of spectroscopic methods to predict sugarcane quality based on stalk cross-sectional scanning. American Society of Sugar Cane Technologists Journal 32, 16-27.

2. Data integration and case studies

As indicated, Figure 1 represents our approach to PA. Aside from the data layers mentioned above, the project also made use of remotely sensed imagery acquired through Dr Andrew Robson (Formerly Qld DAFF, now UNE) as a part of SRDC Project FPP818 or follow-on projects. The imagery derived from the Ikonos, Geoeye and Spot platforms (see Milestone Reports 5, 11; Appendices 5, 11). High resolution electromagnetic soil survey data were also collected using either the EM38 or VERIS sensors (Bramley et al. 2012 - Appendix 24), along with gamma radiometrics, with georeferencing done using a Trimble global positioning system (GPS) with a differentially corrected signal derived from the Omnistar satellite; this system was also used for survey of block boundaries. Elevation data were sourced (where possible) from our collaborating farmers via their machinery guidance systems. Further information is provided in the relevant case studies (Appendices 12-14) and in selected Milestone Reports (Appendices 6, 9).

Other than where further specific detail is provided in various appendices, the analytical methods used were those that would be broadly regarded as standard methods for PA data. Spatial analysis and map display was done using the ArcGIS desktop suite of software (v. 10.0, ArcInfo licence; ESRI, Redlands, CA, USA), whilst statistical analysis, including *k*-means clustering of spatial data, was carried out using JMP (v. 10.0, SAS Inc, Cary, NY, USA).

3. Agronomic management and variable rate application

Precision Agriculture provides an important opportunity to improve agronomic management through more targeted use of inputs and on-farm operations. In order to implement PA, growers should follow a logical process that enables ultimate use of a cyclical self-learning experience (Figure 1) which may be enhanced through experimentation (see below). In this project we have developed a framework of activities for implementation of PA in the sugar industry based on Figure 1 and have used this at the project study sites to evaluate a PA approach to agronomy. The framework targets:

- Characterising in-field variability
- Ground-truthing
- Interpreting variability and identifying management zones
- Establishing appropriate inputs, their rates, and the feasibility and economics of variable application

Variable rate technology (VRT) provides opportunities to address field requirements (inputs and expected application rate) for zonal management. However, the merits of using VRT needs to be assessed on a case by case basis in terms of whether the variation in crop performance warrants variable application, and whether the equipment available has the capability to deliver the products at the proposed rates.

In assessing the use of VRT as part of this project, we identified the range of nutrients, soil ameliorants, herbicides and insecticides generally associated with sugarcane management, and assessed the relevance of VRT to deliver inputs at appropriate rates and scales. We also conducted an investigation to assess the capability of current fertiliser applicators to deliver products with sufficient accuracy and precision for use within a PA environment.

At our Burdekin study site we investigated a ‘whole of block’ experimental approach with six nitrogen rate strips (Appendix 38). The block was harvested with a yield monitor and yield maps produced. From the yield maps, yield data were extracted every 3 metres along the strip for use in comparison with the other strips. By identifying yield at regular points along each strip we were able to determine areas where yield varied significantly between adjacent strips (Appendix 38); considerable within-strip variation was also identified.

At the same site, we conducted a preliminary assessment of the ‘nitrogen surplus’ (as an indicator of potential nitrogen losses) in a uniformly fertilised block of sugarcane. Here, the nitrogen surplus is defined as the difference between the N applied (in fertiliser) and that exported from the block in harvested sugarcane, a measure that has been shown to be related to potential N losses, with higher surpluses leading to higher losses (Thorburn et al. 2013). In this assessment we wanted to compare how the N surplus at a point scale related to yield, as measured via a yield monitor, and so estimated the surplus at 22 and 25 sites in a 8.5 ha block of Tellus in 2012 and 2013 respectively (Appendix 35).

4. Communication, adoption and capacity building.

The project team developed a communication plan (Appendix 1) and presented this to regional workshops early in the project to obtain endorsement from industry participants. The communication plan drew on the project objectives and participatory project activities to help identify the information needs of stakeholders, and consequently the strategies for communication. In summary, the industry was seen as a rapid adopter of GPS technology, with very little to no PA adoption. There was a need for CSE022 to provide a coordination role for PA in the industry and to ensure adoption would occur from an informed basis.

CSE022 aimed to enhance the knowledge of the industry about the appropriateness of PA application for use at particular locations, to increase the number of extension officers who could provide PA advice, and to enhance the adoption of PA.

The developed communication plan identified various audiences to target, and the key message for those audiences. Tactics and timelines to implement communication were then developed for each key audience. Details are provided in Table 1 of Appendix 1.

To monitor industry needs, adoption and desired directions the project conducted surveys that coincided with regional meetings in 2008, 2010 and 2011. The project also conducted a survey that was sent to 1,500 growers at the conclusion of the project to assess industry wide adoption, thoughts on PA and future needs.

Results:

1. Yield monitoring and other forms of sugarcane sensing

During the life of CSE022, what we have been able to ascertain is that when the data is consistently handled, each yield sensing device is capable of producing yield information that is both commensurate with the other data layers indicated in Figure 1 (Milestone report #6 and 8; Appendices 6 and 8), and is a legitimate basis for farmers to use in management decision-making (e.g. Appendix 13), or to start their implementation of the PA cycle (Figure 1). However, this statement comes with the caveat that when the data are not handled correctly, or the equipment used to generate it is either not suitable or of a lower quality than is necessary, the result is a dramatic reduction in the confidence that we can have in the resultant yield maps. Consignment errors are especially problematic in this regard.

Issues around equipment include the necessity for the use of a good quality GPS to overcome issues identified in Milestone Report #7 (Appendix 7); ideally a dGPS should be used which accesses either an OmniStar or the AMSA beacon correction. Ensuring sensors are free moving, free from material buildup and regularly maintained are also important factors. In summary, a yield monitor is a sensitive instrument and should be treated as such.

