Final Report: SRDC Project BPS001

Attachment 1: Scientific Findings

Identifying management zones within cane paddocks: an essential foundation for precision sugarcane agriculture

by

R.J. Coventry and J.R. Hughes

with contributions by

A.E. Anderson, P.A. McDonnell, D.C. Pollock, J.A. Markley, L.P. Di Bella, A.J. Crowley, A.W. Wood, and P. Sgarbossa

Chief Investigator:
Dr Ross Coventry,
Soil Horizons Pty Ltd,
27 Northwest Crescent,
Cranbrook, Queensland 4814
Telephone: 04 1234 6913
Email: ross@soilhorizons.com.au

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Final Report

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Project Title: *Identifying management zones within cane paddocks: an essential foundation for precision sugarcane agriculture*

Lead Research Organisation

- Burdekin Productivity Services Ltd, Ayr

Participating Research Organisations

- Soil Horizons Pty Ltd, Townsville
- Queensland Department of Employment, Economic Development, and Innovation, Mackay, Townsville, and South Johnstone
- Ag Data Solutions Pty Ltd, Ayr
- Mackay Sugar Cooperative Association Ltd, Mackay
- Herbert Cane Productivity Services Ltd, Ingham
- Independent Agricultural Resources Pty Ltd, Mackay
- Sucrogen Ltd, Ingham
- Terrain NRM, Ingham

Principal Investigator

Dr Ross Coventry
27 Northwest Crescent, Cranbrook, Queensland, 4814
Telephone: 04 1234 6913
Email: ross@soilhorizons.com.au

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Chapter 1

PROLOGUE

1.1 EXECUTIVE SUMMARY

Variability in plant growth across spatial zones within sugarcane crops arises from the complex interactions of soil nutritional status, soil physical properties (especially soil texture), surface and subsurface drainage, seasonal conditions, soil health, pests and diseases, cane variety adaptability to soil type, and paddock management practices.

BPS001 research has shown that no single GIS spatial layer is sufficient to identify and manage the variability inherent in sugarcane paddocks. However, by comparing patterns within three key GIS layers, we have found a way to simplify the complexity among the factors controlling crop yields, and have found answers to the two basic questions driving the research:

- How do satellite imagery and apparent soil electrical conductivity (ECa) map patterns relate to variations in space and time in soils, soil properties, and sugarcane yield?

- Are there general relationships between image analysis, ECa signals, yield, and soil properties that are widely applicable within and between regions?

The three fundamental GIS layers are:

- *A soil layer (stable)*: based on technology such as deep soil ECa responses where detailed soil maps are not available. The map patterns must be checked against actual soil profile data, especially soil texture and sub-surface drainage characteristics, at strategically located sites. We have shown that these spatial data are related to stable soil properties and may be relied on to produce similar, mappable, spatial patterns from year to year and, in the case of our study, over a 5-year cropping cycle.

- *A topography, or 'drainage', layer (stable within a crop cycle, but influenced by paddock earthworks)*: based on detailed topographic data that may be readily accessed during soil ECa surveys, or by tractors equipped with real-time kinematic global positioning systems (RTK-GPS). This layer defines water movement pathways in paddocks and characterises the drainage status of contiguous segments of the crop along each row within the paddock. The surface drainage patterns are closely related to the potential of a site to become waterlogged under wet conditions or to dry out rapidly under dry conditions; in either case, the paddock management zones will have a negative impact on crop yield. The patterns are likely to change if any earthworks are carried out in the paddock. Hence, the patterns are stable within a crop cycle but may change if drainage works or other land-shaping activities are carried out in the fallow period between successive crops in the paddock.

- *A crop yield layer (variable spatial responses to weather, pests and diseases, and paddock management strategies)*: reflects differences in soil and site parameters controlling the growing conditions within yield zones in a paddock. Data may be derived from high resolution satellite imagery captured before harvest or from harvester-mounted yield monitors. BPS001 research has found that patterns in crop yield variability are closely related to the distribution of contrasting soil groups in relation to paddock topography. The repeatability from year to year of the definition of higher-and lower-yielding crop production zones, and the stability of the zone boundaries under different climatic and management regimes remain to be demonstrated.

Enhanced knowledge of relationships among these and other spatial GIS layers will drive progress and the wider adoption of precision agricultural techniques in sugarcane production.

The main benefits to flow from this knowledge include:

Industry
Knowledge of relationships among GIS layers will provide pathways for continual on-farm improvements embracing activities as diverse as soil preparation strategies, zonal ripping, applying plant nutrients, breeding adapted cane varieties, managing irrigation water, refining spatially-defined management techniques based on crop yield potential, and adopting relevant precision agricultural technologies.

Farm productivity
More efficient use of crop inputs (*e.g.* fertiliser, soil amendments, water, pesticides) will result from applying only the input level needed to support crop growth on particular parcels of land and from minimising off-farm losses. Techniques for identifying cane varieties adapted to both soil variability and spatial positions in the landscape are likely to develop, and they will require a 'variable variety planter' to fully capitalise on the possibility of on-the-go planting of varieties that match specific soil conditions.

Environmental
Significant water quality improvements will be generated by paddock inputs based on site-specific management of spatially-defined zones of crop yield potential. It is likely that developments in this area will extend to the revision of State Government regulatory guidelines governing soil nutritional and plant protection inputs in the future..

Economic
Site-specific application of nutrients (e.g. '*Six Easy Steps*'), pesticides, and herbicides should be based on spatially defined management zones within paddocks including, but not limited to, the yield potential and key soil properties of the zones. To fully capture this benefit, the definition of the management zones will require a spatial analysis of the impact of seasonal growing conditions on the patterns of crop yield over long sequences of wet, dry, and 'average' years.

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- Site H1: Alan Pace, Mutarnee,
- Site H2: Geoff and John Morley, Lannercost,
- Site M1: Tony and John Bugeja, Rosella Farm, Mackay.

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It is one thing to have and share ideas, and quite another when it comes to doing the work in the field under hot, dirty, and uncomfortable conditions on blister-making jobs. Other assistance has come from coaxing data from reluctant computers or providing maps from scarce, almost unmappable information. The project has benefited greatly from the efforts of Robbie McKenna and Andy Poveda (Burdekin Productivity Services, Ayr), Graeme Holzberger and Michael Sefton (Herbert Cane Productivity Services Ltd, Ingham), and Barry Salter, Kevin Moore, and David McCallum (BSES and Agriserve, Mackay) who offered assistance in a wide variety of tasks, and probably none as dirty as manually harvesting the burnt cane at the Burdekin sites. Thanks heaps, chaps!

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Andrew Robson and Chris Abbott, Queensland Department of Employment, Economic Development, and Innovation (DEEDI), Kingaroy, took up the challenge of applying to the sugar industry the satellite image analysis techniques that they had developed for determining the yields of peanut crops. We are pleased to acknowledge their success and winning the "Best Poster" award at the 2010 Australian Society of Sugar Cane Technologists conference in Bundaberg for the first presentation of the work with sugarcane crops. We thank them for processing several of the false-colour multispectral satellite images that we have used. We look forward to further developments that might crack open the problems still presented by flowering cane varieties and very high yielding crops.

The project has benefited from discussions with other scientists who have walked along pathways similar to, or somewhat divergent from those traversed from time to time by Project BPS001. We are grateful to Brett Whelan at Sydney University, Rob Fenwick at Regen Pacific Pty Ltd, Mapleton, and Rob Bramley at CSIRO Adelaide for sharing their knowledge with us. It has been extremely helpful to receive a more complete, personal explanation of a technique or an approach to a problem than can be gleaned from a scientific paper or a web site.

Administrative and financial management of the project have been the responsibility of Burdekin Productivity Services Ltd, Ayr. Trevor Berryman (Executive Officer) and Lance Wassmuth (Finance Manager) have maintained close oversight of the budget, and kept it on track – a task that was managed by Peter Kooyman and Michelle Andrews of Canegrowers Burdekin Ltd, Ayr, in the early days of the project.

Finally, it is the greatest pleasure to acknowledge the inputs of all of the Project BPS001 investigators – the team that solves one problem and, like all good researchers, creates a dozen more in its place! Four years ago, at the start of the project, only a few in the group had worked with any of the others. It has been one of life's great experiences to be a member of a team with such complementary scientific and technological skills, with drive and whole-hearted enthusiasm to resolve problems as they arose, and to be able to enjoy each others' company while releasing the bottled smiles and laughter of the happy maidens of McLaren Vale (or a Pepsi Max, or something from a Scottish glen) at the distant end of the working day. It is good to be part of a productive team that works well together, but it's even better to be part of a creative team that knows how to unwind and let ideas flow so richly and freely!

Chapter 2

INTRODUCTION

2.1 PROJECT BPS001: RESEARCH OBJECTIVES

Project BPS001 operated across the Central, Burdekin, and Herbert Cane Districts. The project objectives that were accepted by the Sugar Research and Development Corporation for funding over four years from 1 July 2007 to 1 August 2011 were stated as follows:

> *The project will develop and promote techniques for establishing zones for targeted application of best management practices within cane paddocks. The zones will be identified by mapping features in satellite imagery, soil electromagnetic induction (EM) responses,* [known as *'apparent soil electrical conductivity (ECa) responses'* when collected by the Veris 3100 soil ECa mapping unit] *actual soil properties, and sugarcane yields. They will be georeferenced (assigned latitudes and longitudes) and viewed, queried, and analysed at various scales in a geographic information system, a process that will integrate data collected from different sites and at different times.*
>
> *The resulting map units will allow the subsequent development and promotion of variable rate, site-specific, best management practices for sugarcane production and improved environmental stewardship over and above the management of the crop or paddock as a single, homogenous entity.*
>
> *The research will address two main questions:*
> - *How do satellite imagery and EM* [ECa] *map patterns relate to variations in space and time in soils, and in sugarcane yield?*
> - *Are there general relationships between image analysis, EM* [ECa] *signals, crop yield, and soil properties that are widely applicable within and between regions?*

All of the project activities carried out have been aimed at answering these questions.

2.2 WHAT IS PRECISION AGRICULTURE?

Precision agriculture is a farm management approach that underpins sustainable farm returns by selectively applying inputs and best management practices to spatially defined parcels of land (*i.e.* management zones) within paddocks, farms, or catchments.

Best management practices in sugarcane production have been promoted by the SRDC-funded *Sugar Yield Decline Joint Venture* project (Garside and Bell 2006) and provide a sound foundation for progressing precision agriculture in sugarcane. The new farming system is based on three agronomic principles:

- minimising compaction through controlled traffic farming with GPS guidance;
- interruption of sugarcane monoculture with rotational fallow cropping;
- conservation of organic matter through reduced tillage.

Additional best management practices developed by BSES Ltd, and dovetailing with a precision agriculture approach to improved sugarcane production, include:

- selection of sugarcane varieties based on broad soil types and resistance to disease through the QCANE plant breeding program;

- nutrient inputs based on soil types (*The Six Easy Steps;* Schroeder *et al.* 2010).

Precision agriculture begins with the soil, which is the basic management unit in any paddock, and deals with the responses in crop growth to the complex interactions of soil nutritional status, soil physical properties (especially soil texture), surface and subsurface drainage, seasonal conditions, soil health, pests and diseases, cane variety adaptability to soil type, and paddock management practices. Precision agricultural approaches consider patterns of variation in soils and crop responses, and their likely impacts on cost-effective farming practices.

In summary, precision agriculture is focused on:

- identifying within-paddock variability in soils and crops,
- determining the soil- and site-related constraints to crop growth,
- providing a basis for managing inputs *(e.g. fertiliser, gypsum, lime, herbicides, pesticides, water, tillage, etc)* to selected parts of paddocks.

Soil spatial data interpretation and variable rate application technology are recognised as vital tools in precision agriculture (Bramley *et al.*, 1997), yet their adoption by the North Queensland sugar industry lags behind adoption rates of the technology in other Australian rural industries. The lag may be due, in part, to the sugar industry not taking up one or more of the three basic technologies that precision agricultural farmers must have access to at an acceptable price (Roth and Bramley 1997). These technologies are:

- accurate spatial referencing using a global positioning system,
- variable rate control for application of inputs (*e.g.* fertiliser, soil ameliorants, agrochemicals, water),
- management based on the nature and variation of soil properties (*e.g.* moisture, nutrients) and in crop yield (product tonnage and quality).

Recent technological developments have provided tools to support precision agricultural approaches to agronomy and crop production in the sugar industry (Bramley, 2007), including: controlled traffic through GPS-guided steering of machinery, crop yield monitors on harvesters, and GPS-controlled equipment for site-specific application of inputs such as fertiliser, gypsum, lime, herbicides, and pesticides. Increasing use is being made of spatial data such as georeferenced sites for soil sampling and testing (Di Bella *et al.*, 2009a), apparent soil electrical conductivity (ECa) mapping (Coventry *et al.*, 2009), and crop yield mapping (Di Bella *et al.*, 2009b) to better understand and manage variability in sugarcane paddocks in North Queensland.

Over the last decade, technological advances have provided the sugar industry with precise georeferenced spatial location systems, variable rate control of inputs, and yield monitoring and mapping. However, knowledge of variations in soil properties is still poor, especially at a cane paddock or sub-paddock scale where it is appropriate to manage relatively small land units.

2.3 PADDOCK-SCALE SOIL MAPS FOR PRECISION AGRICULTURE

2.3.1 Inadequacy of existing soil maps

The application of precision agricultural techniques in cropping systems depends on the recognition of georeferenced zones within paddocks. The zones provide a framework for growers who wish to make site-specific decisions in applying appropriate management practices to individual areas within paddocks. In this way, input levels can be targeted for cost-effective production, minimised waste, and reduced environmental impacts. The management decisions must be underpinned by sound knowledge of variations in the underlying soil properties. In the Australian sugar industry, however, there are few areas where detailed soil maps are available at a scale meeting the requirements of precision agriculture.

Coventry *et al.* (2009) reviewed the precision of the soil maps available to sugarcane farmers in Queensland and discussed the inadequacy of the scale of even the most detailed published soil maps for the central and northern sugarcane districts for precision agricultural practices. "Low intensity" soil map have been published at 1:1000,000 scale for the Central Cane District (Holz and Shields 1985), the Herbert District (Wilson and Baker 1990) and for the Cardwell –Mossman sugarcane areas to the north (*e.g.* Cannon *et al.* 1992; Murtha 1986, 1989). Accurate soil mapping at 1:100,000 scale relies on 1 ground observation per 100 – 400 ha, and the smallest area of soil that can be shown on such maps is 40 ha (Table 2.1). The average paddock size in the Mackay Sugar Ltd milling area is 2.43 ha, so none of the details of soil patterns within sugarcane paddocks is evident on the published soil maps for the Central District.

Table 2.1. Scales and precision of the most detailed published soil maps for central and northern Queensland.

The table shows the influence of the scale of the most detailed published soil maps available for the central and northern sugarcane districts on the minimum area that can be portrayed on the map, and on the number of field observations required for reliable and accurate soil mapping. Sources: Coventry *et al.* (2009), Gallant *et al.* (2008).

Sugarcane region	Scale of the most detailed published maps available *(A thin pencil line will be 0.5 mm wide on the map)*		Minimum area that can be depicted on the map	Number of observations required for accurate soil mapping
Sarina –Mackay-Proserpine; Herbert	1 : 100,000	1 mm on map = 100 m	40 ha	1 per 100 to 400 ha
Cardwell-Tully-Innisfail-Cairns-Mossman	1 : 50,000	1 mm on map = 50 m	10 ha	1 per 20 to 100 ha
Burdekin	1 : 25,000	1 mm on map = 25 m	2.5 ha	1 per 5 to 25 ha
Herbert *	1 : 5,000	1 mm on map = 5 m	0.1 ha (~ 32 x 32 m)	4 to 20 per ha

* Available electronically for individual farms from Herbert Cane Productivity Services Ltd, Ingham, and as a GIS layer from Herbert Resource Information Centre (HRIC).

More detailed, “high-intensity” soil maps at 1:25,000 scale, as are available for some the Burdekin District, can display minimum areas of 2.5 ha and are compiled from at least one ground observation per 5 – 25 ha. The soil map for the two study sites in Burdekin District two study, however, is at 1:50,000 scale (McClurg *et al.* 2005) and almost no paddock-scale variability can be portrayed on this soil map.

With the exception of much of the Herbert District, there are no soil maps available to cane growers in central and northern Queensland that are sufficiently detailed to show soil variations within cane paddocks. Wood (1988) and Wood *et al.* (2003) mapped most of the canelands of the Herbert District at 1:5,000 scale, showing topsoil mapping units down to about 1,000 sq m in area (Table 2.1). These soil maps are accessible electronically through the Herbert Cane Productivity Services Ltd, Ingham, for individual farms in the district. While such a map scale can depict the variability of soils within paddocks, their production required 4–20 soil observations per hectare, or 400–2,000 boreholes / 100 ha farm to support reliable and accurate soil mapping at this scale (Table 2.1). Even then, the level of detail is still inadequate for precision agricultural management where soil maps at 1:2,500 scale are more appropriate (Gallant *et al.*, 2008).

The mapping units displayed on even the most detailed published soil maps provide only generalised information about soil distribution patterns. Consequently, soil variations within paddocks cannot be represented on the existing soil maps of any of the regions. Important small occurrences of certain soils are lost at the scale of most of the current soil maps, and complex patterns of different soil types cannot be delineated. Such soil units are either omitted from the map, or are incorporated into other soil mapping units which become, of necessity, even more variable in their soil composition and less useful in precise land management practices (Beckett and Webster, 1971; Kingston and Hyde, 1995).

If a cane farm of 100 ha were to be soil mapped at a very high intensity for precision agriculture (level of accuracy commensurate with a 1:5,000 scale), a minimum of 400 soil boreholes would be required; if complex soil patterns were present, the number of field observations required could blow out to 2000 (Gallant *et al.* 2008). The cost of the soil mapping job can be conservatively estimated as follows, assuming the simplest conditions prevailed. In our experience, two operators can dig, describe, and sample 15 x 1 m soil boreholes per day; 400 boreholes would take at least 53 man-days (427 hours). Allowing as little as $130 / hour salary + on-costs for a professional soil surveyor and $30 / hour for a labourer, the minimum cost for the labour component alone would be $34,000 plus GST. Added to the labour cost would be the costs for travel, accommodation, base maps and aerial photos, soil analysis, and map production costs to complete the soil survey.

Using conventional methods to make a soil map of an “average cane farm” of 100 ha, depicting the variability of the soil at a scale that is appropriate for precision agricultural applications is, therefore, a time-consuming, expensive, and an increasingly impractical task.

2.3.2 Paddock-scale soil mapping

Given the cost and time involved in making conventional soil surveys, surrogate methods are gaining popularity for detecting variations in soil properties at a cane paddock and sub-paddock scale. The methods include the use of electromagnetic induction mapping (commonly known as ‘soil EM mapping’) and apparent soil electrical conductivity mapping (‘soil ECa mapping’), and are based on the magnetic and /or electrical properties of the soil.

Soil EM mapping has been used extensively for identifying soil salinity hazards (Williams and Baker 1982; Slavich and Read 1994; Wu *et al.* 2009). These surveys have generally used Geonics EM31 or EM38 terrain conductivity meters. The EM-31 consists of a transmitter coil mounted at one end and a receiver coil mounted at the other end of a 3.7 m long plastic boom and is carried manually or on a small 4-wheel motorbike. Electrical conductivity and in-phase field strength are measured and stored along with line and station numbers in a digital data logger. The EM31 can explore to depths of about 5.5 m but is most sensitive to materials about 1 m below the ground surface (McNeill 1996). The EM38 has a 1 m coil spacing and is designed for characterising the upper 1.5 m of the soil profile (McNeill 1990); the instrument is usually mounted on a sled that is dragged across the paddock.