How the data are handled can also have a significant impact on yield map utility. Appendix 32 details the data manipulation and filtering required prior to mapping. In summary, the following steps should be undertaken:

- ensuring data has GPS co-ordinates
- removing data when harvester ground speed was <0.75 or >3.0 m/s
- removing data when elevator speed was < 1.5 m/s
- removing data for which there is more than a 3 second gap covering consecutive data points – this removes aberrant yield predictions caused by the harvester speeding up or slowing down as it enters/leaves the field/changes haulouts

The procedures for generating yield maps are detailed in Appendix 31; Appendix 33 presents suggestions as to how the utility of these to growers might be maximised. In summary, the following steps should be undertaken:

- Removal of GPS errors
- Data thinning to a logging interval equivalent to 3 seconds
- Removal of edge effects such as arise when harvesting is uni-directional
- Data normalisation and trimming to within +/- 3 standard deviations of the mean
- Defining a block grid
- Interpolating a yield surface
- Assigning a map legend, north arrow and scale bar

When the above procedures are undertaken, each of the sensors have the ability to produce reliable yield maps as is evidenced in the case studies included as Appendices 12-14. A slight improvement in the accuracy of the sensor prediction was achieved by fusing several sensors (reported in Milestone Report #10) but the added complexity/cost of such a solution was not warranted.

Other forms of sugar cane sensing that has been undertaken as a part of, or in collaboration with this project include:

- Yield prediction from remote sensing (Appendix 27)
- CCS mapping (Milestone reports #10, 11; Appendix 10, 11, 30)
- Field based CCS sensing (PhD student's work)

In the case of our work on CCS mapping, results suggest that within-block variation in CCS contributes to approximately 20-25% of the within-block variation in income from cane growing. Whilst this suggests that 75-80% of the variation in income is due to variation in yield, we consider the contribution due to CCS variation to be sufficient to justify development of a prototype CCS sensor. Indeed, given the low *sample support* underpinning our CCS mapping, such a sensor is arguably needed in order to inform more precisely whether a commercial CCS sensor ought to be developed. The work conducted by the PhD student supports the view that an NIR-based sensor would be an appropriate starting point for developing a CCS sensor.

2. Data integration and case studies

Case studies for each of our key study sites are presented in Appendices 12-14. As will be evident, a major constraint was placed on these at the Bundaberg (Appendix 12) and Herbert (Appendix 14) sites by difficulties associated with yield monitoring and also by the fact that these two sites proved somewhat less variable than the Burdekin site (Appendix 13). Indeed, based on available data, we conclude that our Herbert study site is insufficiently variable to justify investment in PA. Nonetheless, all sites were highly valuable in illustrating the implementation of the process outlined in Figure 1 and of the notion that with further development of key pieces of equipment, PA could be 'fit-for-purpose' for sugarcane production. These studies also demonstrated the appropriateness of PA methodologies for

data analysis employed in other cropping sectors for application in sugarcane. In addition, and as illustrated in Appendix 13, the quasi-perennial nature of sugarcane production both promoted development of the use of 'average imagery' and 'average yield maps' as an aid to understanding variation over several seasons in which fallows may mean that some data are missing. This is important given that readily accessible algorithms for *k*-means clustering, the principle way in which different data layers are integrated, tend to exclude areas from the analysis in which data are missing in some data layers; generation of 'average' maps or images, is a useful means of overcoming this problem.

The common planting of mixed varieties in blocks also promoted the adjustment of yield monitor data in such blocks to a common basis, using the mean yield for one of these varieties for adjusting data on a per harvest event basis to values equivalent to the selected variety (Appendix 33). Discussion with our collaborating Burdekin grower suggested strong support for such an approach (Appendix 13).

Additional key findings from the case studies include:

- Good evidence that where within-block variation in crop performance is of sufficient magnitude to warrant attention, perhaps due to the variable occurrence of a constraint to production, spatial variation in crop performance appears to be temporally stable. A PA approach to addressing it is therefore justified.
- Compelling evidence from the Burdekin site of PA delivering an economic benefit through input cost savings and more efficient use of resources;
- In contrast, strong evidence from the Herbert site that PA is neither a panacea nor a strategy which will deliver ubiquitous benefit. The relatively non-variable nature of the Herbert site in terms of crop performance, coupled with its poor soils suggests that greater benefit:cost would probably accrue through investment in strategies aimed at enhancing soil quality rather than investing in PA;
- EM38 soil sensing is an appropriate alternative to the use of VERIS providing equivalent information on soil conductivity. Whilst there is no suggestion that VERIS should not be used (quite the contrary), EM38 may make electromagnetic soil sensing more accessible to some sections of the Australian sugar industry;
- Whilst gamma radiometrics has been shown to offer valuable information to adopters of PA in many cropping locations elsewhere in Australia and around the world, the coastal lowland soils which support much of the Australian sugar industry (at least in the Bundaberg, Burdekin and Herbert regions) appear to have low radiometric activity. Because these soils also tend to be deep, whereas the gamma signal derives from the top 40 cm of the soil profile, electromagnetic sensing of soil conductivity using EM38 or VERIS is likely to be a more useful means of acquiring soil information at high spatial resolution than gamma radiometrics. The benefit:cost of the latter is likely dependent on an ability to collect gamma data at minimal additional cost over EC_a.
- The common use of laser levelling or land planing may conspire against understanding the drivers of variation in crop performance. For previously unlevelled sites, retention of pre-levelled elevation data may prove to be valuable in understanding and reaction to variation.

3. Agronomic management and variable rate application

The three study sites were used as case studies for identifying and applying agronomic strategies to improve productivity, profitability and environmental stewardship. We used the framework described above to do this (Methodology, section 3); the associated spatial analysis is described in section 2 (above) and associated appendices.