Bennett *et al.* (2000) pointed out that accurate assessment of site salinity using a soil sampling and laboratory analysis approach is time consuming, expensive, and can be highly variable because of large spatial variability compared with small sample sizes and practical sampling densities. They found that Geonics EM31 and EM38 instruments could be reliably used to map soil salinity in southwestern Australia; the instruments were reliable and the information they generated was reproducible. In all the situations studied by Bennett *et al.* (2000), soil salinity was the dominant contributor to the EM response but soil type, moisture, and temperature were found to have secondary contributions, and may be more important when soil EM methods are used to assess and predict plant responses to soil salinity.

With the development of accurate geo-positioning and computerised spatial data management technologies, the soil EM mapping method is evolving into a tool for defining variations in soils on a sub-paddock scale. EM mapping is capable of identifying and highlighting zones in farm soils that reflect potentially different soil physical and chemical properties. The technique has been used in a variety of Australian production systems (wine grapes: Bramley and Williams 2001; cotton: Stewart *et al.*, 2005, Triantifilis *et al.* 2001a; grains: O'Leary and Peters 2005; rice: Beecher *et al.*, 2007) where the influences of soil depth, salinity, clay mineralogy, clay content, and water properties on EM readings have been explored.

EM techniques recognise that soil conductivity is influenced by three primary factors: the concentration of soluble salts in the soil solution; the abundance, mineralogy, and cation exchange capacity of the clay fraction; and the soil moisture content. The relative contribution from each of the salinity, clay, and moisture variables as sources and influences of the soil responses is unclear under field conditions and cannot be quantified, except perhaps in a detailed study in a small area or volume of soil (Auerswald *et al.*, 2001). However, in situations where soil salinity is low and there is little likelihood of a salinity hazard for crop growth, soil conductivity assessment provides a useful insight into other soil properties, notably soil moisture, soil water holding capacity, and soil mineralogy (Triantafilis *et al.*, 2001b).

The uptake of EM technology in sugar cane cropping has been slow. Initial studies focused on the use of the EM38 instrument for mapping soil depth and salinity (Kingston *et al.*, 2005). Nelson and Ham (2000) and Nelson *et al.* (2002) observed strong correlations between EM38 data and the degree of soil sodicity in north Queensland sugar cane soils.

The use of closely related soil conductivity technology has been increasing in the Central and Burdekin Districts since 2001, and more recently in the Bundaberg and Herbert regions, given the availability of Veris 3100 soil mapping units through commercial service providers (Independent Agricultural Resources, Mackay, and Ag Data Solutions, Ayr).

The commercial georeferenced sampling of mapping patterns generated through Veris 3100 soil mapping surveys has been confined to the chemical analysis of the topsoil (0 – 25 cm depth). Progressing precision agriculture practices in sugarcane has been constrained to some extent until now by a failure to recognize the importance and role of other spatial mapping layers which include subsoils, crop yield, and paddock topography. Understandably, it was assumed that within-paddock variability of crop yield was fundamentally driven by the contrasting nutrient status evident from the georeferenced chemical analysis of soil mapping patterns generated from Veris soil mapping surveys.

2.3.3 Soil-related information from surrogate data sources

Bramley (2007) and Davis *et al.* (2007) identified recent advances in spatial data collection techniques that may underpin precision agricultural practices and improved property planning. To capitalise on the wealth of spatial data that is relatively cheaply and readily available from EM surveys, satellite imagery, and yield mapping of cane paddocks, data patterns must be related to similarly detailed information on patterns of variation in soil properties within paddocks. Such data may be combined for site-specific inputs with actual soil profile information, and the patterns of variability in land management zones defined at sub-paddock scales, thus avoiding the prohibitive costs currently involved in conventional soil surveys at such a scale.

The *Veris 3100 Soil EC Mapping System* (Veris Technologies, 2000) measures the apparent electrical conductivity (ECa) of soils, as opposed to the actual soil electrical conductivity. The actual electrical conductivity is an indicator of soil salinity and is determined in the laboratory by using a glass electrode to measure the electrical conductivity of a 1 : 5 soil : water suspension. Apparent soil electrical conductivity is measured by direct contact in the field by passing an electric current through the upper part of the soil profile. Changes in voltage of the return signals, recorded at specific locations in the paddock, indicate the concentration of electrically conductive material in the soil. The factors affecting soil ECa signals include soil salinity and a combination of clay type and percentage, bulk density, moisture, and temperature (Rhoades *et al.*, 1989). In many locations the factors contributing to the soil ECa signals also limit crop yields (Johnson *et al.* 2005).

The Veris 3100 units from Independent Agricultural Resources, Mackay, and Ag Data Solutions, Ayr, were used to carry out soil ECa surveys at all of the study sites of the present project. The methods used to collect and analyse the field data are discussed in Chapter 4 (below). The paddock-scale maps of soil ECa patterns were checked against the properties of the soils occurring at specific sites in the paddock, and were used as reliable surrogates for detailed soil maps where such were unavailable (see Chapter 5, below).

2.4 SOIL ECa MAPPING IN CENTRAL AND NORTH QUEENSLAND

In this section we have attempted to provide an outline of the importance of soil ECa mapping to the development of precision agricultural practices in the northern sugar industry before the implementation of Project BPS001 in 2007.

A Veris 3100 soil mapping unit was introduced in 2001 as a component of a commercial sugarcane consultancy service offered by Independent Agricultural Resources, Mackay, which heralded the start of precision sugarcane agriculture in the Central Cane District. The consultancy offered a range of agronomic services to a relatively small client base and

included soil ECa surveys and georeferenced soil testing at sites based on computer-generated soil ECa mapping patterns. Due to the high cost of soil chemical analysis, soil tests were generally limited to three surface soil samples per paddock and were focused on the high, medium, and low soil ECa mapping zones. Georeferenced soil test locations, analytical results, and nutrient recommendations were stored for each client in the SMS GIS system (Ag Leader Technology 2009). Where required, soil ameliorants were site-specifically applied to defined zones within a paddock.

The Veris 3100 mapping technology was quickly extended to the Burdekin District where it was particularly well received because the unit was able to delineate areas of soil sodicity in paddocks. The site-specific application of gypsum to ameliorate soil sodicity was an effective means of reducing costs compared with a traditional blanket application over an entire paddock.

Major nutrient recommendations (nitrogen, phosphorus, potassium, and sulphur) were based on industry-endorsed nutrient guidelines. The nutrient inputs were applied, however, on a whole paddock basis. Production figures from individual client paddocks were electronically accessed through the relevant mill on an annual basis and nutrient inputs were adjusted according to the anticipated block yield potential. Generally nutrient inputs were marginally reduced as the productivity of the block declined with the aging of ratoons. Crop yield estimations, based on analyses of Landsat satellite images (20 m resolution), were available through the mill and were used by the consultancy predominantly as an extension tool to highlight the variability that occurred within cane paddocks.

In addition to Veris 3100 soil ECa mapping, GPS technology was increasingly being used by the sugar industry for machinery guidance in controlled traffic farming systems to reduce soil compaction, which was one of the main contributors to poor yield identified by the SRDC-funded Sugar Yield Decline Joint Venture (Garside and Bell 2006). Many within the sugar industry regarded GPS-guided steering as being synonymous with ‘precision agriculture’.

By 2007, at the start of Project BPS001, cane harvester-mounted yield monitors were introduced into the Central District, although a number of harvesters were already operating with yield monitors in the Herbert District and very few in the Burdekin District. From a precision agriculture context, the data generated by the yield monitors had not been used to any extent in influencing grower management decisions. However, the yield maps generated through yield monitors were a pivotal extension tool used by the Independent Agricultural Resources consultancy to promote precision agriculture as a means of managing paddock variability

Variable rate technology was becoming available to the sugar industry and the use of the technology as a means of reducing yield variability was widely promoted by industry personnel with a poor understanding of the complexities associated with defining and managing crop yield variability within paddocks. A number of growers who had invested in variable rate application equipment had difficulty in determining nutrient rates to apply in relation to the anticipated yield from specific areas in paddocks. In addition, the industry was facing increasing environmental pressure to improve the quality of water entering the Great Barrier Reef lagoon and the threat of government regulation of the sugar industry’s environmental performance was looming.

This was fundamentally the level of precision agriculture in the central and northern parts of the sugar industry at the commencement of Project BPS001 in July 2007. Given this background, the overall aims of the project were two-fold:

- to provide stepping stones to a better understanding of the principles that underpin precision agriculture methods for sugarcane production,
- to develop a foundation for delivering some of the benefits of precision agriculture to the sugar industry.

Project BPS001 is the result of an amalgamation of two independent, but complementary soil ECa mapping proposals that had been submitted for consideration for SRDC funding in August 2006. Both of the research groups were aware of the growing use of soil ECa maps in the Central and Burdekin Cane Districts as tools in farm management strategies that aimed to provide farm inputs to specific parts of paddocks instead of managing the crop or paddock as a single, homogenous entity. One research group was keen to obtain SRDC funds to analyse the relationships between the soil ECa signals and the properties of soils and sites that gave rise to those signals. The other group wanted to use SRDC funds to explore the nature of the relationships between patterns of soil ECa signals and patterns of crop yield. With SRDC provisional approval of project funding, the research groups worked together to incorporate both of these themes into the objectives of Project BPS001 that was funded in 2007.

The two major research questions to be addressed in the revised project proposal remained:

- *How do satellite imagery and ECa map patterns relate to variations in space and time in soils, soil properties, and sugarcane yield?*
- *Are there general relationships between image analysis, ECa signals, yield, and soil properties that are widely applicable within and between regions?"*

The answers to these questions, and the methods used in finding the answers, are set out in the following chapters of this report. But first, it is important to introduce the people who carried out the research, and their linkages with SRDC-funded activities and with other organisations.

2.5 THE BPS001 PROJECT TEAM

This project was developed as a multi-disciplinary and multi-institutional initiative involving investigators from nine research organisations located over the 500 km between Mackay and Ingham, North Queensland, with the overall project administration provided by Burdekin Productivity Services Ltd, Ayr. The other participating groups were:

- Soil Horizons Pty Ltd, Townsville;
- Queensland Department of Employment, Economic Development, and Innovation (DEEDI), Mackay, Townsville, and South Johnstone;
- Ag Data Solutions Pty Ltd, Ayr;
- Mackay Sugar Cooperative Association Ltd, Mackay;
- Herbert Cane Productivity Services Ltd, Ingham;
- Independent Agricultural Resources Pty Ltd, Mackay;
- Sucrogen Ltd, Macknade;
- Terrain Natural Resource Management, Ingham.

Don Pollock, formerly Burdekin Productivity Services, agronomist: was the initial Project Leader while serving as the Executive Officer of Burdekin Productivity Services Ltd, the grower- and miller-funded, sugar industry group in the Burdekin District. Pollock coordinated and managed the processes of bringing together the research team and preparing the original research funding proposal. He relinquished the project leader role a month before Project BPS001 formally began (1 July 2007), following a change to employment outside of the sugar

industry. He has retained a close working interest in the project, chairing several Project BPS001 Meetings and being involved as a scientific author and editor.

Ross Coventry, Soil Horizons, soil scientist and Project Leader: soil description, sampling, and interpretation of soil analytical results; geomorphological and soil stratigraphical interpretations; scientific author; dissemination of outputs and outcomes; extension activities; financial control and budget preparation; coordination and production of project milestone reports.

John Hughes, DEEDI Mackay, agronomist: with practical skills and special interests in growth responses of sugarcane; relationships between soils, crop yield, and paddock management; oversight of yield monitoring at all sites; electronic data collection, analysis, storage, and use in geographical information systems; scientific author; dissemination of outputs and outcomes; leader of the project's overall extension program and of the extension program in the Central District.

Angela Anderson (nee Reid), DEEDI Townsville and South Johnstone, biometrician: analysis of numerical and spatial data; interpretation and display of quantitative data; preparation and dissemination of outputs and outcomes; extensive data analysis experience in previous precision agricultural research in viticulture; scientific author; involvement in extension activities.

John Markley, Mackay Sugar, Cane Production Manager and GIS Officer: Provision of GIS, GPS, and remote sensing data; preparation and interpretation of GIS and remotely sensed information; extensive experience in the interpretation and analysis of sugarcane-related satellite imagery, crop productivity, soils, and landscape data.

Tony Crowley, Independent Agricultural Resources, agronomist: provision of soil ECa and GIS data; preparation and dissemination of outputs and outcomes; strong support for the project's extension program in the Central District.

Andrew Wood, Sucrogen (formerly CSR Sugar), soil scientist / agronomist: development of experimental protocols; soil mapping; interpretation of soil and agronomic data; scientific editor; dissemination of outputs and outcomes; extension activities in the Herbert District.

Lawrence Di Bella, Herbert Cane Productivity Services (formerly Terrain NRM), agronomist and sugarcane grower: growth responses of sugarcane; relationships between soils and crop yield; oversight of yield monitoring in the Herbert District; electronic data collection, analysis, storage, and use in geographical information systems; coordinator of cane harvest monitor linkages with Techagro™ Australia; scientific author; dissemination of outputs and outcomes; leader of the project's extension program in the Herbert District.

Peter McDonnell, Ag Data Solutions (formerly Burdekin Productivity Services), ECa mapper and electronic data manager: growth responses of sugarcane; relationships between soils, crop yield, and paddock management inputs; oversight of yield monitoring in the Burdekin District; electronic data collection, analysis, storage, and use in geographical information systems; dissemination of outputs and outcomes; leader of the project's extension program in the Burdekin District.

Paul Sgarbossa, Chairman of Burdekin Productivity Services Ltd, and a sugarcane grower: general oversight of project administration and operations; extension activities; dissemination

of outputs and outcomes; strong support for the project's extension program in the Burdekin District.

2.6 PROJECT LINKAGES

2.6.1 Linkages with SRDC-funded activities

Project BPS001 investigators were strongly linked with three other SRDC-funded Grower Group Initiated Project (GGIP) activities. The following projects offered excellent avenues for communication directly with innovative growers in the Central, Burdekin, and Herbert Districts:

Project GGP052: The next step for precision agriculture aimed to understand the interaction of the variables contributing to spatial variability within sugarcane paddocks and, in particular, the impact of traffic (soil compaction) and plant disease on crop yield.

Project GGP057: SECMAPPER (Soil Electrical Conductivity Mapper) developed a new, heavy duty machine for mapping apparent soil electrical conductivity patterns below green cane trash blankets and crop stubble.

A new GGIP proposal (to be submitted for SRDC funding consideration in September 2011) to develop a smart GIS system to allow non-specialists to adopt the approaches, and to capture the benefits of Project BPS001 by managing and interrogating spatial datasets (*e.g.* ECa maps, satellite imagery, soil test sites, paddock elevation, crop yield, etc) to produce predictive maps of management zones within paddocks.

Another SRDC-funded linkage was through a Travel and Learning Opportunity Project to enable Angela Anderson to attend the 1st Global Workshop of High Resolution Digital Soil Sensing and Mapping in Sydney in February 2008.

2.6.2 Linkages with *Project Catalyst* for coastal land management

BPS001 project investigators have occupied significant positions in the planning and operation of *Project Catalyst*, an on-going project that is supported by the Coca-Cola Foundation, the World Wildlife Fund, and managed by Reef Catchments Mackay Whitsunday. It is administered from the Central District with operations recently extended to the Burdekin and Herbert Districts. *Project Catalyst's* focus is on innovation. It aims to increase the adoption of improved coastal land use and management practices by providing practical knowledge and sugarcane grower support for technological change in ways that are being increasingly utilised. The project has a strong fit with the Queensland Government desire to improve agriculture and environmental stewardship in the coastal zone. The precision agriculture component of *Project Catalyst* is underpinned by, and promotes the adoption of, BPS001 project outcomes.

Three BPS001 investigators have been directly responsible for delivering *Project Catalyst's* strategies for improved plant nutrient, herbicide, and soil management practices on sugarcane farms across the region (Tony Crowley in the Central District, Peter McDonnell in the Burdekin, and initially Lawrence Di Bella in the Herbert). This link has provided a unique and exciting opportunity to connect agricultural management practices, increased farm

productivity, and environmental icons such as the Great Barrier Reef, with the scientific perceptions developed in Project BPS001.

Project Catalyst has been a significant vehicle for the communication of BPS001 project outcomes. In this way, the extension component of BPS001 has been, and will continue to be delivered directly to all levels of the sugar industry, to political leaders, and to the wider community using established and respected local networks in Queensland's sugarcane lands. As *Project Catalyst* evolves, the potential to deliver BPS001 outcomes to a wider audience will also evolve, perhaps even reaching an international audience.

Chapter 3

THE BPS001 FIELD STUDY SITES

3.1 FIELD CHARACTERISTICS OF THE STUDY SITES

Project BPS001 established five study sites that represent a range of climatic conditions, soil types, and farming operations in the Central, Burdekin, and Herbert Cane Districts (Fig. 3.1).

In the **Central District**, site M1 is located on clayey alluvial sediments of the Homebush area and 12 km south of Mackay.

In the **Burdekin District**, site B1 is located on generally light-textured, sandy loam 'Burdekin Delta soils', and site B2 is on the heavier textured clay soils that are typical of the Burdekin River Irrigation Area; the two sites are located about 6 km apart and lie 7 km and 13 km west of Ayr.

In the **Herbert District**, site H1 is located on younger alluvial sediments of Crystal Creek, at Mutarnee, and 35 km south-southeast of Ingham; site H2 is on predominantly clay soils of the older alluvial deposits of the Herbert River at Lannercost and 15 km west-northwest of Ingham.

Figure 3.1. Locations of the five field study sites in Central and North Queensland.
Source: www.maps.google.com.au

Except for site H2, all of the sites lie in coastal lowlands at distances of 4 – 20 km from the Coral Sea and at altitudes of 8 – 25 m, and are underlain by very gently sloping, relatively young alluvial sediments that have been deposited by small streams on wide coastal plains. Site H2 at Lannercost, 15 km northwest of Ingham, lies 35 km inland and at an altitude of 30 m; it is underlain by clay-rich, older alluvial sediments of an ancestral floodplain of the Herbert River. Local relief within each site was rarely more than 1.5 – 2 m. The flatness of the landscape at each site, clearly evident in the low slope angles seen in the on-ground

photographs of Figs 3.2 – 3.6, has necessitated the installation of farm drains to remove excess stormwater runoff in wet seasons, and excess furrow irrigation water at the two Burdekin sites.

The general characteristics of each site, and the dates of significant farming operations or data collecting activities at the sites, are listed in Table 3.1.