For each of the study sites (Bundaberg (Appendix 2, 12), Burdekin (Appendix 3, 13) and Herbert (Appendix 2, 3, 14)), farm and soil maps were accessed together with the history (crop yields, varieties, etc...) and features (layout, irrigation system, topography, access, etc...) of each block. This information was provided through discussions with the project collaborators and was collected in addition to the high resolution spatial data acquired at each site. Such information enabled a good base understanding of each block's characteristics and suitability for PA research.

- Characterising in-field variability

As summarized in the case study descriptions (section 2 above), the Bundaberg site was found to be somewhat non-variable in terms of both crop performance (Appendix 12) and also the underlying soils as assessed using EM38 (Appendix 12, 24). The Burdekin site was the most variable primarily due to the existence of sodic soil conditions in one section of the field. The Herbert site was also relatively non-variable whilst the extensive land grading operations implemented there conspired against the project team being able to readily understand the patterns of variation in crop performance in relation to variation in soils. Indeed, at this site the soil variation did not appear to be of much agronomic significance in terms of driving spatial variation in crop performance (Appendices 9, 14); this site is also characterized by strongly acidic soils. As a result, PA is an unlikely management option at this site in our view. The soil data presented in Appendix 34 support our view that investment in strategies aimed at enhancing soil quality may deliver greater benefit:cost than investment in PA.

- Ground truthing, interpreting variability and identifying management zones

Our focus in this section is on the use of more 'traditional' agronomic information to assist in the identification and understanding of possible within-block management zones as outlined in the previous sections focused on high resolution spatial data. Note that the Tables referred to here are presented in Appendix 34.

Analysis of soil samples collected from the Bundaberg study site showed moderate variation as indicated in Table 1 of Appendix 34. However, once these data are interpreted using the SIX EASY STEPS guidelines, the required nutrient and ameliorant inputs were found to be relatively uniform across the site (Table 2). This confirms the initial assessment that splitting the block into nutrient management input zones at this site would be of little benefit.

The mapping of leaf sample analysis (N, P, Ca and Zn) from the Bundaberg site (samples collected in March 2012) showed little similarity to cane yield in either 2011 (Appendix 9, 12) or 2012 (Appendix 12). However, patterns of leaf N (%) were somewhat similar to the zones

seen in the CCS map of 2011 (Appendix 10, 12). If further work on CCS sensing is able to provide higher resolution CCS maps and also demonstrate stability in patterns of CCS variation, an additional study examining CCS-crop nutrition interactions could be highly valuable.

In contrast, soil data indicated that sodicity was the key driver of variability at the Burdekin site (Table 3). Gypsum requirement, based on the SIX EASY STEPS guidelines, ranged from 0 to 7.5 t/ha. A discrete zone of sodic soil was apparent in the lower-lying western side of the study area. This logically allowed for the grower to treat this zone with an appropriate amount of gypsum (Table 4) rather than applying it to the entire block. The merits of this approach are discussed further in the above case study section and Appendix 13.

As the Herbert site had been extensively land graded with uncertain variation in crop performance, (Appendix 9, 14), PA-related management options were not further pursued. However, a summary of soil data relating to this site is included in Appendix 34 together with nutrient inputs determined using the SIX EASY STEPS process.

- Establishing appropriate inputs and considering rates, feasibility and economics

The SIX EASY STEPS guidelines were assessed to determine if they were appropriate for use within a PA management system. In the case studies we found that N input could be varied according to zonal requirements and that the variable rate was both feasible and economically appropriate (Appendix 9). Similarly, the zonal application of gypsum at the Burdekin site was also found to be in line with the SIX EASY STEPS approach and economically advantageous (Appendix 7; see also the Burdekin case study – Appendix 13).

Although fertiliser applicators were found to be suitable for delivering product at required rates for a given area (e.g. 650 kg/ha), current technology does not appear to apply fertiliser with sufficient accuracy and precision at multiple rates to suit in-field zonal requirements. This issue is discussed in some detail in Milestone Report #10 (Appendix 10).

- Assessing the applied PA program in terms of productivity, profitability and environmental consequences

As PA is a cyclical learning and improvement program, it is important for PA users to undertake periodic assessments of the success of their zonally based strategies. Yield maps are a logical instrument for this supported by appropriate economic analysis. This will promote development and implementation of further changes to enhance any gains / savings that result from their adoption of PA (Appendices 8 and 10).

- Whole of block experimentation

Analysis of nitrogen rate strips at the Burdekin site showed yield to vary significantly ($p < 0.01$) between nitrogen (N) strips that were only 14 metres apart. Very large areas along a strip where 37 kg N/ha was applied to a plant crop (after a cowpea break crop that contributed 113 kg N/ha in residue) were significantly lower yielding than strips either side where 153 and 132 kg N/ha was applied. However, the highest yielding area of the 37 kg N/ha strip (up

to 190 t/ha) yielded very close to the higher N rate treatments either side. This area could have yielded more with extra N, but may not need as much as 132 kg N/ha. This area of the block would require further investigation to determine appropriate rates (Appendix 38).

- Estimation of potential N surplus

Nitrogen surplus appears to be correlated to yield, with higher surpluses corresponding to points with lower yields in a block of Tellus in 2012 and 2013 at our Burdekin case study site (Appendix 35). The yield map from this block shows temporal stability between 2012 and 2013 (Appendix 13). When plotted on the yield map, points with a higher N surplus are grouped in the lower yielding part of the block. As higher N surpluses are associated with higher N losses (Thorburn and Wilkinson, 2013), we conclude that the low yielding areas of blocks are more likely to be losing more N than high yielding areas under uniform management. Targeting reduced applications of N to these low yielding areas has the potential to reduce N losses from sugarcane.

4. Communication, adoption and capacity building.

All of the tactics designed by the project for communication were implemented. General media articles, web site presence and YouTube videos were created to provide the general sugarcane industry with information about PA. Six journal papers and twelve conference papers were produced to inform the research community of PA in the Australia sugarcane industry. Project staff have been involved in agriculture information sessions where they have presented on PA to extension staff and productivity officers.

The surveys have identified an increase in the adoption of PA by the Australian sugarcane industry since the project inception (albeit from a low base). The 2014 survey of 327 industry participants indicates the industry believes there is strong commercial benefit from implementing PA, and there are plans by 65% of the industry that grows more than 200 hectares to implement variable rate application in the coming five years.

The survey suggests that PA is starting to become a part of the Australian sugarcane industry, and the respondents indicate that future implementation is highly likely. There is still some uncertainty in the industry about exactly how implementation will occur, with a number of limitations identified, but a strong belief that commercial benefits will result. Support for further investment to help the industry research and develop precision agriculture exists. Appendix 36 presents the questions used in the survey whilst Appendix 37 provides an analysis of the responses received.

Outputs:

1. Yield monitoring and other forms of sugarcane sensing

A major output from the project has been the increased understanding of the yield sensing concepts that might be used for sugarcane yield monitoring. This understanding started from

an evaluation of the commercially available yield monitoring equipment circa 2009. When interrogated, it was clear that these devices provided low confidence in the data that they generated. Subsequent testing proved that various yield sensing concepts were much better than was evident in the commercial devices. A key issue was the proprietary methods of handling the data which, when coupled to calibration against Mill data at coarse scale rather than on a harvest event basis, had a considerable influence over the utility of information generated (Appendix 31). With careful and consistent manipulation of data, useful results can be achieved. Data handling, yield map generation and display protocols (Appendices 31-33) are important outputs of this project. The potential for an automated process to interrogate the yield monitor values to determine if confidence can be had in the data, and to greatly reduce the need for manual data manipulation is a major area of focus in the new project “Product and profit – Delivering precision to users of Precision Agriculture in the Australian Sugar Industry”-preliminary number RB001.

2. Data integration and case studies

See Results section above and the relevant case study appendices (12-14). Note that by its nature, PA is site-specific and accordingly, the outputs from its adoption are also site-specific. Our case studies nevertheless demonstrate the suitability of conventional approaches to PA data analysis and of our protocols relating to sugarcane yield monitoring and mapping.

3. Agronomic management and variable rate application

- Developed procedure for determining in-field variability based on general information, EC mapping and soil tests acquired through ground truthing (Appendices 2 and 3).
- Despite the unresolved issues with yield monitors, it is still possible to determine nutrient inputs for specific zones within blocks using the current SIX EASY STEPS guidelines. These are based on district yield potential (DYP) and an N mineralisation index for differentiating soil types (Appendix 9). With access to more robust yield monitoring, it would be realistic to substitute DYP with zonal yield potential.
- Identified inputs that have potential for application using VRT within the sugarcane farming system (Appendix 9).
- Identified feasible variable rates for fertilisers, ameliorants and herbicides within a PA environment (Appendix 9).
- Evaluation of granular fertiliser applicators indicated that they do not deliver products with sufficient accuracy and precision for use with PA (Appendix 8, 10).
- Liquid and spray applicators are inherently more accurate and precise, and therefore suitable for VRT applications; these are commonly used in other broadacre cropping systems.
- Showed that whole of block experimentation results can add value to analysis of yield maps for determination of appropriate nitrogen application rates (Appendix 38).
- Identified that low yielding areas of a sugarcane block are more likely to be losing nitrogen than high yielding areas under uniform management, and thus could be targeted with reduced nitrogen application under variable rate application to reduce nitrogen losses (Appendix 35).

4. Communication, adoption and capacity building.

The project has produced a number of communication outputs which are detailed in the 'list of publications'. The result of these communications has been an increase in the understanding of many sectors of the Australian sugarcane industry (most notably growers, extension and research) about PA and its role in the industry. The 2014 survey analysis (Appendix 37) provides a summary of industry support for PA.

In summary, we refer back to Figure 1 which illustrates the concept of PA using examples drawn from previous work conducted in the wine industry – specifically from a 7.3 ha vineyard in the Coonawarra region. However, as a consequence of the work conducted in this project, we can now provide a sugar industry analogue to Figure 1 derived from our Burdekin site and the associated case study (Figure 2). It is the view of the project team that Figure 2, supported by the other material contained in this report and referred to in the Communication Plan and other Appendices, provides ample indication of the overall outputs which have arisen from the work conducted.

Intellectual Property and Confidentiality:

Considerable domain knowledge has been brought into the project by virtue of the significant research experience of the project team in Precision Agriculture, Agricultural Engineering, Soil Science and Sugarcane Agronomy. Specific examples include:

- Grains and grape yield mapping protocols (development of) have influenced the sugarcane yield mapping protocol; grape protocol owned by the Australian Wine Research Institute – copyright
- Alternative sensor arrangement for measuring roller opening based on a BSES design (not protected) for sugarcane harvester research
- Various in-house tools and technologies i.e. sensors and software used to assist research efforts.
- Project IP developed on institutional knowledge; equipment provided effectively as in-kind, i.e. EM38, GPS, Gamma Radiometrics, GIS and analysis software

There has been no registrable IP developed by research activities; however, the following project IP has been identified including:

- Protocols for processing sugarcane yield monitor data with the potential to develop guidelines protected via copyright or trade secret that could be exploited via engagement with equipment manufacturers.
- Sugarcane yield mapping protocol that is protected via copyright and could be exploited via industry engagement and yield map industry training.
- Alternative sensor arrangements (i.e. roller opening) with potential to engage with manufacturers although requiring some engineering design and significant infield testing with a manufacturer.
- Field data that has been presented in various reports, scientific publications and media articles which is protected via copyright.