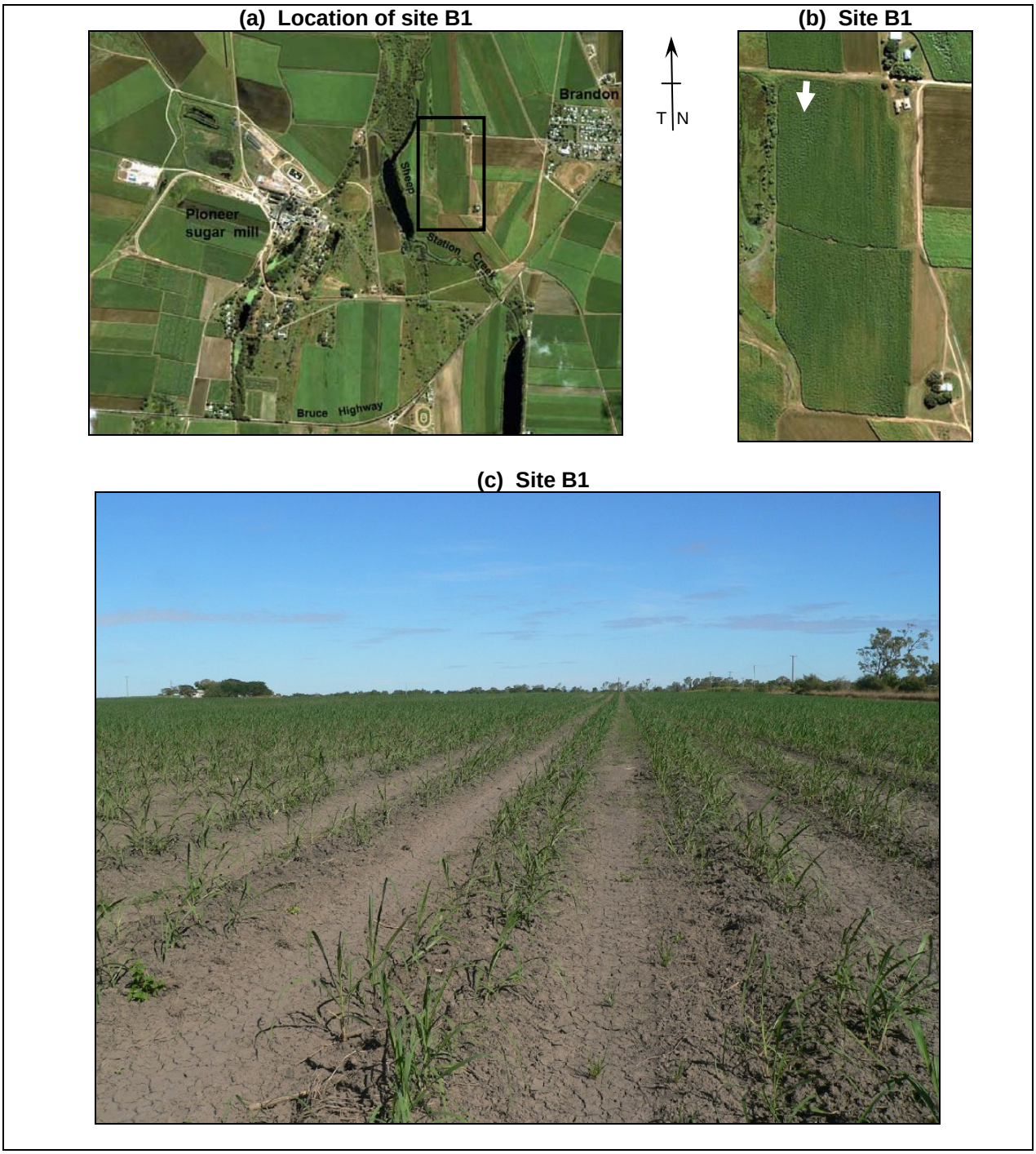


Figure 3.2. Study site B1, Brandon. The site is 7 km northwest of Ayr, Queensland.
(a) Site context. The black rectangle indicates the study site location. Source: IKONOS satellite image captured on 28/05/2009.
(b) The site. Furrow irrigation to the north and south is sourced from the curving headland on a low ridge across the middle of the paddock. The broad arrow shows the camera position used for taking the landscape photograph below. Source: IKONOS satellite image captured on 28/05/2009.
(c) Poor establishment of plant cane crop on the clay soil in foreground, photograph taken on 13/06/2008, 67 days after planting.

Figure 3.3. Study site B2, Brandon. The site is 13 km west of Ayr, Queensland.

(a) Site context. The black rectangle indicates the location of Fig. 3.3b. Source: IKONOS satellite image captured on 28/05/2009.

(b) The study site. A dark band of self-mulching clay runs northeastwards across the site from the southwestern corner of the bare, fallowed land. The broad, short arrow shows the camera position used for taking the landscape photograph below. Source: IKONOS satellite image captured on 28/05/2009.

(c) Photograph was taken on 03/04/2009, 3 days after ECa mapping had been carried out.

Figure 3.4. Study site H1, Mutarnee. The site is 35 km south-southeast of Ingham, Queensland.

(a) Site context. The black rectangle indicates the study site location. Crystal Creek runs along the northwestern side of the study site. Source: Aerial photograph supplied by the Department of Environment and Natural Resources, image captured on 25/08/2006.

(b) The site. The broad, short arrow shows the camera positions used for taking the landscape photograph below. Source: Google Earth satellite image captured on 31/07/2007.

(c) Red earth soils on a stream levee in foreground slope down to sodic duplex soils with very pale topsoils, depleted in organic matter, on lower floodplain; photograph was taken from the highest point in the paddock on 22/4/2008, the day after ECa mapping and 4 days before planting.

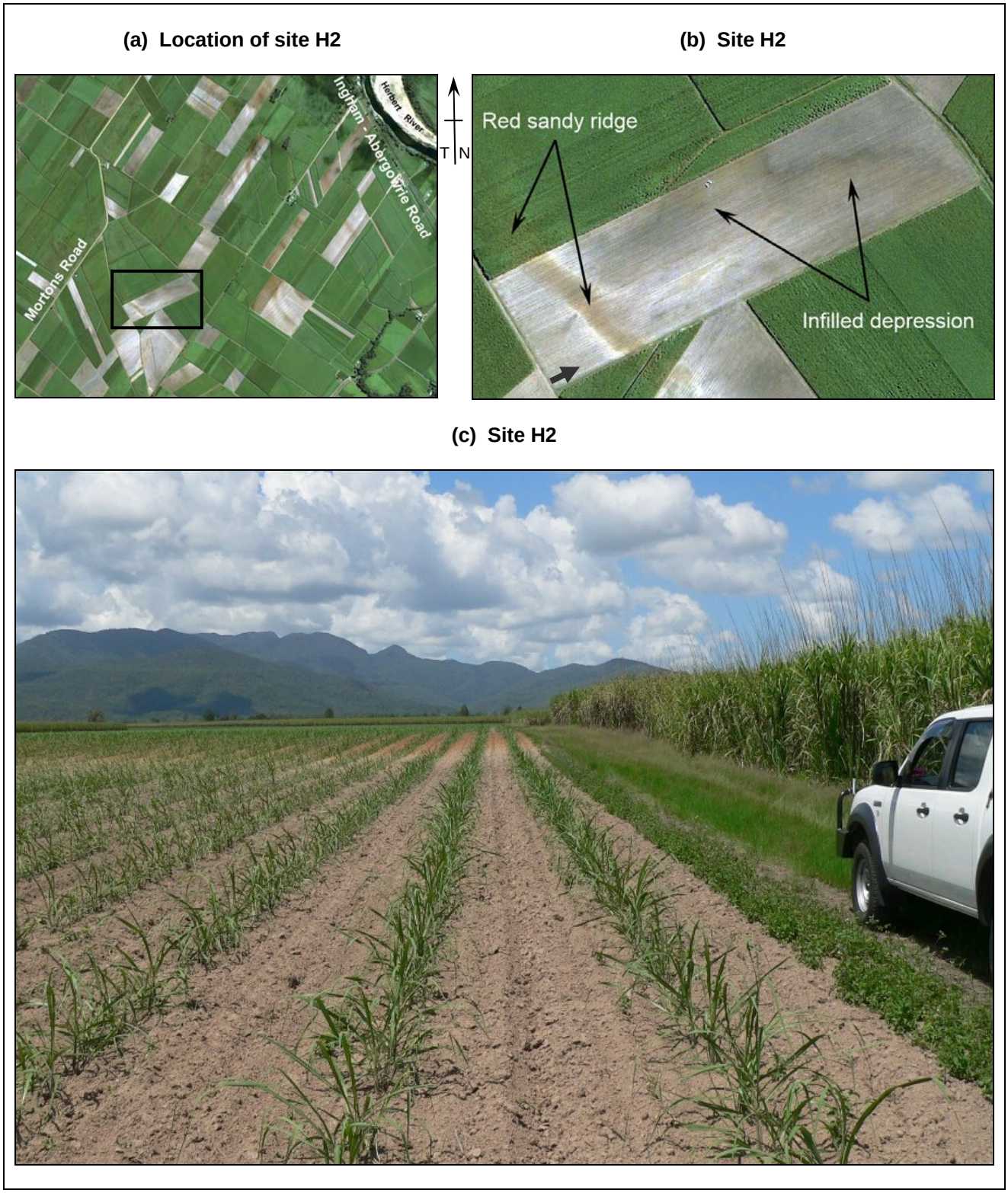


Figure 3.5. Study site H2, Lannercost. The site is 15 km west-northwest of Ingham, Queensland.
(a) Site context. The black rectangle indicates the study site location. Source: IKONOS satellite image captured on 13/06/2008.
(b) The site. A red sandy ridge traverses grey clay soils that have infilled a shallow depression. The broad, short arrow shows the camera position used for taking the landscape photograph below. Source: IKONOS satellite image captured on 13/06/2008.
(c) Photograph taken from the lowest point on the western side of the paddock, looking northeast over grey clay soils in the foreground and a low, red sandy ridge that is more obvious in older crop on the right. Photograph taken on 15/10/2008, 155 days after planting.

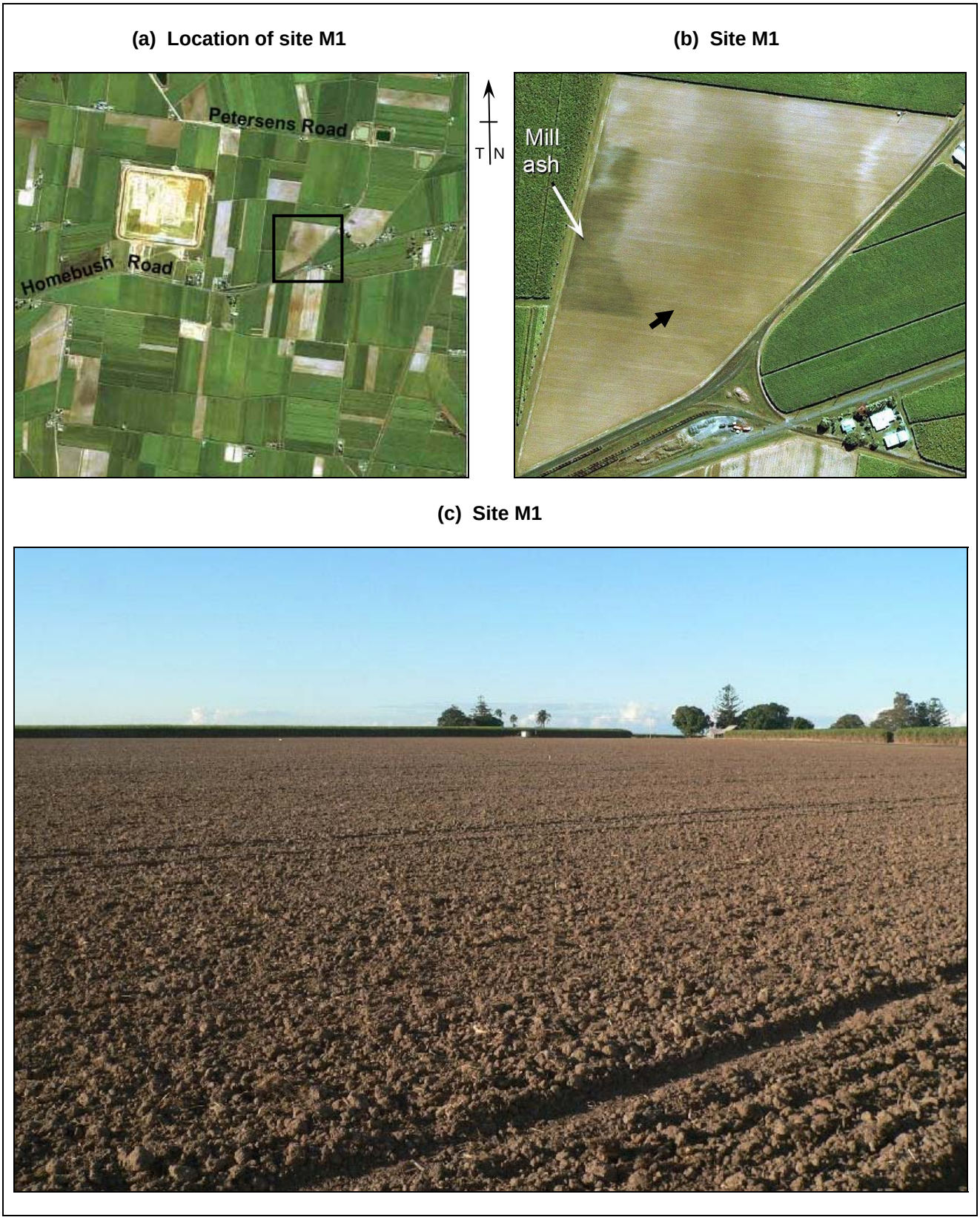


Figure 3.6. Study site M1, Homebush. The site is 12 km southwest of Mackay, Queensland.

(a) Site context. The black rectangle indicates the study site location. Source: IKONOS satellite image captured on 24/06/2008.

(b) The site. Mill ash had been spread over some of the poorly yielding land on the western side of the paddock. The broad arrow shows the camera position used for taking the landscape photograph below. Source: IKONOS satellite image captured on 24/06/2008.

(c) Cultivated land ready for planting. Photograph taken on 19/06/2008, the day after ECa mapping.

Table 3.1. Characteristics the BPS001 field study sites and the dates of significant site activities

Site characteristics	Site B1, Burdekin	Site B2, Burdekin	Site H1, Herbert	Site H2, Herbert	Site M1, Homebush
Farm owner	I. Haigh, Sandy Corner, Brandon	S. Lando, Collinson's Lagoon, Brandon	A. Pace, Crystal Creek, Mutarnee	G. & J. Morley, Lannercost	A. & J. Bugeja, Homebush
Farm & block number	Farm 6488B, Block 18-1	Farm 6443A, Block 7-1	Farm 0708A, Block 3-5	Farm 0258A, Block 5-1	Farm 04074B, Block 13-1
GPS location of the centroid of the paddock	MGA94 (55): (X) 35856.78 (Y) 837641.15	MGA94 (55): (X) 29080.12 (Y) 836154.52	MGA94 (55): (X) 25471.93 (Y) 904774.59	MGA94 (55): (X) 397121.41 (Y) 7942742.02	MGA94 (55): (X) 20694.94 (Y) 649719.52
Paddock area (ha)	11.97	10.24	5.30	11.07 reduced to 9.33 in August 2009 (ripping trial)	10.80 reduced to 9.3 ha in 2008 (Project GGP052)
Median annual rainfall, Bureau of Meteorology station name	968 mm BOM station: 033002 Ayr DPI	968 mm BOM station: 033002 Ayr DPI	1831 mm BOM station: 032101 Mutarnee Store	2340 mm BOM station: 032191 Hawkins Ck	1619 mm BOM station: 033047 Te Kowai
Crop irrigation	Furrow irrigation	Furrow irrigation	Rain-fed	Rain-fed	Supplemented rain-fed
Predominant soils	Burdekin Delta Soils: Light sandy loams, minor sodic clays	BRIA Clays: heavy clay, some sodic, some self-mulching on floodplain	Red clay loam on stream levee; yellow and grey sodic duplex soils on floodplain	Herbert River clays; minor stream channel sands under a low ridge	Sodic duplex soils; acidic-neutral clays
Most detailed published soil map (author)	Christianos & McClurg (2003), McClurg *et al.* (2005)	Christianos & McClurg (2003), McClurg *et al.* (2005)	Wilson & Baker (1990) Wood *et al.* (2003)	Wilson & Baker (1990) Wood *et al.* (2003)	Holz & Shields (1985)
Published soil map scale	1:50,000	1:50,000	1:100,000 and 1: 5,000 (nominal)	1:100,000 and 1: 5,000 (nominal)	1:100,000
Previous soil mapping units	Black Kandosols or Black Dermosols, Black or Grey Vertosols	Black or Brown Dermosols	Bluewater Soil (red earth) on levee; Althaus or Manor Soils (soloths) on lower floodplain	Hamleigh Clay and Toobanna Solodic Soils	Sandiford: Yellow Chromosol; Mirani: Grey Sodosol; Marian: Brown Chromosol
Date of ECa mapping	12 December 2007 25 March 2008 19 July 2009	31 March 2009	21 April 2008	12 May 2008	17 December 2007 24 December 2007 18 June 2008
Date paddock ripped	Not ripped	Not ripped	Not ripped	11 July 2008	Before planting
Date: EM38 mapping	Not mapped by EM38	Not mapped by EM38	23 September 2009	24 September 2009	Not mapped by EM38
IKONOS satellite image capture dates	28 May 2009 11 June 2010	No capture in 2009 11 June 2010	No capture in 2009 19 June 2010	2 August 2009 16 August 2010	24 June 2008 16 July 2009 21 June 2010 23 May 2011
Cane variety planted	Q208	Q228	Q200	Q200	Q208
Planting Date	31 March 2008	1 May 2009	24 April 2008	15 August 2008	29 August 2008
Harvest Date: Plant cane	9 July 2009	17 June 2010	2 July 2009	24 August 2009	31 July 2009
Harvest Date: First ratoon	15 - 17 September 2010	Due in 2011	16 September 2010	Not harvested (too wet)	1 November 2010 (part)

3.2 CLIMATE OF THE STUDY SITES

3.2.1 Weather station records

The study sites lie on a climatic gradient from dry tropical at sites B1, B2 with long-term median rainfall of 967 mm, to wet tropical at site H2 with a long-term median rainfall of 2340 mm. There are no Bureau of Meteorology (BOM) weather recording stations at any of the study sites. Hence, the daily weather observation records from the nearest official recording station have been used to indicate the weather conditions at each of the field study sites over the duration of the project (2002 – 2011). The daily records have been consolidated by into monthly data sets that are available for downloading from the Bureau's *'Climate Data Online'* web site (www.bom.gov.au/climate/data). The stations used were:

- Te Kowai Experiment Station, BOM station 033047, 8 km north of site M1, in the Central District;
- Ayr DPI Research Station, BOM station 033002, 8 km south-southeast of site B1 and 11 km southeast of site B2 in the Burdekin District;
- Mutarnee Store, BOM station 032101, 2 km west of site H1, in the Herbert District;
- Hawkins Creek, BOM station 032191, 8 km east of site H2, in the Herbert District.

The monthly rainfalls at each of these stations, and the long-term median monthly rainfalls, are shown in Table 3.2. The 16 annual rainfall values recorded at all of the stations throughout the four-year project were all greater than the median rainfall for each specific station, indicating that any results derived from Project BPS001 relate to a study that was undertaken in 'wetter than normal' years.

In terms of crop management strategies, it is realistic to divide the year into a generally wetter *'growing season'* of five months (January – May, inclusive) and a generally drier *'harvest season'* of seven months (June – December, inclusive). Analysing the rainfall in the two cropping seasons allows an estimate to be made of deviations from typical ('average') rainfall conditions, and a possible interpretation of the impact of wet weather on access to paddocks for farming operations, especially harvesting and re-planting crops.

The results of one such approach are set out in Table 3.2 in which the actual monthly rainfall in each year have been summed over the growing and harvest seasons; those rainfall values have then been expressed as a percentage of the long-term median rainfall values for the same months.

During only one of the 20 growing seasons analysed did a rainfall recording station receive less than the recording station's long term median for that season (Hawkins Creek in 2008; Table 3.2). Except for 2009, rainfall in the harvest season across the region was at least 1.5 times greater than the long-term median rainfall (Table 3.2). The 2010 harvest season was the wettest of all: the rainfall recording stations, and the study sites that lay only 2 – 11 km from the rainfall stations, received between 4 and 6.4 times the long-term median rainfall (Table 3.2). The prolonged, unusually heavy rainfall throughout the 2010 harvest severely disrupted farming operations across the region. The rain prevented cane harvester access to site H2 and to part of site M1, with the crops at these sites being stood over to the forthcoming 2011 harvest.

Table 3.2. Monthly, seasonal, and annual rainfall over the project sites: 2007 – present.

Data from Commonwealth of Australia, Bureau of Meteorology, Climate Data Online. www.bom.gov.au/climate/data. Date viewed 21 May 2011.