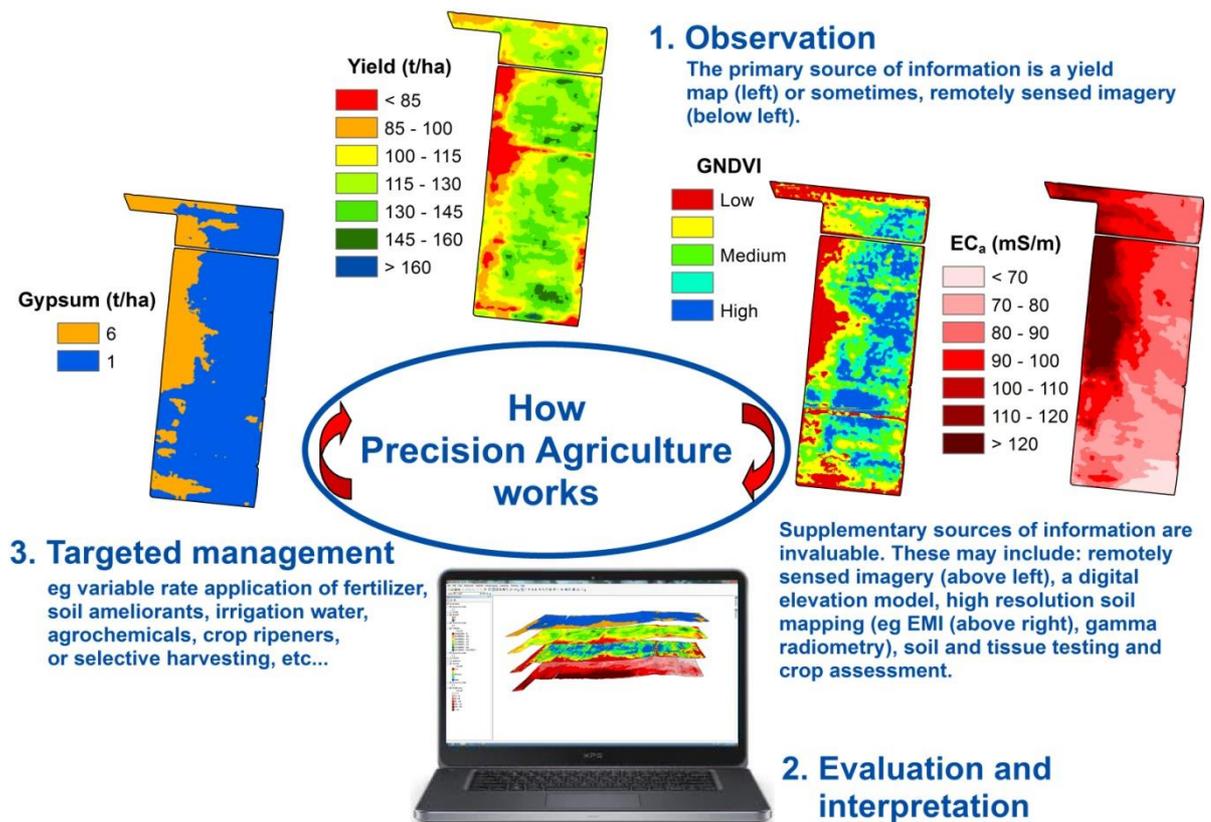


Figure 2 The process of Precision Sugarcane Production as applied to a 26.7 ha sugarcane field in the Burdekin region. Here, observations of crop performance in the form of a yield map (average of three seasons) and remotely sensed imagery (GNDVI; average of 4 seasons), have been combined with an electromagnetic survey of soil electrical conductivity (EC_a) and a digital elevation model obtained via the farmer's tractor guidance system, to understand and manage the impact of sodic soils on cane production. Spatial analysis of these data promoted the identification of two zones for the targeted application of gypsum. In this example, the proposed strategy led to a saving of \$330/ha in the cost of gypsum application compared to the conventional uniform application of 3.5 t/ha; an additional benefit through yield response to alleviation of the sodic constraint would also be expected.

Commercialisation of IP relating to yield monitoring equipment is not likely to occur around hardware given that current sensing equipment is based on off-the-shelf sensors. Our weigh pad unit has been sourced from Case New Holland and we understand that they will be re-releasing this product in the near future.

Potential IP may reside in the analysis of data from various yield monitoring concepts, as the concepts have outperformed their commercial equivalents. Further research is required in this area and is the subject of ongoing activities funded by SRA.

Earlier in the project it had been noted that there was also potential IP from sugar sensing work (Milestone Reports #4 and 5; Appendices 4, 5). The IP here was strictly via a NCEA/USQ undergraduate project that was not funded by SRDC / SRA except for supervision of the activity under the auspices of CSE022. Potential IP that was identified included:

- Matlab model for analysing digital images of macerated cane samples for determining ccs, brix, pol and fibre
- Modified camera for capturing digital images; protection of hardware unlikely; commercial opportunity depends on model / software for analysing images which would require a lot more work.

Environmental and Social Impacts:

Adoption of PA and a consequent fine-tuning of inputs targeted at increasing their efficiency of use is expected to deliver both profitability (see elsewhere in this report) and environmental (inferred) benefits, both of which have obvious follow-on social benefits for rural communities dependent on sugarcane production. It is also worth pointing out a possible additional social benefit: PA is difficult and to get some benefit from it requires some effort and thought to be put in. However, experience in other industries shows this effort to be worthwhile. The upskilling implicit in this process is of potentially significant social benefit and may also lead to employment opportunities by way of PA service provision and consulting.