Shaded cells indicate the one 'growing season' (January-May) and three 'harvest seasons' (June-December) that received less than the long-term median rainfall.

BOM rainfall station	Year	Jan	Feb	Mar	Apr	May	Growing season: Jan - May	% of growing season median rain	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Harvest season: Jun - Dec	% of harvest season median rain	Annual total
Te Kowai Exp Stn	**2007**	383	614	182	72	112	1362	140	305	0	2	36	36	74	260	713	182	2075
Stn 033047	**2008**	463	1241	31	5	34	1773	182	32	114	0	13	19	26	219	422	153	2195
8 km N of site M1	**2009**	370	577	199	210	30	1385	143	29	1	0	10	36	121	127	324	**89**	1709
	2010	436	594	412	118	59	1619	167	8	6	122	263	69	515	783	1765	547	3384
	2011	200	303	1052	145	35	1736	179										
	Median	**258**	**289**	**230**	**112**	**83**	**972**	**100**	**49**	**20**	**17**	**17**	**33**	**61**	**143**	**338**	**100**	**1619**
Ayr DPI	**2007**	341	286	75	2	2	707	129	159	0	4	8	27	17	133	349	288	1055
Stn 033002	**2008**	362	607	62	0	0	1032	188	2	105	0	10	2	40	88	249	205	1280
8 km SSE of	**2009**	594	880	79	85	7	1645	300	3	0	0	4	5	19	22	54	**44**	1699
site B1,	**2010**	489	286	190	19	6	990	181	5	1	65	100	39	243	319	770	636	1759
11 km SE of	**2011**	249	88	224	25	14	599	109										
site B2	**Median**	**162**	**213**	**133**	**24**	**17**	**548**	**100**	**12**	**5**	**4**	**3**	**7**	**31**	**60**	**121**	**100**	**968**
Mutarnee Store	**2007**	414	932	245	25	12	1628	137	104	0	10	6	50	164	296	629	168	4022
Stn 032101	**2008**	601	531	110	15	21	1278	108	3	110	0	87	43	314	244	801	214	3465
2 km W of site H1	**2009**	1172	1152	185	247	22	2778	234	2	1	0	21	74	129	169	396	106	3174
	2010	548	495	303	147	5	1498	126	40	12	60	85	226	543	539	1506	403	3004
	2011	589	612	1204	60	31	2496	210										
	Median	**414**	**424**	**200**	**99**	**51**	**1188**	**100**	**19**	**15**	**10**	**11**	**44**	**110**	**165**	**374**	**100**	**1831**
Hawkins Ck	**2007**	523	1079	270	91	137	2099	137	204	8	68	25	104	98	292	798	178	2897
Stn 032191	**2008**	600	407	286	22	80	1394	**91**	31	216	0	178	83	188	186	882	197	3762
8 km E of site H2	**2009**	1317	1689	208	198	143	3557	233	40	18	1	6	55	163	63	346	**77**	3902
	2010	517	716	364	421	47	2065	135	90	155	99	231	294	554	666	2087	466	4152
	2011	386	1222	1289	115	43	3055	200										
	Median	**320**	**494**	**388**	**199**	**128**	**1528**	**100**	**62**	**60**	**39**	**24**	**42**	**76**	**146**	**448**	**100**	**2340**

3.2.2 La Niña weather conditions

The seasonal pattern of rainfall throughout the study period fits moderately well with the occurrence of a sequence of La Niña years based on the nature of the average sea surface temperature anomaly in the eastern equatorial Pacific Ocean and indices of upper ocean heat content and Indo-Pacific winds (Fig. 3.7). The NINO3.4 index of Clarke and Van Gorder (2003) has been a useful predictor of El Niño (dry) and La Niña (wet) years when related, many months in advance, to positive and negative anomalies in the index respectively (Fig. 3.7).

This climate model indicates that Project BPS001 has been operating in a sequence of wetter than average La Niña years, which is endorsed by the data in Table 3.2. Despite the model implying the occurrence of a relatively dry El Niño period in 2009, Table 3.2 shows that the actual rainfall for the 2009 growing season, at all stations except for Te Kowai in the south, were the highest for the study period. Reconciling these very wet growing seasons with the El Niño – La Niña model of Clarke and Van Gorder (2011) suggests that the model still requires some development in order accommodate local rainfall data from North Queensland.

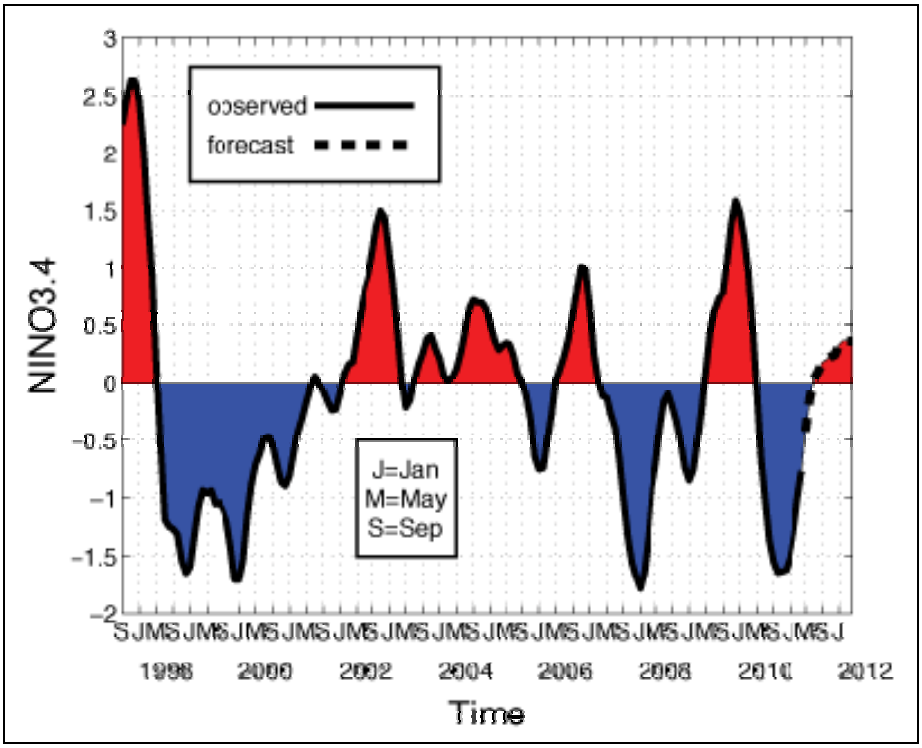


Figure 3.7. Relationship between the El Niño index (NINO3.4) of Clarke and Van Gorder (2003) and the occurrence of dry El Nino years (positive index) and wet La Niña (negative) years.
Source: Clarke and Van Gorder (2011).

3.3 SOILS OF THE STUDY SITES

The most detailed, published soil maps available to the project for sites M1, H1, and H2 were at scales of 1:100,000 (Holz and Shields 1985, Wilson and Baker 1990), and 1:50,000 scale maps for sites B1 and B2 (McClurg *et al.* 2005). The scales of these maps have a dramatic effect on the amount of detail that can be portrayed. A 1:100,000 scale map means that 1 mm on the map is equivalent to 100 m in the field and on a 1:50,000 scale map 1 mm equates to 50 m in the field; this

means that the width of a thin (0.5 mm) pencil line on a soil map is the equivalent to a distance in the field of 50 m and 25 m respectively. Gallant *et al.* (2002) suggested that the minimum area that can be delineated on a soil map of 1:100,000 scale is 0.4 cm^2, which is equivalent to 40 ha on a 1:100,00 scale map and 10 ha on a 1:50,000 scale map. Clearly, the coarse resolution of the existing, most detailed published soil maps is inadequate to even delineate the boundaries of all but the largest sugarcane paddocks in a district. They are simply too coarse to allow the variations in the soil patterns on any of the cane paddocks to be displayed.

The coarse spatial resolution of the 1:100,000 soil map of the Herbert District (Wilson and Baker 1995) was supplemented by detailed maps of topsoil patterns that were available electronically through the Herberet Cane Productivity Services Ltd for individual farms (Wood 1998; Wood *et al.* 2003) at sites H1 and H2. These detailed maps, however, provided no information on the nature and properties of the soil profile below the depth of penetration of a spade blade.

In the following soil group descriptions, an attempt has been made, where possible, to relate the soil characteristics to the three soil classification schemes used in Australia over the period that the original soil reports for each site were written, namely:

- The *Australian Great Soil Group* classification scheme (Stace *et al.* 1968) yielding soil names such as red earth, soloth, etc;
- The principal profile forms defined in *The factual key for the recognition of Australian soils* (Northcote 1979) yielding codes such as Gn2.14, Ug5.11, etc;
- *The Australian Soil Classification* (Isbell 1996) yielding soil names such as Red Chromosol, Grey Sodosol, etc.

3.3.1 Burdekin sites

The most detailed published soil map for sites B1 and B2 is the 1:50,000 scale map of McClurg *et al.* (2005) and the related soil report of Christianos and McClurg (2003). The soils of both sites both units occur in landscape units identified by McClurg *et al.* (2005) as stream levees, floodouts, or backplains, and their characteristics have been amplified using information from Donnollan (1991) and Loi *et al.* (1994).

3.3.1.1 Site B1

Two soil mapping units were identified by McClurg *et al.* (2005) at site B1 (Fig. 3.8a), which is located on typical 'Burdekin Delta Soils', a locally recognised group of soil generally with light textured topsoils. Unit BUfa, consists of relatively sandy soils and covers most of the area with the much heavier textured clay soils of unit BUga occupying the northwestern corner of the paddock (Fig. 3.2c).

The soils of mapping unit BUfa were characterised by McClurg *et al.* (2005) as having profiles with 0.5 – 1 m of brown, not seasonally cracking, fine sandy, light to light medium clay overlying coarser-textured subsoils of brown, occasionally yellow, sand to fine earthy sand to a depth of at least 1.5 m and with a neutral soil reaction (pH) trend. These soils may be classified as Black Kandosols or Dermosols, depending on how sharp the transition was from the topsoil to subsoil, with principal profile forms of Uf6.71, Uf6.7, or Uf 6.2.

The more clayey soils of mapping unit BUga lie in drainage depressions and were characterised by 0.2 – 0.4 m of black, seasonally cracking, weakly crusting, light medium clay that overlies subsoils of similar texture but may be black, grey, or brown; neutral to alkaline soil reaction trends prevail. These soils have been classified as Black or Grey Vertosols with principal profile forms of Ug5.16, Ug5.17, Ug5.1, and Ug5.24 (McClug *et al.* 2005).

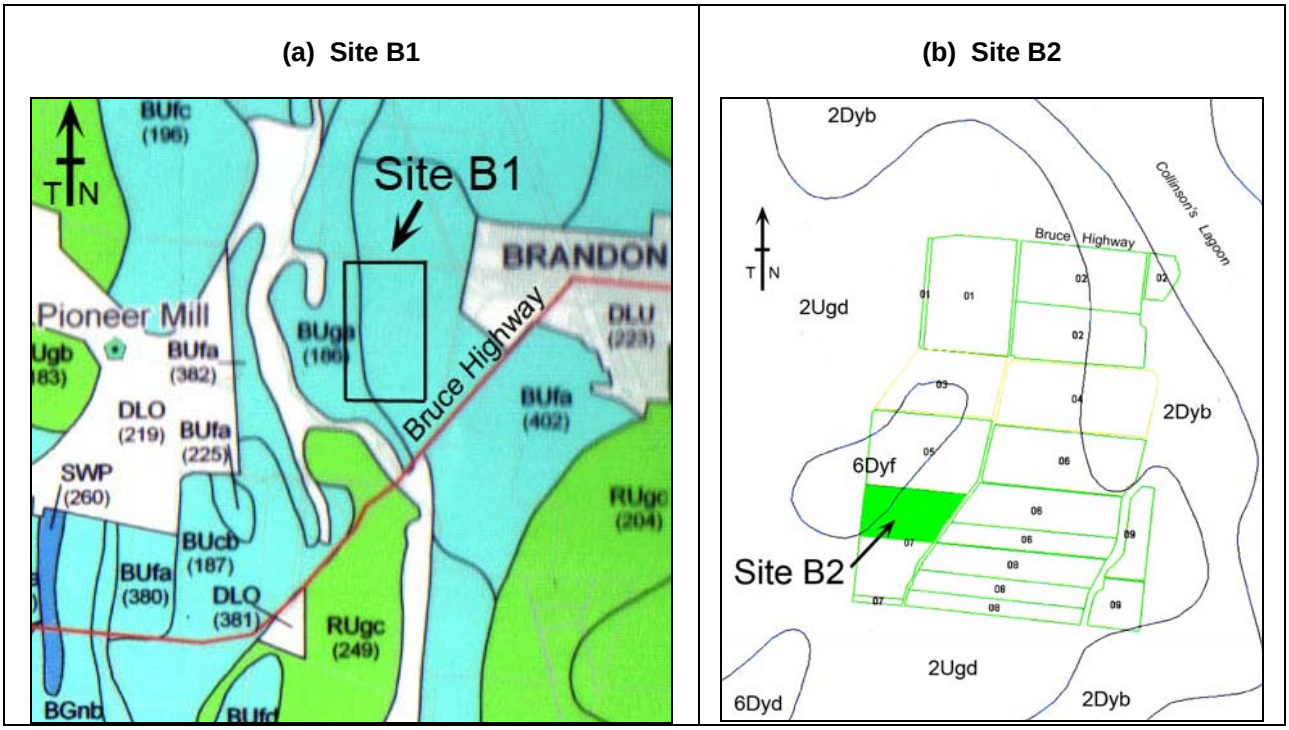


Figure 3.8. The soils of the Burdekin sites B1 and B2.
(a) Site B1, predominantly light textured sandy loams (BUfa) with minor grey clay soils (BUga). Source: McClurg *et al.* (2005).
(b) Site B2 is underlain by cracking clay (2Ugd) and sodic duplex (6Dyf) soils typical of the Burdekin River Irrigation Area. Source: Burdekin Productivity Services Ltd.

3.3.1.2 Site B2

Site B2 was chosen to be on the heavy clay soils and sodic duplex soils that typically occur on the clay-rich alluvial sediments of the Burdekin River Irrigation Area (Fig. 3.8b). The site was located to be close enough to site B1 such that one IKONOS satellite image (7 x 7 km footprint) would cover both sites.

The grey clay and black earth soil profiles of mapping unit 2Ugd (Fig. 3.8b), which crack on seasonally drying, present black, light to light medium clay topsoils overlying mottled grey or black subsoils of similar texture with a neutral soil reaction trend that becomes strongly alkaline by 90 – 120 cm depth. The soils have principal profile forms of Ug 5.15, Ug5.16, Ug5.24, and Ug5.28 (Donnollan 1991). The soils are associated with areas of non-cracking clay soils with principal profile forms of Uf6.31, Uf6.21, Uf6.22, and Uf6.23. The cracking clay soils have been be classified as Black Vertosols and the non-cracking clays as Black or Brown Dermosols (McClurg *et al.* 2005).

The northwestern part of Site B2 has been mapped as 6Dyf (Fig. 3.8b), which consists of sodic duplex soils with pale coloured topsoils of clay loam texture that, at depths of 20 – 50 cm, abruptly overlie light medium – heavy clay subsoils that are strongly structured, strongly alkaline (pH 7.9 – 9.0), and sodic, becoming strongly sodic (exchangeable sodium percentages greater than 15) below 90 cm depth. The soils have been classified variously as yellow solodic or solodised solonetz depending on the presence of coarse, domed columnar structure in the subsoils of the latter group. They include principal profile forms Dy3.33, Dy3.43 and occasionally darker or redder equivalents; they were classified as Grey or Yellow Sodosols (McClurg *et al.* 2005).

3.3.2 Herbert sites

3.3.2.1 Site H1

Site H1 lies on young alluvial sediments on the southern side of Crystal Creek at Mutarnee, which is 35 km south of Ingham and 75 km northwest of Townsville. The 1:100,000 scale soil map of the wet tropical coast in the vicinity of Ingham on which Wilson and Baker (1990) identified two soil mapping units at site H1 whose properties were summarised as follows.

On the well drained, elevated stream levee adjacent to the stream, are red earth soils (Stace *et al.* 1968) of the Bluewater Series. These soils have thin (0.1 – 0.2 m thick), dark, topsoils (A1 horizons) of sandy clay loam to clay loam texture that commonly grade into slightly paler subsurface (A2) horizons that may be 0.1 – 0.3 m thick. The sandy loam – sandy clay loam A2 horizons change gradually into acidic, massively structured, red brown – brown subsoils of sandy clay loam – light medium clay texture that continue to depths greater than 1.2 m. These soils may be classified as Red Kandosols and Red Dermosols with principal profile forms of Um4.21, Um5.52, Gn2.14, Gn2.24, and Gn2.11.

The red soils of the stream levee pass down a gentle slope to the grey, generally sandy topsoils of the stream floodplain (Figs 3.4c, 3.9) where two similar groups of mottled yellow, brown and grey duplex soils occur. The soils were classified as soloths (Stace *et al.* 1968), or as having soloth affinities, with Dy3.41 principal profile forms. They may also be classified (Isbell 1996) as Yellow or Grey Sodosols and Dermosols.

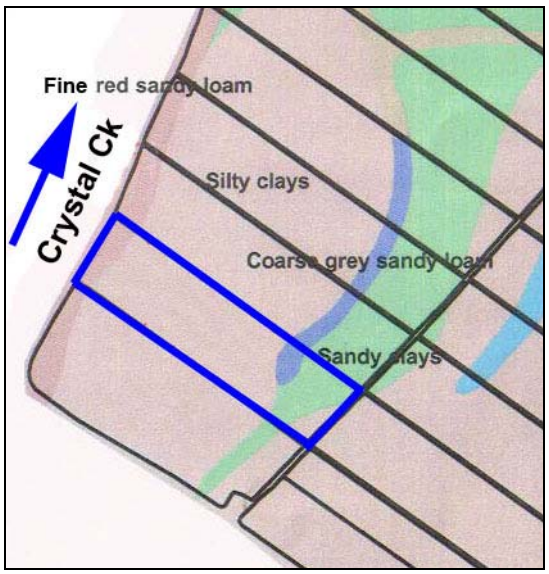


Figure 3.9. Soils of study site H1, Mutarnee.
Site H1 (approximately 160 m x 120 m) is outlined by the blue box. This map forms part of the Soils Map, Pace Farm 0708A, and was provided by the Herbert Cane Productivity Services Limited with the owner's permission.

Highest, and closest to the stream levee, is the Manor Soil Series which is characterised by thin (0.05 – 0.15 m), dark, clay loam topsoils (A1 horizons) grade into sporadically bleached A2 horizons (0.15 – 0.3 m thick) of similar texture. In many of the soil profiles there is a rapid change with depth into structured subsoils (B2 horizons) that are acidic, mottled, yellow-brown and yellow, and of light to medium clay texture. These soils have a Dy3.31 principal profile form. Elsewhere in this soil mapping unit the soils have gradational changes between the A and B horizons where Gn3.01 principal profile forms are common.

Lower on the stream floodplain, the soils of the Althaus Series have somewhat sandier topsoils than the Manor Series, with conspicuously bleached A2 horizons, marked texture contrasts between sandy loam – sandy clay loam topsoils and sandy clay – heavy clay subsoils that are mottled, yellowish brown and grey in colour which suggest relatively poor soil profile drainage.
The detailed topsoil texture mapping of Wood (1988) and Wood *et al.* (2003) shows a suite of soils across the H1 site, from fine red sandy loam on the stream levee, to silty clay, coarse grey sandy loam, and sandy clays occurring on the floodplain (Fig. 3.9).

3.3.2.2 Site H2

Site H2 is underlain by the older, heavy textured, alluvial sediments of the Herbert River floodplain carrying grey clay soils. The sedimentary deposits accumulated during ancient floods on the Herbert River and some of the larger distributary streams have deposited coarse sandy – fine gravelly sediments in former channels, now abandoned and infilled, across the clay plains. Site H2 is underlain by an extensive area of clay soils with a remnant of an infilled distributary channel now forming a low, red, sandy ridge towards the western end of the site (Figs 3.5, 3.10). The site has been the subject of significant land-forming operations over time and few of the original soil profiles, if any, have been left undisturbed.

Fig. 3.10. Soils of study site H2, Lannercost.
Site H2 (approximately 670 x 170 m) is outlined by the blue box. This map forms part of the Soils Map, Pace Farm 0708A, and was provided by the Herbert Cane Productivity Services Limited with the owner's permission.

Wilson and Baker (1990) identified the Hamleigh Soil, the largest single soil mapping unit that supports sugarcane growth in the Ingham area, as the dominant soil in the vicinity of site H2. The soil is characterised by seasonally cracking clays with 0.1 – 0.2 m of dark to grey-brown, hard-setting, silty clay to medium clay textured topsoil, often with a sporadically bleached A2 horizon extending to a depth of 0.35 m, overlying acidic to alkaline , mottled, grey and grey-brown, medium to heavy clay subsoils. The soils were classified as bleached grey clay with a Ug3.2 principal profile form.

The red sandy ridge at site H2 has been partially scalped by land-forming operations that spread the higher sandier soil into adjacent low-lying parts of the paddock. Where the impact of laser leveling has been least, the dark topsoil has a gritty sandy loam and gradually changes with depth to weakly

acidic, coarsely mottled, reddish brown and light yellowish brown, gritty, sandy clay loam – light clay. The soil is similar to the Abergowrie Series of Wilson and Baker (1990) and, depending on how rapidly the topsoil grades into the subsoil, is classified as a red earth or red podzolic soil, Red Kandosol or Red Chromosol, with a Gn2.14 or Dr5.21 principal profile form.

The detailed topsoil texture mapping of Wood (1988) and Wood *et al.* (2003) shows the dominance of clay soils across the H2 site with the prominent red sandy ridge identified towards the western end of the site (Figs 3.5 and 3.10).

3.3.3 Homebush site

The most detailed published soils map of the Homebush area near Mackay is that of Holz and Shields (1985) on which the bulk of the soils of site M1 are shown as the Sandiford Series (Yellow Chromosol; Fig. 3.11); smaller areas have been mapped as the Mirani Series (Grey Subnatric Sodosols) and Marion Series (Brown Chromosols).

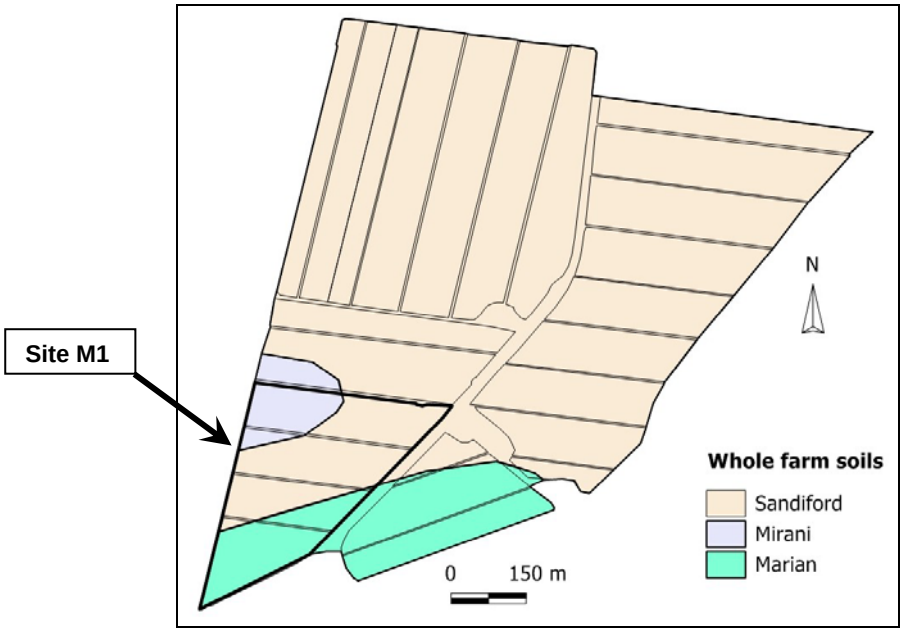


Figure 3.11. Soils in the vicinity of site M1, Homebush.
The boundaries of the various blocks of the Rosella Farm (Farm 04074B) have been laid over the 1:100,000 scale soil mapping units of Holz and Shields (1985). The soil boundaries are from the digitised soil mapping data base of Mackay Sugar Ltd, which is accessible through the Agdat program (http://www.agtrix.com /products-agdat) for managing spatial data from sugarcane farms. Site M1, outlined with a heavy line, lies at the southwestern corner of the farm.

The Sandiford Soil is characterised by 0.25 m of brownish grey to greyish yellowish brown, acidic topsoils with sandy clay loam texture and sporadic to conspicuously bleached A2 horizons, that pass rapidly with depth into dark greyish yellow – yellowish brown, weakly acidic to alkaline subsoils of light medium clay to medium heavy clay. The subsoils are sodic and dispersive at depth (Hardy *et al.* 2000) and contain ferromanganiferous nodules indicative of poor soil profile drainage.

The Mirani Soils (Grey Subnatric Sodosols) are similar to the Sandiford Soils but differ in the more abundant grey colours of the yellow-grey mottled subsoils and the lighter textures (sandy clay – medium clay) of the Mirani subsoils; both soil groups have weakly sodic and dispersive subsoils.

Holz and Shields (1985) showed an occurrence of Brown Chromosols of the Marion Soils just to the south of site M1 (Fig. 3.11). These soils have very dark topsoils of sandy clay loam texture and a sporadic bleach. They pass rapidly into heavy textured, mottled, greyish yellow, yellowish brown, and brown subsoils. Like the Sandiford Soils, the medium clay – medium heavy clay subsoils contain ferromanganiferous nodules indicative of poor drainage, but unlike the Sandiford Soils, they are not sodic and are not dispersive.

Chapter 4

METHODS FOR COLLECTING AND PROCESSING SPATIAL DATA

4.1 APPARENT SOIL ELECTRICAL CONDUCTIVITY MAPPING

The concept of mapping the apparent electrical conductivity (ECa) of the soil by injecting an electrical current and measuring voltage changes in the return signals at georeferenced locations was introduced in Section 2.3.3 (above). The present chapter describes the nature of the equipment used in the field by Project BPS001 for soil ECa mapping, the methods used to collect other georeferenced spatial data, and the protocols involved in interrogating, processing, displaying, and storing the spatial data of various kinds.

4.1.1 Collection of soil ECa and other spatial data in the field

The Veriș Model 3100 Soil ECa Mapping System has been developed by the Veris Technologies Company at Salina, Kansas, for mapping apparent soil electrical conductivity patterns in soils (Veris Technologies 2000). The responses of the instrument are dominated by soil salinity in saline areas, and by soil texture in non-saline areas (Lund and Christy 1998). Soil texture, or the relative proportions of sand, silt and clay in the soil, is a very important soil physical property that is related directly to the cation exchange capacity of the soil, its water-holding capacity, and the response to cultivation – all of which are critical to defining paddock management zones for precision agricultural operations.

The Veris 3100 mapping unit consists of a trailer with coulters (electrodes) set at different spacings and in contact with the soil, a GPS receiver, and an on-board data logger (Fig. 4.1). An electrical current is injected into the soil through some of the coulters and the resultant voltage changes are measured through the other coulters. The coulter spacings are arranged such that the unit records the apparent electrical conductivity of the uppermost 300 mm of the soil profile, which is effectively the disturbed topsoil in the cultivation zone of a sugarcane paddock (Fig. 4.1c). A second electrical signal is recorded at the same site from the uppermost 900 mm of the soil profile, which includes the bulk of the root zone of sugarcane plants in undisturbed subsoils. As the trailer is pulled through the paddock at a speed of 18 – 20 km / hr on runs 10 – 15 m apart, its position and the soil ECa responses from the soil profile are logged at one second intervals (approximately 5 m intervals along the run) by the data logger (Fig. 4.2a). When used on 10 m run spacings, the system produces soil ECa readings at about 380 points per hectare.

In Project BPS001, the apparent soil electrical conductivity mapping was carried out during the fallow phase between cropping cycles, and in cultivated land or prepared seed beds just prior to planting the sugarcane crops at each study site (Table 4.1).

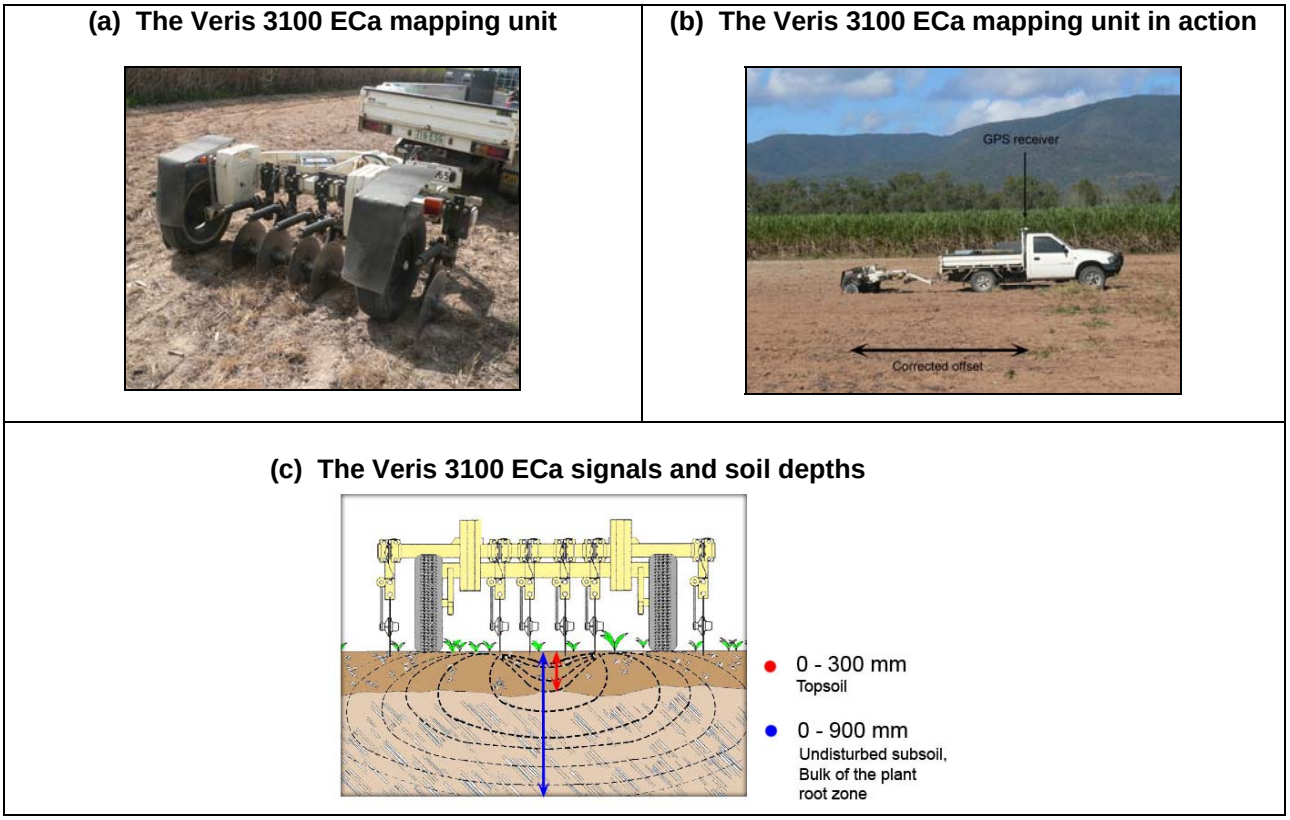


Figure 4.1. The Veris 3100 apparent electrical conductivity (ECa) mapping unit
(a) The coulters form an electrical array by passing a current through the soil between transmitting and receiving coulters.
(b) Paddock locations are logged at one second intervals (approximately 5 m along the run) by differential GPS technology. A software package corrects for the offset between the position of the coulters and the GPS receiver. Use of real time kinematic (RTK) GPS allows the elevation of the logged site to be recorded to 2 cm accuracy under ideal conditions.
(c) The shallow ECa signal is measured over the uppermost 300 mm of the soil profile at the recording site, and the deep ECa signal over the uppermost 900 mm of the soil profile (Veris Technologies 2000).

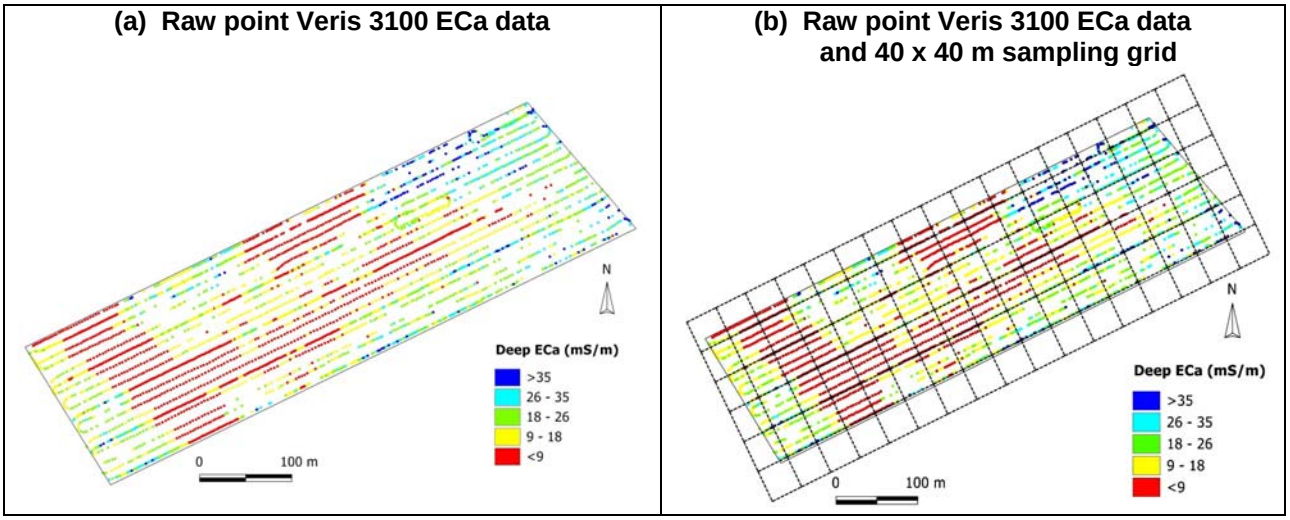


Figure 4.2. Veris 3100 apparent soil electrical conductivity mapping at Site H2.
(a) Veris 3100 tracks are displayed as raw point data at 10 m spacings between paddock runs of the instrument.
(b) The raw data has been themed and coded into a 5-zone, equal count, deep ECa mapping layer with a 40 x 40 m grid overlay for collection of bulk density and surface moisture sampling from georeferenced intersections of the grid.

In order to understand better the stability of shallow and deep Veris 3100 data over time, a comparative study was carried out. Sites B1 and M1 were Veris-mapped twice during the same fallow period, and site B1 was re-mapped a third time a year later (after the plant cane harvest), in order to evaluate the stability of the soil ECa maps within a seasonal timeframe. To determine the stability of soil ECa mapping patterns over a full crop cycle, a bare fallow paddock (located 5.4 km west of site M1) had been mapped in March 2003; it was re-mapped in May 2008 and the similarity of the soil ECa patterns was analysed.

These data sets were processed using the protocols set out below, and the results are discussed in Chapter 5.

4.1.2 Veris 3100 data processing and display

To achieve different project outputs, the soil ECa and GPS location point data generated during soil mapping surveys were processed in the three ways:

- for field mapping (Section 4.1.2.1, below),
- for data interrogation and statistical analysis (Section 4.1.2.2, below),
- for comparisons of soil ECa maps in the same area, but of different vintages (Section 4.1.2.3, below).

4.1.2.1 Processing for field mapping

The first data processing requirement was the rapid in-field production of shallow and deep soil ECa mapping patterns on a laptop computer. Immediately after Veris mapping of a site, the raw soil ECa data (Fig. 4.2a) were imported into Manifold GIS software and themed into a 5-zone, equal count, point data mapping layer. The soil mapping layer values were coded with red representing the low soil ECa values, through yellow, green, and light blue, to dark blue which represented the high soil ECa values. This colour code protocol has been applied to all spatial mapping layers throughout Project BPS001.

A 40 x 40 m grid was created in Manifold and laid over the Veris track map to facilitate the georeferenced collection of bulk density and surface moisture samples at grid intersection points (Figure 4.2b). To check the validity of the soil ECa data, borehole sites for investigating the nature of the soils included in the soil ECa mapping patterns were strategically selected according to point data colour patterns and were spatially located along the Veris 3100 tracks. The selected validation borehole locations were then uploaded from the study site map file in Manifold into a Garmin GPSmap 76 Cx hand-held GPS unit for field location of the sites.

4.1.2.2 Processing for data interrogation and statistical analysis

A second protocol for post-processing of spatial data and integration of sampling data from the field was established to ensure the spatial and statistical compatibility of data sets. The same GIS and data management protocol was applied to processed satellite imagery (normalized difference vegetation index values), site elevation, and yield monitor data collected later in the course of the project.

The raw soil ECa data from the Veris 3100 track paths was converted from a WGS84 projection to MGA94 (55) in Manifold. The preferred method of interpolation for converting discrete measurement points to continuously graded maps is kriging (Cressie 1990), as this takes into account the variability of the data to help calculate estimated smooth values. Following the

approach of Bramley and Williams (2001), intervening soil ECa values (and values from the other spatial data sets) were interpolated on a site by site basis through a kriging process on a 7 x 7 m grid within a defined site boundary using an exponential variogram (program VESPER; Minasny *et al*., 2005). The area of each grid cell, almost 50 m^2, offers fine spatial resolution for site maps and is smaller than the minimum area that a sugarcane grower is likely to adopt for site-specific management inputs.

All the matched spatial data on the kriged 7 x 7 m grid for each study site were subsequently linked in Manifold and the table exported for interrogation and statistical analysis. Similarly, the spatial data was attached to the suite of soil physical and chemical data collected for each georeferenced soil profile at each of the five study sites; these tables were also exportable for statistical analysis.

In Manifold (and other GIS software programs), spatial mapping layers may be digitally displayed as kriged, colour coded surfaces which can be transformed into contoured mapping layers or three dimensional terrain layers (Figure 4.3). The maps may be displayed electronically on a laptop computer in the field, or in hard copy form at an appropriate scale (1:5,000, or more detailed for precision agriculture purposes; Gallant *et al.* 2008). The nature of the soils within selected soil ECa map patterns was then determined by drilling a borehole by hand-auger to 1 m and observing the soil profile, recording its characteristics, and collecting samples for analysis, as required, from standard depth intervals (see Section 4.2.2, below).