Through demonstrating that nitrogen surplus appears to be related to yield, we can propose that losses of nitrogen from sugarcane blocks are more likely to be originating from lower yielding areas of blocks than higher yielding areas (Appendix 35). In situations where there is spatial stability of yield (e.g. our Burdekin site – Appendix 13) variable nitrogen applications can target lower rates to these lower yielding areas. These lower nitrogen application rates to lower yielding areas could be expected to lead to lower potential for nitrogen losses to the environment.

Expected Outcomes:

Appendix 13 describes the economic benefits accruing to our collaborating farmer in the Burdekin through targeted application of gypsum. An economic analysis of variable rate nitrogen application over ten years to a block of sugarcane in the Herbert mill area showed an annual benefit averaging \$32 per hectare (range \$26 to \$38) with two block zones and an average benefit of \$40 (range \$33 to \$48) per hectare with three zones (Appendix 7). The analysis did not account for the spatial variation in CCS and the interactions between N supply and CCS. The same analysis identified benefits of zonal N management in reduced N surplus, which could lead to lower environmental N losses.

Future Research Needs / Recommendations:

CSE022 has made significant progress by:

- demonstrating shortcomings in the yield monitoring technology used by industry at project commencement, evaluating alternatives and repositioning this technology for robust application;
- producing a protocol for yield data acquisition and mapping
- identifying the need for a new approach to consignment and/or yield monitor calibration;
- demonstrating the value of high resolution soil survey (VERIS, EM38) and elevation modelling in understanding drivers of within block yield variation;
- highlighting the utility of remotely sensed imagery (collaboration with DPI021 - Robson, DAFFQ, now UNE), for understanding the extent of within paddock variation in crop growth;
- highlighting the impact of within-block CCS variation on paddock gross margins and the consequent need for an on-the-go (i.e. high resolution) CCS sensing capability to complement yield monitoring;
- demonstrating the inaccuracy of existing solid fertilizer application systems, raising questions about the merit of retro-fitting spreaders with variable rate controllers;
- explaining the pathway to PA adoption through case studies (see Appendices 13-14), PEC videos, technical workshops, regional grower meetings and conferences (e.g. ISSCT, 2012; ASSCT 2010).

However, effective adoption of PA depends on the resolution of several outstanding issues, in particular, the on-going lack of a robust, commercially available yield monitor. Further work is needed which aims to build on CSE022 and capture the full return on the PA RDE investment by:

- exploring improved consignment/yield monitor calibration options, translating outputs from CSE022 relating to yield mapping and monitoring to a robust commercialisable format which to some extent is addressed in the new SRA project No. RB001);
- gaining greater clarity about temporal stability in patterns of variation in crop performance and the robustness of management zone delineation. A useful component of this could be to explore the possible use of remotely sensed imagery (collaboration with Andrew Robson yield prediction work) as a means of identifying the existence (or not) of sufficient within-block variation to justify investment in other PA technologies at specific locations;
- understanding whether PA should be implemented on the basis of variation in cane yield, CCS or sugar produced (i.e. whether yield and CCS variation have the same drivers);
- exploring options for on-the-go CCS sensing;
- further developing case studies aimed at enumerating the benefit:cost of PA adoption through input cost savings and enhanced productivity;
- deriving a basis for the site-specific application of 6 EASY STEPS using sub paddock-scale estimates of potential yield and N mineralisation rate and crop modelling; and

- implementing spatially distributed experimentation to inform site-specific norms for the use of agronomic inputs.

The present CSE022 team and its collaborators has strong potential and the appropriate expertise to address these issues and would like to discuss doing so with SRA.

List of Publications:

The project has produced six journal papers and twelve conference papers to date. In addition project team members participated in the production of four SRA 'CaneClips' – Youtube videos highlighting various research topics. The project also produced seven general media articles for the sugar industry. The published journal and conference papers are attached in the appendices list of this report.

Journal papers:

1. Bramley RGV, Trengove, S. 2013. Precision Agriculture in Australia: present status and recent developments. *Engenharia Agricola* 33 575-588.
2. Bramley RGV, Panitz JH, Jensen TA, Baillie CP. 2013. Within block spatial variation in CCS – Another potentially important consideration in the application of Precision Agriculture to sugarcane production. *International Sugar Journal* 115 431-436.
3. Jensen TA, Baillie C, Bramley RGV, Panitz JH. 2012. An assessment of sugarcane yield monitoring concepts and techniques from commercial yield monitoring systems. *International Sugar Journal* 115 53-57.
4. Bramley, RGV. 2009. Lessons from nearly 20 years of Precision Agriculture research, development and adoption as a guide to its appropriate application. *Crop and Pasture Science* 60 (3), 197-217.
5. Bramley RGV, Jensen, TA. 2013. Sugarcane yield monitoring: a protocol for yield map interpolation and key considerations in the collection of yield data. *International Sugar Journal* 116 370-379
6. Rodrigues FA, Bramley RGV, Gobbett DL. 2014. Proximal soil sensing for Precision Agriculture: Simultaneous use of electromagnetic induction and gamma radiometrics in contrasting soils. *Geoderma* – submitted / in review.

Conference papers:

1. Bramley R. 2012. Mixed fortunes in crop quality sensing. Proceedings of the 15th Precision Agriculture Symposium in Australasia, held at the Grand Hotel, Mildura, 5-6 September. SPAA / University of Sydney. pp 22-26.
2. Bramley RGV. 2012. Precision Agriculture: Opportunities for Improved Management of Sugarcane Production. In: RA Gilbert (Ed) Sustainable sugarcane production. Proceedings of the ISSCT agronomy and agricultural engineering workshop, 9-14 September, Townsville.
3. Bramley RGV, Gobbett DL, Panitz JH, Webster AJ, McDonnell P. 2012. Soil sensing at high spatial resolution – broadening the options available to the sugar industry. Proceedings of the Australian Society of Sugar Cane Technologists, 34th Conference, Cairns. Electronic format. 8 pp.