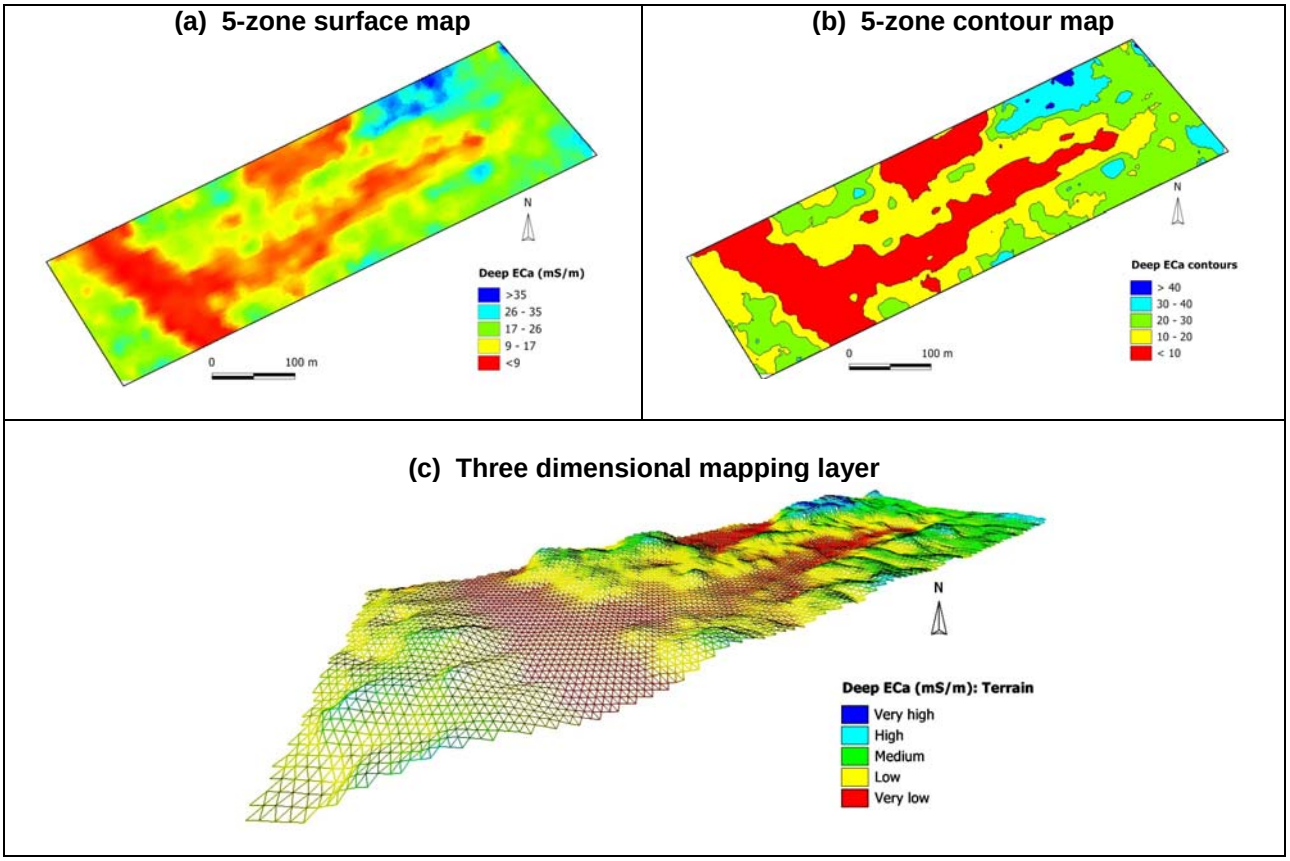


Figure 4.3. Soil ECa data generated by Veris 3100 mapping may be displayed in a number of ways.
(a) Deep (0-900 mm) soil ECa data has been displayed as a kriged, 5-zone, equal count surface mapping layer.
(b) The kriged surface layer has been transformed into a 5-zone contour mapping layer.
(c) The kriged surface layer has been displayed as a three dimensional mapping layer.

The soil ECa maps provide a basis for depicting inferred soil patterns, and may be coupled with other spatial information such as (paddock topography, crop yield maps, soil reference sites, satellite imagery, etc.), to assist in the interpretation of the resultant patterns of zones within a paddock.

Maps of shallow and deep soil ECa patterns over a 10 ha paddock of bare fallow can be produced in an hour or two of the arrival of the Veris 3100 unit and operator in the paddock. The cost of Veris 3100 mapping is currently of the order of $30 / hectare in the Central and Burdekin Districts, which compares very favourably with the high cost and long time required to produce a soil map at a similar scale using conventional soil survey methods (Section 2.3.1, above).

4.1.2.3 Processing for comparisons of different soil ECa maps

The third data processing protocol was to normalise the data from soil ECa maps that had been produced at different times from the one area. This is done by subtracting the overall mean from each data value then dividing by the standard deviation of the data (Steel and Torrie 1981). The process converts the data to that of a standard normal distribution, with a mean of 0 and a variance of 1. This process enables the soil ECa data sets collected by separate Veris 3100 mapping operations at different times on the one property to be compared on the same scale.

This approach was applied, in the following example, to the data collected at site M1 and the other 15 paddocks that comprise the Rosella sugarcane farm (82 ha) of A. and J. Bugeja. This farm has been progressively ECa mapped since 2002 with the M1 site being the final paddock to be mapped. The previous 1:100,000 scale soil survey of Holz and Shields (1985) allocated the soils of the farm to the north of site M1 to a single soil mapping unit (the Sandiford Soil; Fig. 4.4a). The normalised deep soil ECa map patterns indicated significant contrasts in soil properties across the farm (Fig. 4.4b) and they were used as the basis for a soil validation exercise over the farm.

In collaboration with an SRDC-funded Grower Group Innovation Project *(GGP052: The Next Step in Precision Agriculture)*, soil morphological properties were described and recorded for each profile to a depth of 1 m. Chemical and particle-size analyses were not undertaken due to their high cost. The gross differences in the nature and properties of the soil horizons in the 40 individual soil profiles clearly show a variety of soil characteristics within a single Sandiford Soil mapping unit. They are evident in Fig. 4.4c in different soil horizon thicknesses, colours and mottle patterns, textures, and gravel contents and compositions, and were consistent with the variability in soil properties indicated by the deep soil ECa patterns across the farm.

The soil profile differences exhibited by the 40 individual soil profiles are great. They indicate major soil texture, water infiltration, and internal drainage differences in the soils that relate to significant soil management issues such as cultivation responses, potential waterlogging, and areas prone to over- and under-watering when a whole-block irrigation strategy is used. Detailed, deep soil ECa mapping, and its validation by the examination of soil profiles at strategic locations within the ECa map patterns, has highlighted the limitations of soil survey information on a coarse 1:100,000 scale for progressing precision agriculture in a sugarcane production system.

The whole farm validation of soil EC mapping patterns has underpinned grower confidence in this mapping technology. A number of growers in the region now base their chemical soil testing programs on the patterns displayed in deep soil ECa maps as opposed to mixing soil

cores collected in a zigzag or grid pattern across paddocks of less that 2 – 3 ha of the BSES *Six Easy Steps* guidelines for crop nutrient management (Schroeder *et al.* 2006). The geo-referencing of soil test samples provides the grower with a powerful tool for monitoring soil nutrient trends over time and to determine whether nutrient input programs are maintaining, depleting, or building macronutrient levels. Georeferenced soil testing, targeted to specific soil types, paves the way for site-specific application of ameliorants such as lime, gypsum, and mill by-products where the soil ameliorants are applied at the correct rates, and to specific spatial locations within a paddock. In time, this process will be further refined to the 'on-the-go' variable rate application of nutrients within paddocks. However, the practical application of variable rate technology requires a lot more research including an enhanced understanding of the stability of yield zones under a variety of seasonal conditions and over a number of crop cycles.

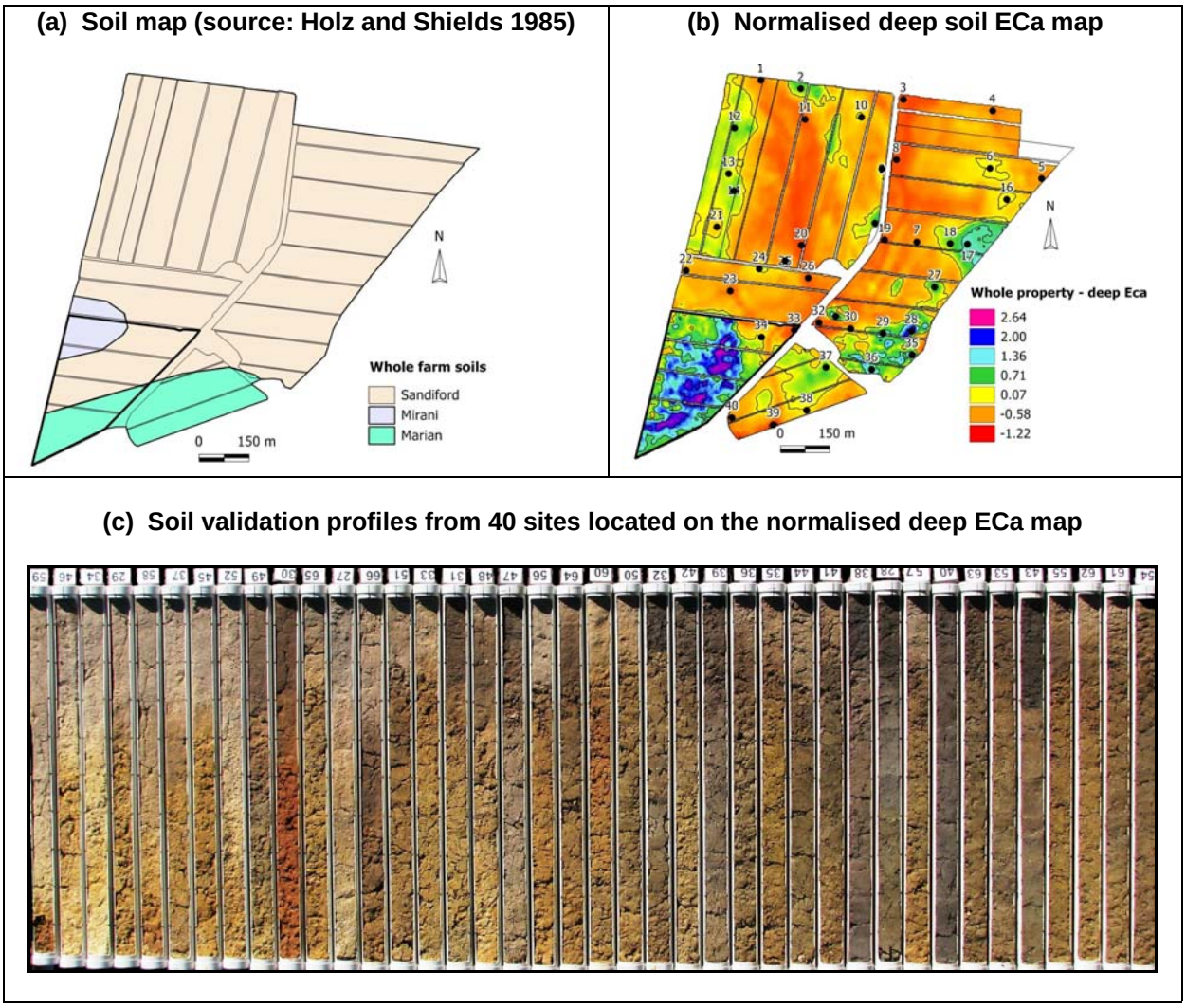


Figure 4.4 Forty soil profiles from the Sandiford Soil mapping unit (previously mapped at 1:100,000 scale) on the Rosella Farm of which site M1 is a part.

(a) Part of the pre-existing 1:00,000 scale soil map of the area (Holz and Shields 1985) laid over the paddock boundaries for the Rosella Farm. Site M1, at the southwestern corner of the farm, is enclosed by the heavy line.

(b) A normalised, deep soil ECa map for the Rosella Farm produced from nine individual Veris 3100 soil ECa surveys over the period 2002 – 2008.

(c) Variability in the 40 soil profiles collected from locations in the Sandiford Soil mapping unit that lay outside study site M1. The profiles are arranged with the topsoil towards the top of the page, and from the lowest deep soil ECa value on the left to the highest on the right. The profile numbers refer to the locations shown as "•" in part (b) of this figure.

4.1.2.4 Veris run spacings and ECa map quality

Commercial soil ECa mapping of sugarcane paddocks using the Veris 3100 unit is normally conducted at 10 - 15 m width run spacings across the paddock. Surface maps generated at these run spacings contain a relatively high content of interpolated data. To assess the integrity of commercially-generated surface soil mapping layers at these run spacings, Project BPS001 compared soil ECa mapping layers from 3 m and 15 m spacings at the B2 site. The comparative soil mapping exercise was conducted during the fallow phase at the B2 site on the 31 March 2009.

The 10.24 ha paddock was mapped at both 3 m and 15 m run spacings. Both data sets were transformed onto a 7x7 grid through program VESPER. The mapping patterns were very similar (compare Figs 4.5a and 4.5b) and a linear regression of the matching georeferenced, deep soil ECa cells (7 x 7 m) derived from the 3 m and 15 m run spacings was highly significant with an adjusted R^2 value of 0.92 (Fig. 4.5c).

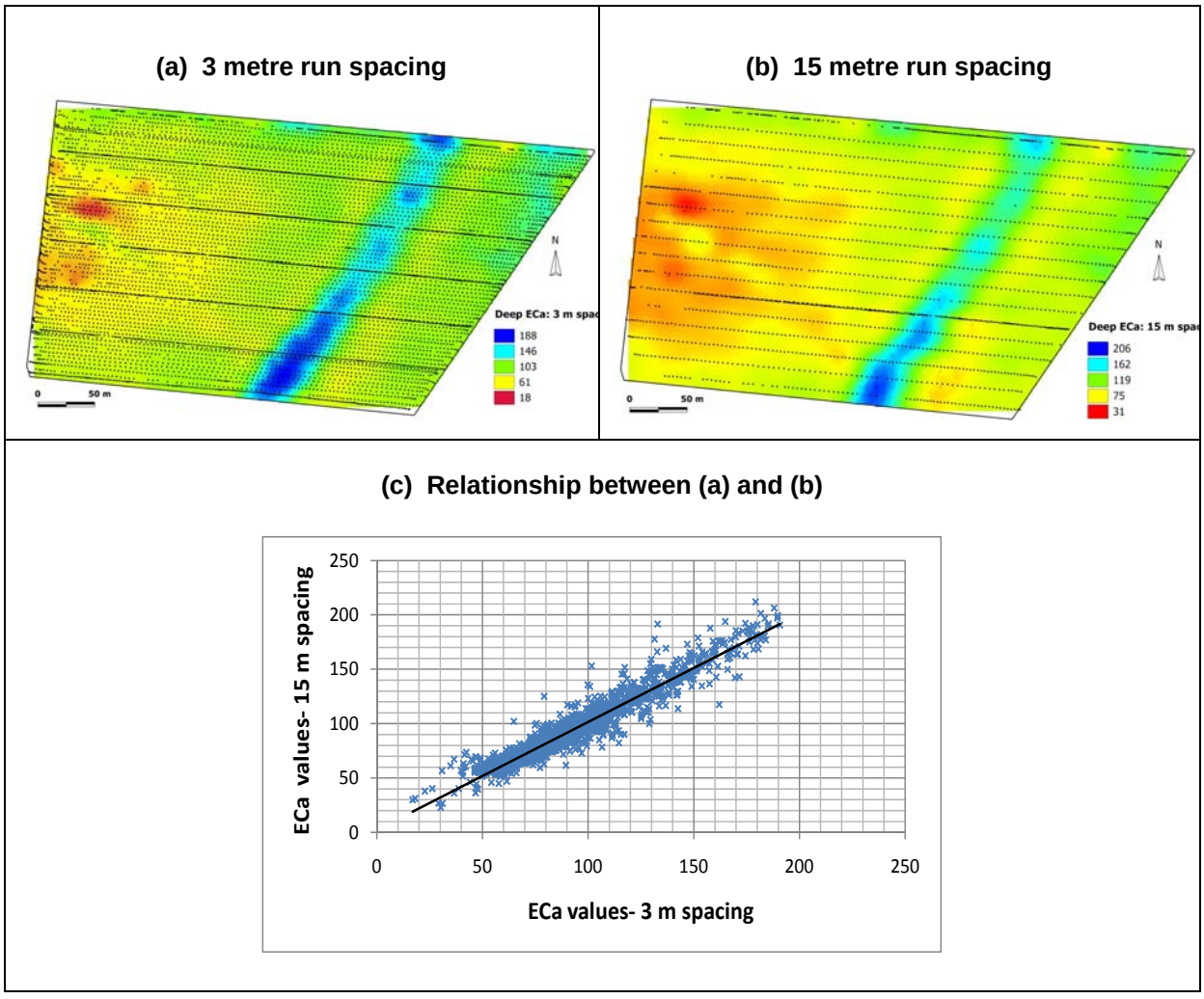


Figure 4.5. Comparison of deep ECa mapping patterns at site B2 derived from Veris 3100 run spacings of 3 m and 15 m.
Comparative soil ECa mapping was carried out during the fallow period on 31 March 2009.
(a) Deep ECa mapping patterns generated from 3 m Veris 3100 run spacings.
(b) Deep ECA mapping patterns generated from 15 m Veris 3100 run spacings.
(c) Strong linear relationship between corresponding 7x7 m cells for the 3 m and 15 m run spacings (adjusted R^2 = 0.92, n = 2,084)

We draw two conclusions from these results:

- a 10 - 15 m run spacing is commercially acceptable for soil ECa soil mapping;
- the integrity of interpolated soil mapping surfaces is not compromised by expanding run spacings from 3 m to 15 m.

It is important to note, however, that the clay soils of site B2 are reasonably homogeneous. Therefore, some narrowing of run spacings may be required when surveying paddocks with significant variability in soil properties.

4.1.3 Soil conditions for effective soil ECa mapping

Veris 3100 soil ECa mapping carried out over hard, compacted soils that prevent good soil contact with the coulter electrodes produces a 'noisy' data set that contains missing values where poor contact was made between the machine and the soil. The resultant maps lack details that usually become evident after disruption of the compacted soil. For example, the harvest at Site M1 (Homebush) on 6 December 2007 was carried out less than a week after 45 mm of rain was recorded at the Te Kowai weather station, some 8 km from the field site; another 6 mm of rain fell on the day of the harvest. The movement of harvester and haul-out traffic over the moist soil resulted in severe soil compaction and wheel rutting of the wet topsoils that also set very hard as they dried out after the harvest (Fig. 4.6).

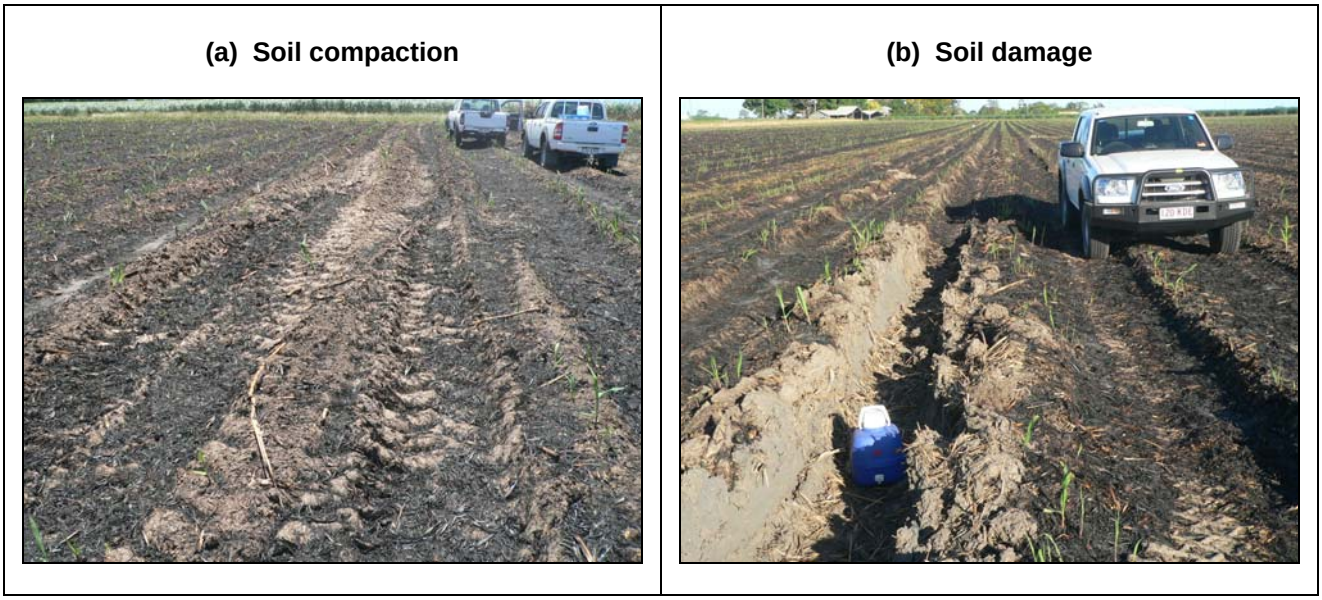


Figure 4.6. Soil damage during a wet harvest late in 2007 at site M1, Homebush, prior to plough-out and preparation of the soil for planting of a new crop in August 2008.
Photographs taken on 17 December 2007.
(a) Soil compaction caused by wheeled haul-out vehicles, if not confined to the inter-row spaces and along the planted hill, will diminish subsequent crop yields by severely interfering with the ability of the ratoon crop to send out tillers through the dense, compacted soil.
(b) The loaded haul-out units (30 + tonnes) can cause serious soil damage when close to bogging in the wetter parts of a paddock. The wheel rut was considerably deeper than the 36 cm high 10 L water bottle in the rut.