4. Bramley RGV, Jensen TA. 2013. Sugarcane yield monitoring: a protocol for yield map interpolation and key considerations in the collection of yield data. Proceedings of the Australian Society of Sugar Cane Technologists, 35th Conference, Townsville. Electronic format.
5. Bramley RGV, Panitz JH, Jensen TA, Baillie CP. 2012. Within block spatial variation in CCS – Another potentially important consideration in the application of Precision Agriculture to sugarcane production. Proceedings of the Australian Society of Sugar Cane Technologists, 34th Conference, Cairns. Electronic format. 8 pp.
6. Bramley RGV, Trengove S. 2012. Precision Agriculture in Australia: present status and recent developments. In ConBap 2012 - Congresso Brasileiro de Agricultura de Precisão, Ribeirão Preto - SP, Brasil. 24 to 26 September. www.sbea.org.br/conbap2012/arquivos/R_BRAMLEY.pdf
7. Jensen T, Baillie C, Bramley R, DiBella L, Whiteing C, Davis R. 2010. Assessment of sugarcane yield monitoring technology for precision agriculture. Proceedings of the Australian Society of Sugar Cane Technologists, 32nd Conference, Bundaberg. 410-423.
8. Jensen TA, Baillie C, Bramley RGV, Panitz JH. 2012. An assessment of sugarcane yield monitoring concepts and techniques from commercial yield monitoring systems. Proceedings of the Australian Society of Sugar Cane Technologists, 34th Conference, Cairns. Electronic format. 7 pp.
9. Jensen, T.A., Fokkema, B., Baillie, C. 2011. Assessing various techniques to monitor yield in sugarcane. In: Diverse Challenges Innovative Solutions – Society for Engineering in Agriculture Conference, Gold Coast, 28-30 September, 2011. Pp248-256.
10. Jensen, T.A., Fokkema, B., Baillie, C and Bramley, R.. 2010. Assessment of sugarcane yield monitoring technology for precision agriculture – 14th Precision agriculture symposium in Australasia, Albury, 2-3 September 2010 pp 7.
11. Robson R, Abbott C, Lamb D, Bramley R. 2012. Deriving Sugarcane Yield Maps from SPOT 5 Satellite Imagery at a Regional Scale. In: RA Gilbert (Ed) Sustainable sugarcane production. Proceedings of the ISSCT agronomy and agricultural engineering workshop, 9-14 September, Townsville.
12. Robson R, Abbott C, Lamb D, Bramley R. 2012. Developing sugar cane yield prediction algorithms from satellite imagery. Proceedings of the Australian Society of Sugar Cane Technologists, 34th Conference, Cairns. Electronic format. 11 pp.

General industry media:

1. Bramley, R. 2011. Precision Agriculture: what it is and what it isn't. BSES Bulletin 31, 18-21.
2. Bramley, R. 2009. Precision farming for sugarcane production. Australian Canegrower. 9 March, 2009. 12-13.
3. Jensen, T. 2011 Bitter sweet success for sugar yield monitoring. Australian Sugarcane 15 (1), 11.
4. Jensen, T. 2010. Bitter sweet success for sugar yield monitoring. Precision Ag News 7 (1), 16-17.
5. Jensen T, Panitz J, Baillie C, Bramley R, Whiteing C, Schroeder B, Webster T. 2012. Sugarcane yield monitoring update – CSE022. BSES Bulletin 33, 9-10.

6. Schroeder, B., Panitz, J., Baillie, C., Jensen, T., Bramley, R., Whiteing, C. And Webster T. 2011. Precision Agriculture (PA) project study sites. BSES Bulletin 32, 24-27.
7. Webster, T, Panitz, J, Jensen, T. 2014. Precision agriculture survey results. SRA e-newsletter.
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Videos:

1. Precision Agriculture: <http://www.youtube.com/embed/4jcKarUHkeM>
2. Yield monitors: <http://www.youtube.com/embed/mFQAY4fUdYg>
3. What is Precision Agriculture: <http://www.youtube.com/embed/sLu5t9t-67k>
4. CCS sensors in Precision Ag: <https://www.youtube.com/watch?v=5w6Uj0DGfSw>

Acknowledgments

In addition to the Principal Investigators identified on page 1, the input of the rest of the project team needs to be acknowledged in full. In particular, Dr Troy Jensen (USQ/NCEA) has taken the lead in the work focussed on yield sensing; Tony Webster (CSIRO) and John Panitz (SRA) have made critical inputs to the agronomic aspects of the project with Tony Webster also coordinating the industry survey; and David Gobbett (CSIRO) provided critical support in regard to many aspects of non-yield sensing, data processing and GIS. The input and assistance of Angel Garcia Garmendia (USQ/NCEA), Cam Whiteing (BSES/SRA) and many other staff of the former BSES (now SRA) is gratefully acknowledged as is the support and assistance of many industry personnel, especially in the regions where our case studies were conducted. The project would not have been possible at all without the critical input of Jay Hubert, Denis Pozzebon and Brian Tabone on whose farms the case studies were conducted; their participation in the project has been valued highly.

In addition to these collaborating farmers and others acknowledged in the case studies, we are also most grateful to Summer Olsen of the SRA PEC unit who contributed valuably by chasing us for participation in the PEC Caneclips videos. Dr Francelino Rodrigues (visitor to CSIRO, now at CIMMYT, Mexico) made valuable contributions through fieldwork associated with the high resolution soil survey and provision of GIS support to the project.

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List of Appendices:

- Appendix 1** Project Communications Plan
- Appendix 2** CSE022 Milestone Report 2. 1-12-2008
- Appendix 3** CSE022 Milestone Report 3. 1-05-2009
- Appendix 4** CSE022 Milestone Report 4. 1-12-2009
- Appendix 5** CSE022 Milestone Report 5. 1-05-2010
- Appendix 6** CSE022 Milestone Report 6. 1-12-2010
- Appendix 7** CSE022 Milestone Report 7. 1-05-2011
- Appendix 8** CSE022 Milestone Report 8. 1-12-2011
- Appendix 9** CSE022 Milestone Report 9. 1-12-2012
- Appendix 10** CSE022 Milestone Report 10. 1-12-2013
- Appendix 11** CSE022 Milestone Report 11. 1-05-2014
- Appendix 12** Case Study - Bundaberg site
- Appendix 13** Case Study – Burdekin site
- Appendix 14** Case Study – Herbert site
- Appendix 15** Bramley R. 2013. Precision Agriculture in the Australian sugar industry – past, present (Nov’ 2013) and future. Briefing note prepared for Sugar Research Australia.
- Appendix 16** Bramley RGV. 2009. Lessons from nearly 20 years of Precision Agriculture research, development and adoption as a guide to its appropriate application. *Crop and Pasture Science* 60 (3), 197-217.
- Appendix 17** Jensen T, Baillie C, Bramley R, DiBella L, Whiteing C, Davis R. 2010. Assessment of sugarcane yield monitoring technology for precision agriculture. *Proceedings of the Australian Society of Sugar Cane Technologists, 32nd Conference, Bundaberg.* 410-423.
- Appendix 18** Jensen TA, Fokkema B, Baillie C, Bramley, R. 2010. Assessment of sugarcane yield monitoring technology for precision agriculture – 14th Precision agriculture symposium in Australasia, Albury, 2-3 September 2010 pp 7.

- Appendix 19** Bramley R. 2011. Precision Agriculture: what it is and what it isn't. BSES Bulletin 31, 18-21
- Appendix 20** Schroeder B, Panitz J, Baillie C, Jensen T, Bramley R, Whiteing C, Webster T. 2011. Precision Agriculture (PA) project study sites. BSES Bulletin 32, 25-27.
- Appendix 21** Jensen, T.A., Fokkema, B., Baillie, C. 2011. Assessing various techniques to monitor yield in sugarcane. In: Diverse Challenges Innovative Solutions – Society for Engineering in Agriculture Conference, Gold Coast, 28-30 September, 2011. pp 248-256.
- Appendix 22** Bramley R. 2012. Mixed fortunes in crop quality sensing. Proceedings of the 15th Precision Agriculture Symposium in Australasia, held at the Grand Hotel, Mildura, 5-6 September. SPAA / University of Sydney. pp 22-26.
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- Appendix 24** Bramley RGV, Gobbett DL, Panitz JH, Webster AJ, McDonnell P. 2012. Soil sensing at high spatial resolution – broadening the options available to the sugar industry. Proceedings of the Australian Society of Sugar Cane Technologists, 34th Conference, Cairns. Electronic format. 8 pp.
- Appendix 25** Jensen T, Panitz J, Baillie C, Bramley R, Whiteing C, Schroeder B, Webster T. 2012. Sugarcane yield monitoring update - CSE022. BSES Bulletin 33, 9-10.
- Appendix 26** Jensen TA, Baillie C, Bramley RGV, Panitz JH. 2012. An assessment of sugarcane yield monitoring concepts and techniques from commercial yield monitoring systems. International Sugar Journal 115 53-57.
- Also published in: Proceedings of the Australian Society of Sugar Cane Technologists, 34th Conference, Cairns. Electronic format. 7 pp.
- Appendix 27** Robson R, Abbott C, Lamb D, Bramley R. 2012. Deriving Sugarcane Yield Maps from SPOT 5 Satellite Imagery at a Regional Scale. In: RA Gilbert (Ed) Sustainable sugarcane production. Proceedings of the ISSCT agronomy and agricultural engineering workshop, 9-14 September, Townsville.
- Appendix 28** Robson R, Abbott C, Lamb D, Bramley R. 2012. Developing sugar cane yield prediction algorithms from satellite imagery. Proceedings of the Australian Society of Sugar Cane Technologists, 34th Conference, Cairns. Electronic format. 11 pp.
- Appendix 29** Bramley RGV, Trengove, S. 2013. Precision Agriculture in Australia: present status and recent developments. Engenharia Agricola 33 575-588.

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Appendix 30 Bramley RGV, Panitz JH, Jensen TA, Baillie CP. 2013. Within block spatial variation in CCS – Another potentially important consideration in the application of Precision Agriculture to sugarcane production. *International Sugar Journal* 115 431-436.

Also published in: Proceedings of the Australian Society of Sugar Cane Technologists, 34th Conference, Cairns. Electronic format. 8 pp.

Appendix 31 Bramley RGV, Jensen TA. 2013. Sugarcane yield monitoring: a protocol for yield map interpolation and key considerations in the collection of yield data. *International Sugar Journal*.

Also published in: Proceedings of the Australian Society of Sugar Cane Technologists, 35th Conference, Townsville. Electronic format. 12 pp.

Appendix 32 Sugar Yield monitor data manipulation

Appendix 33 Refinements to the procedures used in converting yield sensor data to robust yield maps – An analysis of different approaches to sensor calibration aimed at identifying the most appropriate yield sensor for use in CSE022 case studies and the most appropriate map presentation format.

Appendix 34 Soil analytical data from the Bundaberg, Burdekin and Herbert sites and their interpretation for nutrient management.

Appendix 35 Spatial nitrogen surplus relationship to yield in sugarcane

Appendix 36 Questions used in the industry PA survey, 2014

Appendix 37 Views of sugarcane industry participants on Precision Agriculture

Appendix 38 Exploring the opportunity of spatially distributed experimentation – a Burdekin strip trial.