The post-harvest green cane trash blanket at Site M1 was burnt and soil ECa mapping was carried out across the site on 17 December 2007, 11 days after harvest. The resultant deep (0 – 900 mm) soil ECa map (Fig. 4.7a) showed poorly defined patterns across the paddock that are interpreted as a consequence of the dryness and compaction of the soil, and poor machine-soil contact. As part of the cane plough-out process, the paddock was ripped to a depth of 600 mm

and cultivated by offset discs to 200 mm depth on 21 December 2007; it was soil ECa mapped a second time on 24 December at essentially the same soil moisture content as at the time of the mapping a week earlier (Fig. 4.7b). The Te Kowai weather station, 8 km away, received 1805 mm of rain between the second ECa mapping on 25 June 2008. The paddock was cultivated after each significant period of rain (7 times) to relieve soil crusting prior to the final soil ECa mapping (17 June 2008; Fig. 4.7c) and the associated soil profile description and soil sampling before planting on 29 August 2008.

Disruption by ripping and cultivation of the human-induced soil compaction across the paddock permitted the Veris 3100 machine to make good contact with the soil and it produced a useable map of the variations in soil-related properties across the paddock (Fig. 4.7b). Those patterns were emphasised, and subtle differences in the data were clarified, by the Veris 3100 mapping that was carried out after multiple cultivations and substantial rainfall to produce excellent contact between the soil and Veris 3100 coulters prior to planting (Fig. 4.7c). Clearly, the quality of the soil ECa map produced by the Veris 3100 unit is dependent on cultivation to remove the negative impact of soil compaction on the data collection process.

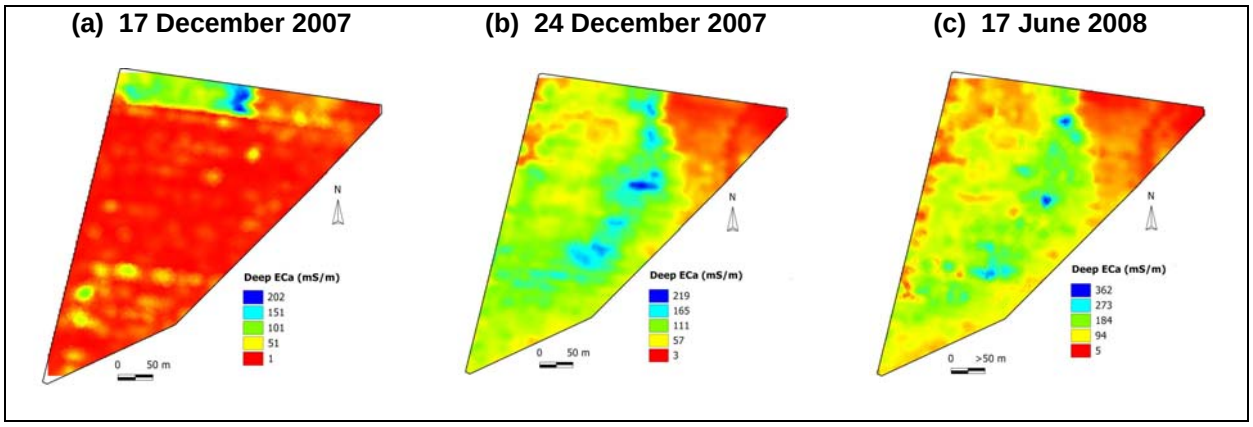


Figure 4.7. The effect of cultivation on the quality of deep (0 – 900 mm) Veris 3100 soil ECa mapping at Site M1, Homebush.

(a) Deep soil ECa map (12/12/2008) of dry, compacted soil 11 days after harvest. Five rows had been disced at the northern end of site as a weed control.

(b) Deep soil ECa map (24/12/2008) of dry soil after ripping to 600 mm depth and offset ploughing to 200 mm depth; 1.6 mm of rain fell at Te Kowai weather station (8 km away) between ECa mappings on 17 and 24 December 2007.

(c) Deep soil ECa map (17 June 2009) of the cultivated soil ready for planting. The Te Kowai weather station received 1,805 mm of rain and the site had been cultivated 7 times to alleviate soil crusting after significant rainfall events between 24 December 2007 and 17 June 2008.

4.1.3.1 Recommendations for soil ECa mapping operations

For best results using the Veris 3100 Mapping System in sugarcane soils, it is recommended that soil ECa mapping is performed on loose, cultivated soil that has been prepared for planting the seed cane; such soils offer good contact between the soil and the coulters (electrodes) and produces a continuous data set from which the best quality maps may be produced.

It is also recommended that the soil ECa mapping be conducted on soils with about 10% moisture content, preferably after rain has uniformly wet up the soil profile.

4.1.4 Veris 3100 and EM38 mapping

The use of the Geonics EM38 instrument and non-contact electromagnetic methods to map soil moisture and soil salinity have been discussed briefly in Section 2.3.2 (above). Like the Veris 3100 unit, the EM38 is designed for relatively shallow applications within the agricultural root zone. It provides measurements of ground conductivity and magnetic susceptibility within two effective depth ranges: 1.5 m in the vertical dipole mode and 0.75 m in the horizontal dipole mode (Geonics 2011). It can be used to survey large areas quickly, without any requirement for ground-to-instrument contact.

Soon after harvesting of the plant cane crops at sites H1 and H2, EM38 surveys were carried out by Mr T. Parker of the Northern Gulf Resource Management Group, Mareeba. The survey was performed on 23 and 24 September 2009, some 15 – 16 months after the study sites had been mapped by the Veris 3100 unit (Table 3.1). The aim of the mapping exercise was to examine the relationships between the soil sensor results when compared to georeferenced soil test data, cane yield monitoring, soil mapping data, and other remotely sensed data (Di Bella *et al*. 2010).

The study found quite close similarities between the capabilities of the Veris 3100 and EM38 instruments to identify the lighter textured soils within the paddocks (Fig. 4.8). The shallow Veris readings detected a broader band of sandy soil close to the crest of the ridge (Fig. 4.8a); this result appears to have been influenced by the re-distribution of the sandy soils of the ridge during land-forming operations prior to planting sugarcane in the early 1990s and discussed in Section 5.3.4.2 (below).

The shallow and deep operational mode of both instruments were capable of identifying the red sandy ridge in the western part of the paddock (Fig. 3.5), and a prominent, curving area of low soil electrical conductivity or electromagnetic responses to the east of the red sandy ridge (Figs 4.8).

There were, however, poor matches in the abilities of instruments, in either shallow or deep operational mode, to produce matching results in the heavier clay soils over the eastern part of the site (Fig. 4.8). These differences may be related partly to differences in soil moisture content at the times of the field surveys that were 15 months apart, and partly to the different depth ranges sensed by the different instruments.

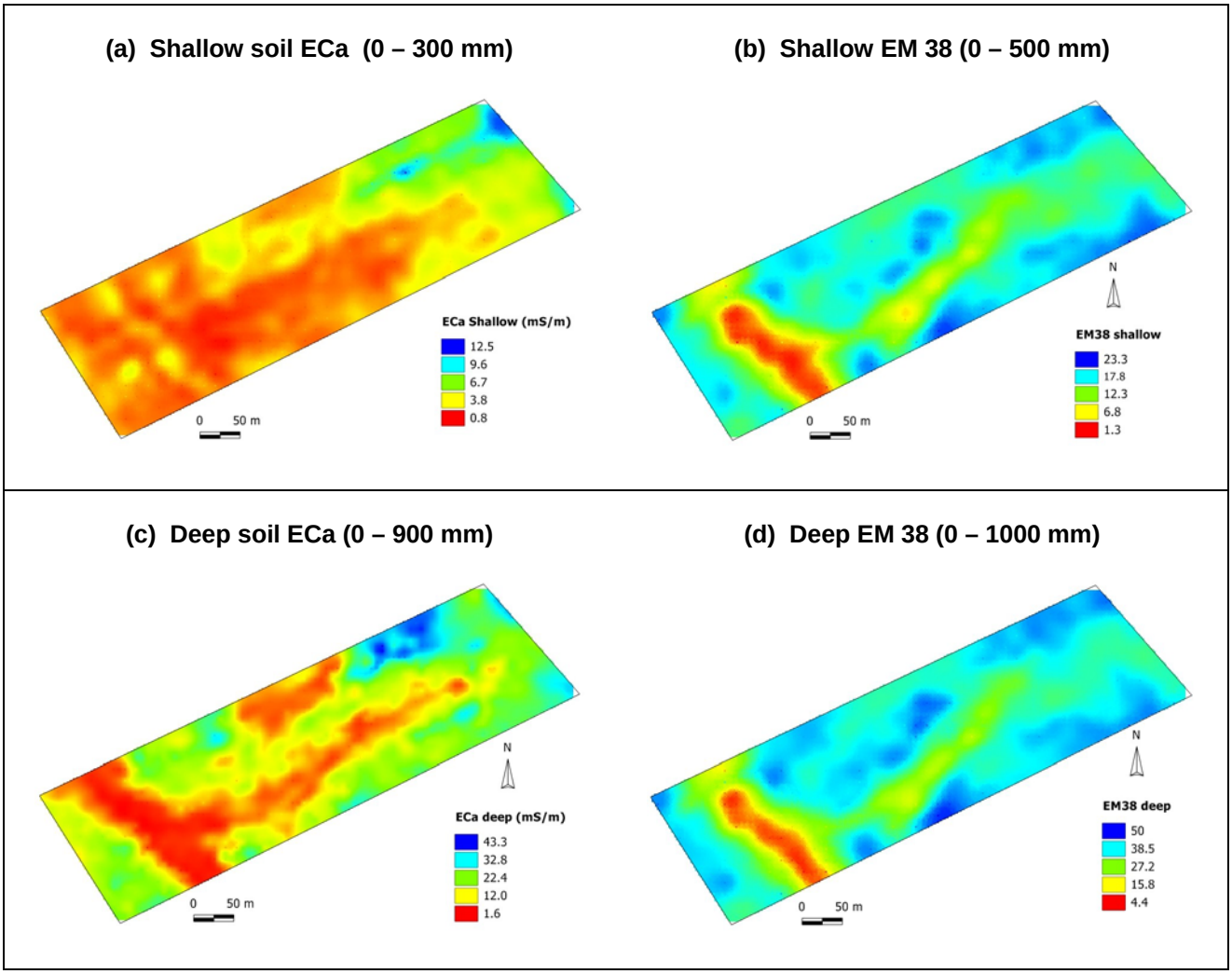


Figure 4.8. Comparison of map patterns produced by the Veris 3100 and EM38 instruments at site H2, Lannercost.
Soil ECa mapping by Ag Data Solutions, Ayr, on 12/05/2008; EM38 mapping by T. Parker, Northern Gulf Resource Management Group, Mareeba, on 23/09/2009.
(a) Shallow Veris 3100 map (0 – 300 mm depth).
(b) Shallow EM38 map (0 – 500 mm depth).
(c) Deep Veris 3100 map (0 – 900 mm depth).
(d) Deep EM38 map (0 – 1000 mm depth).

4.2 SOILS: DATA COLLECTION

4.2.1 Soil description methods

In order to provide crucial soil data against which interpretations of the utility of soil ECa mapping could be made, soil profiles were selected for description and analysis from key locations within mapped zones based on:

- specific soil ECa mapping units,
- distinctive patterns evident on high resolution satellite imagery or aerial photographs,
- irregularities or discontinuities in the topography, topsoils, weed patterns, or other characteristics of the site.

Soil sampling for determining topsoil gravimetric moisture content and bulk density was conducted at the intersections of a 40 x 40 m grid layer across each study site (Fig. 4.2b). Soil morphological descriptions and sampling for soil physical and chemical analysis, soil moisture analysis, and soil penetrometer resistance measurements were conducted at strategically located borehole sites for the verification of soil ECa mapping patterns. This field work commenced during or immediately after the soil ECa mapping operation.

Either a 50 mm or 75 mm hand auger was used to expose the soils in boreholes to a depth of 1 m at 21 – 32 key locations at each BPS001 study site. The excavated soil materials were laid out in 30 cm increments and were described, soil horizon by soil horizon, using the methods and terminology of the National Committee on Soil and Terrain (2009).

4.2.1.1 Soil texture determinations

The texture of the soil reflects the size of the particles that constitute the fine earth fraction of the soil (*i.e.* the fraction finer than 2 mm) and has a major influence on a number of key soil properties, such as: porosity and permeability and their impact on the infiltration of rain or irrigation water, the water-holding capacity of the soil, nutrient supply and retention, contaminant management, ease of cultivation, and susceptibility of the soil to erosion (Brady and Weil 2008).

In Australia, the field texture classes determined by experienced soil surveyors are based on the feel and coherence of moist soil, and not on laboratory determinations of particle-size classes and triangular plots of sand, silt, and clay, as is done in the USA. But there is only an approximate relationship between field texture and particle-size distributions as factors other than the relative amounts of sand, silt, and clay are involved, including: the type of clay, the amount and composition of exchangeable cations, and the presence of organic matter, oxides, carbonates, and structural aggregates (National Committee on Soil and Terrain, 2009).

Project BPS001 has attempted to develop protocols for sugarcane growers and other non-specialist soil surveyors for use in precision agriculture practices in the Australian sugar industry. Therefore, we recognise that determining the field texture of a moist soil sample by manipulating it between the fingers is a somewhat specialised skill that is often very difficult for non-specialists to perform accurately and in a reproducible manner.

Throughout this report, therefore, we have used the term “field texture” when describing soil profiles in the field. We have used the terms “soil texture” or “texture” when we have used particle-size analyses and triangular plots of percent sand, silt, and clay of the fine earth fraction (National Committee on Soil and Terrain, 2009, p. 163). This method, while not

strictly comparable with standard Australian soil description methodology, may be used by non-specialist soil investigators to make an unambiguous and repeatable assessment of the soil's texture. The basic particle-size information can be provided by a reputable soil-testing laboratory for an additional charge over standard charges for a soil chemical (fertility) assessment of a soil sample.

4.2.1.2 Soil colour determinations

The colours of soil samples were recorded in the field in terms of three variables (hue, value, chroma) using Munsell Soil Colour Charts, and the name of the colour chip that most closely matched the colour of the moist, undisturbed soil. There are, however, 350 different colour chips in a set of Munsell Soil Color Charts, so the details of colour names used in the field descriptions of the soils have been reduced by reference to the broad colour group names (red, black, brown, yellow, grey) applied by the current Australian soil classification system (Isbell 1996, p. 126) to groups of Munsell soil colour chips. This method means that any dark colours are almost always called 'black', and mottled soils (*i.e.* those with blotches of different colours that are still evident when the soil has been moistened) may contain distinctively different yet close shades of red, yellow, brown, or grey and is likely to have been called 'mottled brown', or a similar name.

4.2.2 Soil sampling methods

Soil samples were collected from standard depths for specific soil properties from each of the described soil profiles; the gravimetric moisture, chemical, and particle-size properties of the soil samples have been characterised by laboratory analysis. A range of soil information was collected from specific sampling depths at each georeferenced borehole site. Some of the information relates to the whole of the soil profile at a site (Section 4.2.2.1, below) and other data is relevant to specific layers in the profile (Section 4.2.2.2, below)

4.2.2.1 Whole of soil sample site data

- *shallow (0 – 300 mm) and deep (0 – 900 mm) apparent soil conductivity (ECa) values:* taken from kriged data from the Veris 3100 tracks that were 10 m apart across each study site.

- *topsoil moisture content:* determined on samples collected from a depth of 10 cm at points on a 40 x 40 m grid intersections on the Veris 3100 tracks (Fig. 4.2b).

- *topsoil bulk density:* determined to a depth of 10 cm at each 40 x 40 m grid intersection on the Veris 3100 tracks (Fig. 4.2b).

- *cone penetrometer resistance:* the cumulative depth of penetration after each hammer blow was recorded from four replicates to a penetration depth of 48 cm depth at every soil validation borehole at each study site.

- detailed topographic data was obtained from differential GPS data collected as part of the soil ECa mapping process early in the life of the project and, much more precisely, from an RTK-GPS unit added to the commercial Veris 3100 units in the last year of the project's operations.

4.2.2.2 Information from specific soil sampling depths

- *soil chemical properties of topsoil samples (generally 0 – 25 cm depth):* analytes were pH, electrical conductivity, chloride content, cation exchange capacity, exchangeable basic cations (Ca, Mg, K, Na), exchangeable sodium percentage, organic carbon, nitrate nitrogen, sulphate sulphur, nitric acid potassium, plant available phosphorus, extractable silicon.

- *a restricted set of soil chemical properties of the upper and lower subsoils (generally 40 – 60 cm, and 75 – 100 cm depths, respectively):* analytes were electrical conductivity, chloride content, cation exchange capacity, exchangeable basic cations (Ca, Mg, K, Na), exchangeable sodium percentage.

- *coarse sand, fine sand, silt, and clay contents:* 3 samples per soil profile (determined at the same sample depths used for soil chemical analysis).

- *soil moisture content of the described profiles:* gravimetric soil moisture content determined on samples collected from each described soil profile at 10 cm intervals to from 5 cm to 95 cm depth (10 samples / profile).

- *soil morphological properties:* the field properties of all of the soil horizons evident in each of the selected soil profiles have been described to a depth of 1 m. The depths of the upper and lower depth limits of each soil horizon were recorded. Where this information has been used in statistical analyses, the data has been related to the standard depths used for the analysis of the soil chemical properties (*i.e.* 0 – 25 cm, 40 – 60 cm, and 75 – 100 cm);

- *cone penetrometer resistance:* the cumulative depth of penetration after each hammer blow was recorded from four replicates at each described soil profile to a penetration depth of 48 cm.

- *bulk density of the topsoil:* determined on samples collected from the 0 – 10 cm depth from each described soil profile.

4.3 PADDOCK TOPOGRAPHY

In the early phase of Project BPS001, the only paddock elevation data that the project team had access to was differential GPS data (e.g. Fig. 4.8b) collected at the time of the Veris 3100 soil mapping surveys of the various study sites with a typical pass to pass accuracy of approximately 1 m and a repeatable accuracy of approximately 5 m. At that stage, the significance of paddock elevation was not considered to be important and research activities were channeled towards gaining a better understanding of the relationships between soil ECa mapping patterns and within paddock yield variability. However, during the subsequent validation of soil ECa mapping patterns and the calibration of NDVI mapping layers, the influence of topography on within-paddock yield variability and soil distribution patterns became more apparent, particularly at the higher rainfall study sites.

The requirement for detailed knowledge of both paddock and farm topography is very important at each of the gently sloping study sites: the location and design of farm drains was critical for the rapid removal of excess water from the paddocks to minimise crop losses from soil waterlogging. The two Burdekin sites are furrow irrigated, hence the subtleties of paddock topography have been important in supplying water to the crop as well.

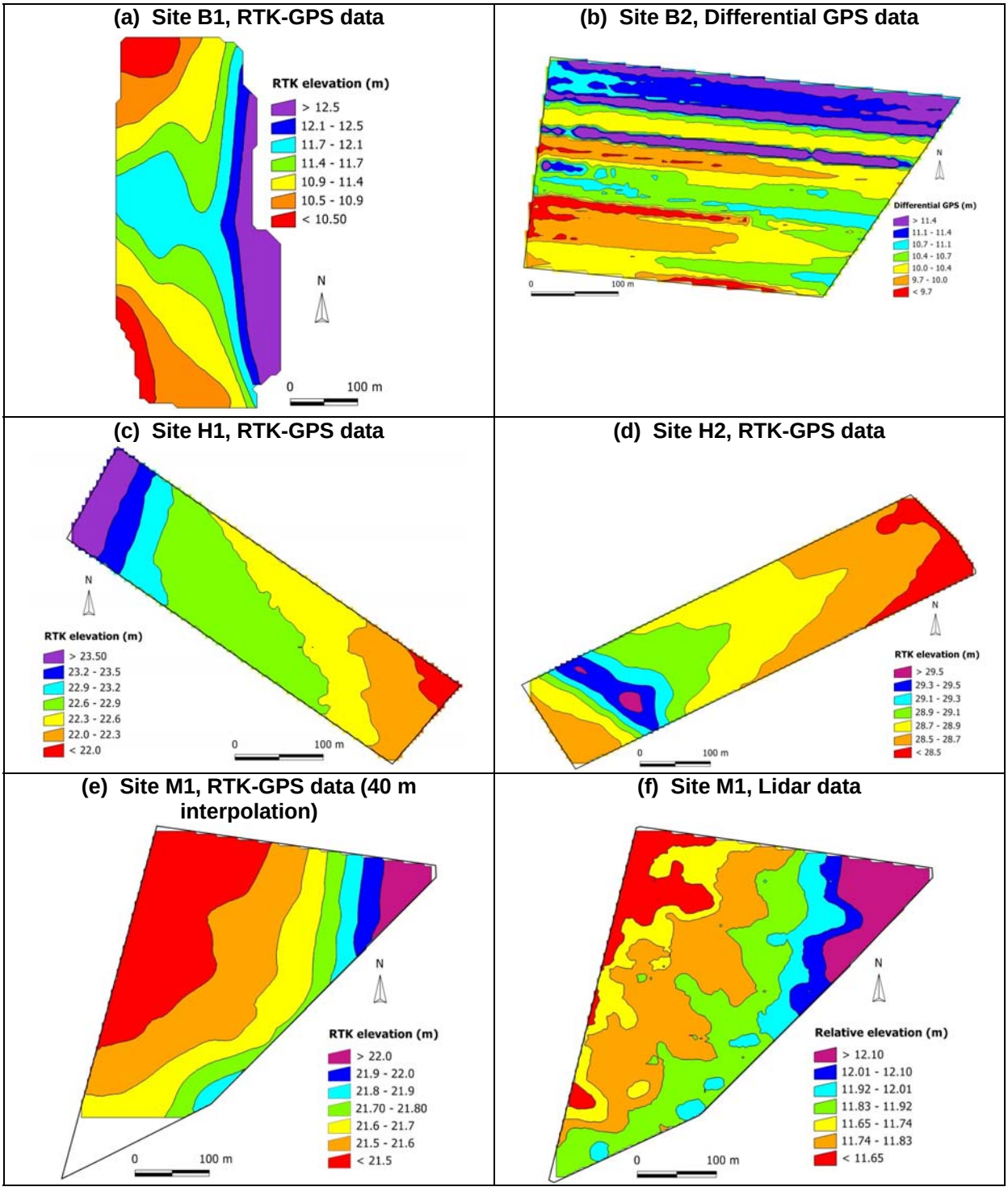


Figure 4.9. Paddock elevation derived from differential GPS, RTK-GPS, and Lidar data from the different study sites.

(a) Site B1: RTK-GPS data collected after 2010 harvest on 19 September 2010.
(b) Site B2: Differential GPS data collected before planting on 31 March 2010.
(c) Site H1: RTK-GPS data collected after 2009 harvest on 23 September 2009 by T. Parker, Northern Gulf NRM, Mareeba.
(d) Site H2: RTK-GPS data collected after 2009 harvest on 23 September 2009 by T. Parker, Northern Gulf NRM, Mareeba.
(e) Site M1: RTK-GPS data collected after 2010 harvest on 6 May 2011.
(f) Site M1: 1 km^2 Lidar data supplied by Queensland Department of Environment and Resource Management and used with permission.

Each of the study sites has been laser leveled, but it has not always been easy to remove the excess water from individual paddocks because some of the farm drainage systems fill up with stormwater runoff in the wet season and may take weeks to drain away. Rainfall frequency and inadequate drainage infrastructure through the 2010 harvest and subsequent wet season (2010-11) were such that the whole of site H2, and a section of site M1, did not dry out sufficiently to allow access for crop harvesting equipment, and the crops in the wet areas were stood over for harvest in 2011.

In September 2009, sites H1 and H2 were EM38 mapped by T. Parker, Northern Gulf Resource Management Group, Mareeba, as part of a comparison of the efficacy of Veris 3100 and EM38 methods to detect soil-related patterns in the paddocks (Di Bella *et al.* 2010). At the same time an RTK-GPS topographic survey was carried out with a typical pass to pass vertical accuracy of 5 cm and a repeatable accuracy of approximately 10 cm (Fig. 4.9c, d).

Towards the end of the project, the commercial soil ECa suppliers in the Burdekin and Mackay districts added RTK-GPS facilities to their Veris 3100 units and detailed elevation data became available for site B1 after the 2010 harvest (Fig. 4.9a). Site M1 was RTK-GPS surveyed on 6 May 2011, but the standing ratoon crop precluded data collection along 10 m run spacings, as is the project's protocol for collecting GPS elevation data during soil ECa mapping operations. The map shown in Fig. 4.9e was constructed from interpolated RTK-GPS elevation data collected from along the headlands around the perimeter of the crop, and from data collected along water winch tow-lines across the paddock and approximately 40 m apart. The southern corner of the paddock was still too wet in May 2011 to allow the passage of a four-wheel drive vehicle carrying the RTK-GPS sensor.

The data points underpinning the study site elevation maps were converted to a continuous surface using the same processing protocol as for the soil ECa data points (Section 4.1.2, above), namely: block kriged by program VESPER, interpolated onto a 7 x 7 m grid and displayed as surfaces.

4.4 CROP YIELD MONITORING AND MAPPING

4.4.1 Harvester monitors

Only fifteen years ago David and Graeme Cox, Burdekin cane farmers, created the world's first sugarcane yield map using a mass flow sensor in a cane harvester (Cox *et al.* 1996). Sugarcane yield monitoring systems evolved globally over the next few years in various companies, with the Cuban company (Techagro^{TM}) developing a distinctive yield monitoring system in North Queensland. AgGuide^{TM} and Techagro^{TM} field tested their yield monitors in the Herbert District in the 2005 harvest (Esquivel *et al.* 2007). By the end of the 2008 harvest there were 20 harvesters operating on the Techagro^{TM} system, and 25 will be operational in the 2011 harvest. To date, over 22,000 hectares have been mapped using these yield monitors in the Herbert District.

A detailed study of the efficacy of a variety of commercially available harvester monitors (AgGuide^{TM}, MTData^{TM} , and Techagro^{TM}) is currently being undertaken in the SRDC-funded Project CSE022, entitled: *A coordinated approach to precision agriculture RDE for the Australian sugar industry.* Some preliminary results were presented by Jensen *et al.* (2010) who concluded that, *"The Techagro unit was found to provide the best result and is a potentially viable sugarcane yield monitor for precision agriculture (with some caution)."*

As a general guide, however, they recommended that the unit be operated at low ground speed and low pour rates (as occurred at all of the BPS001 study sites, except for the plant cane harvest at Site B2), and that further work be undertaken to improve its operation where it may encounter high pour rates in heavy crops, and variations in machine speed in lodged, tangled crops.

4.4.1.1 Using the Techagro™ crop yield monitor

The crops grown at all of the BPS001 Project study sites were harvested in 2009 and, where possible, in 2010 using Techagro™ yield monitors; the growers in the Herbert and Burdekin were already in harvesting groups using this technology, and a unit was provided on a long-term loan from Techagro Pacific to the Mackay harvesting group. The Techagro™ yield data generated at site M1 during the 2009 harvest period was compromised through mechanical failure of the sensor bracket. The 2010 data from site M1 was also of limited value as a section of the study site was harvested by a second machine introduced in an attempt to speed up the overall harvesting process during the unseasonally wet 2010 harvest period.

The nature and operation of Techagro™ harvester yield monitors has been discussed by Di Bella *et al.* (2009) who also explored the usefulness of this yield monitoring system in three case studies in 2007 – 2009 in the Herbert District to identify the site and soil properties that underpin variability in yields from different parts of cane blocks.

- *Case study 1:*

Field observations in the first case study demonstrated that the patterns of high and low sugarcane yields were reproducible from year to year in the same paddock, even though a better growing season increased the overall block yield from 56 tonnes of cane / ha in 2007 to 90 tonnes of cane / ha in 2008.

- *Case study 2:*

The second case study explored the impact on sugarcane yield of waterlogging in a low-lying, poorly drained sodic duplex soil. The site was harvested dry in October 2008. In the two weeks after harvest, however, approximately 150 mm of rain fell and the combination of clay-rich subsoils and poorly functioning farm drainage infrastructure, impeded soil profile drainage so badly that surface water ponded for at least 2 weeks in drains and in the slightly lower parts of the paddock. The areas of poor drainage corresponded directly with the areas of low yields that were identified on the Techagro™ yield map; similarly, the areas of better drained soils on slight rises (relief was less than 2 m over 2 km) were associated with the areas of higher yield on the yield maps. Periods of intermittent waterlogging in the lower areas of poor yield have produced hydromorphic features in the soils such as ferromanganiferous gravel, grey mottles, and manganese stains on cracks in the soil. They indicate that the poor soil drainage conditions have persisted for a long time and that they have most likely caused the areas of poor yields that were detected by the Techagro™ yield monitor.

- *Case study 3:*

In the third case study, the Techagro™ yield monitor detected consistent and appropriate patterns in the crop produced in a simple nitrogen rate trial (24 and 140 kg of nitrogen / ha).

4.4.2 Processed satellite imagery

4.4.2.1 Choice of imagery used

Since the launch in 1972 of the LANDSAT 1 satellite producing images with 75 m spatial resolution, scientists and economists have attempted to predict crop yields from remotely sensed, satellite-based information. The possibility of applying remote sensing approaches to sugarcane yield monitoring was explored by McDonald and Routley (1999), and the first practical work was carried out in the Herbert District (Noonan 1999), and then by Mackay Sugar Ltd in the Central District (Markley *et al.* 2003; Markley and Fitzpatrick 2004) using LANDSAT 4 and 7 (25 m resolution) and SPOT 2 and 4 (20 m resolution) multispectral satellite data.

In order to be able to define sub-paddock scale management zones within sugarcane paddocks, the BPS001 Project Team initially investigated various options to acquire high resolution, georeferenced paddock images. Initially, we considered using CropCam™, a remote-controlled, electric-powered aeroplane with a 2.4 m wingspan and equipped with autopilot, GPS, and digital camera (Moore 2007). The big advantages of the CropCam™ system were that:

- it could acquire images under heavy cloud cover when satellite-borne sensors could not function,
- computer software for compiling georeferenced mosaics of images could be supplied,
- there was a unit available for commercial hire in North Queensland.

It was recognised, however, that whatever image analysis protocols were developed by Project BPS001, they had to have the potential to be applied in a cost-effective manner over the paddocks of a whole cane district, and they had to be based on data that is available in a standard format across districts.

High resolution, multi-spectral data from the IKONOS satellite was chosen as the system for image analysis in Project BPS001 and images of the study sites are shown in Figs 3.2 – 3.6). Remote sensing image providers, AAMHatch Brisbane, offered a multi-site, IKONOS image capture deal of three x 50 sq km areas at a cost of $1,800 per individual capture. Data were made available as 4 band (red, green, blue, NIR) colour mosaiced with a 0.8 m pixel resolution. A successful image capture was regarded as having less than 20% cloud cover and a guaranteed 2 km x 2 km cloud-free zone over the area of interest could be nominated. All data were supplied in a GIS ready format with a user specified projection. Future project developments will explore the potential for using the much cheaper, archived SPOT 5 satellite data.

The dates of image captures over the project study sites are listed in Table 3.1. The last BPS001 study site to be established was Site B2 in the Burdekin; its location was chosen to be on heavy textured soil typical of the Burdekin River Irrigation Area, and close enough to the well-established Site B1 (lighter textured Burdekin Delta soils) to allow a single IKONOS image to cover both sites.

The satellite images were used in conjunction with historic aerial photographs over some of the sites to interpret geomorphological history and soil patterns in the landscape. Differences in reflectances in various spectral bands were processed pixel by pixel to demonstrate patterns in crop growth across paddocks and to allow predictions of crop yield from different crop growth zones. The latter could be summed to derive a prediction of crop yield from the whole

paddock, compared with similar data from a harvester mounted crop yield monitor, and matched to the tonnage of sugarcane delivered to the sugar mill (see Section 6.2, below).

4.4.2.2 Image processing for crop yield monitoring

Using program ENVI software, Robson *et al.* (2010) transformed the crop reflectance values of the georeferenced IKONOS multispectral imagery captured over designated study sites to derive raw normalised difference vegetation index data files (NDVI; Kriegler *et al.* 1969) for each 0.8 x 0.8 m pixel) using the base formula:

NDVI = (NIR - Red) / (NIR + Red)

where: **NIR** is the reflectance measured in the near infrared region of the electromagnetic spectrum (757 – 853 nm),
Red is the reflectance measured in the visible red region (632 – 698 nm).

The raw NDVI data supplied to Project BPS001 was imported into the Manifold GIS system and converted into a 5-zone, equal count, surface mapping layer and colour coded, as for the soil ECa data, with a red colour indicating low NDVI values or reduced crop vigour, followed by yellow, green, pale blue, and dark blue colours indicating increasing crop vigour. To facilitate the calibration of NDVI mapping patterns at selected sites, strategic sampling sites were selected from the NDVI surface mapping patterns using a similar protocol developed for peanuts (Robson *et al*. 2007). To compensate for the 5 m accuracy of non-differential, handheld Garmin GPS units used in the field, strategic sites were located at the centroid of zones of homogenous colour on the mapping layer (equivalent to at least a 40 m^2 area in the field).

The georeferenced crop sampling sites were then uploaded into Garmin GPS units for location in the paddock. A protocol for the sampling of strategically located small plot calibration sites was required because of the difficulties associated with manual harvesting and weighing of material within a standing crop of mature sugarcane. This issue was overcome by carrying out the calibration sampling exercise at the same time as the commercial harvesting of the study site. Careful monitoring of the harvester movement enabled relatively unimpeded access of weighing equipment and project personnel to the georeferenced sites. Ensuring a sufficient safety buffer of unharvested cane rows between the referenced sampling site and the harvester enabled the hand-cutting and weighing of 5 metres of cane row without interfering with the commercial harvesting operation. All millable stalks within the 5 m rows were counted, cut, and weighed. At some of the study sites a sub-sample of six stalks was randomly selected for CCS determination at the sugar mill. The results of the calibration process are discussed in Section 6.2.1 (below).

The H2 site was initially selected for the manually harvested calibration of NDVI mapping patterns to quantify the spatial variability of the plant cane crop (2009 harvest). Further hand sampling of strategic small plot locations evident in on processed satellite were undertaken during the 2010 harvest season namely:

- the first ratoon crops of the B1 and M1 sites;
- the plant cane crop at the B2 site.

Wet conditions in 2010 prevented harvesting of first ratoon crops at site H2 and part of Site M1. Small plot calibration sampling was not undertaken a the H1 site during 2010 as the commercial harvesting of that site coincided with the calibration of yield patterns at the B1 site (16 – 17 September 2010); there were insufficient resources (*i.e.* weigh trailer, labour) to carry out calibration regimes at both sites.

All NDVI data sets from the sites selected for satellite imagery captures were subsequently transformed onto a 7x7 metre grid in program VESPER and linked with other spatial data in the Manifold system to facilitate statistical interrogation (as described for the georeferenced soil ECa data in Section 4.1.2.2, above).

4.5 STATISTICAL ANALYSES

4.5.1 Data sources

The analyses discussed in this section are related to data derived from the 21 – 32 georeferenced individual soil profiles described and sampled from each study site (Section 4.4, above), and from the various data sources that were mapped across each study site such as soil ECa (shallow and deep), normalised difference vegetation index (NDVI) values, crop yield (from processed satellite imagery or harvester-mounted, Techagro™ yield monitors), and paddock elevation.

The individual soil profile data included measurements of soil physical and chemical properties from three sampling depths: topsoil (0–25 cm depth), upper subsoil (40–60 cm depth), and deep subsoil (75 – 100 cm depth).

The soil physical properties included particle-size analyses (percent coarse sand, fine sand, silt, clay; and the derived values for percent total sand = coarse + fine sand, and the percent total fine fraction = silt + clay) that were carried out on all of the soil samples regardless of sampling depth. Gravimetric soil moisture contents were determined on 10 samples collected from each described soil profile at 10 cm intervals from 5 cm to 95 cm depth, and averaged according to standard soil sampling depths. The cone penetrometer resistance of the upper part of the soil profile to a depth of 480 mm and the bulk density of the soil layer 0 – 10 cm deep were determined at each individual soil profile site.

The soil chemical properties, including pH, electrical conductivity, cation exchange capacity, and contents of chloride, exchangeable basic cations, organic carbon, nitrate nitrogen, sulphate sulphur, nitric acid potassium, plant available phosphorus, and extractable silicon were determined on samples of topsoils. A restricted subset of analyses (pH, electrical conductivity, cation exchange capacity, and chloride content) was performed on the upper subsoil and deep subsoil samples.

The process of kriging, using program VESPER (Minasny *et al*. 2005), converted irregular point-based data collected from multiple locations across each site into a continuous grid of georeferenced 7 x 7 m cells. Each of the kriged data sets consisted of hundreds of data points for each study site, thus allowing a statistically predicted value to be extracted from the mapped data at each individual soil profile location for use in analyses with the soil profile data.

All of the analyses were performed using GenStat statistical software (VSN International 2010). In presenting the results in the chapters below, the soil physical properties have been separated from the chemical properties.

4.5.2 Analysis methods

4.5.2.1 Soil properties

To quantify the strength of the association between the interpolated soil ECa (shallow and deep) values and the other soil properties measured at individual profile locations, correlations were calculated between the soil characteristic values and the soil ECa value extracted from the kriged surface from exactly the same 7 x 7 m pixel location. It has been assumed that the extracted kriged values are at an adequate distance from each other to be considered independent. Graphs of soil ECa value versus soil variable (for each soil layer) were produced to determine validity of linear correlations. The data were also averaged across sites for each soil depth to gain an overall figure. However, subsequent analyses indicated that site effects needed to be accounted for, or that the sites should be analysed separately, given the different soil conditions between sites.

4.5.2.2 Crop yield

Correlations were calculated between soil properties (at the profile locations) and crop yield (at the same locations, as extracted from the kriged surface). This was done for each of the five sites for each of the three soil sampling depths.

Principal components analysis was used to investigate whether any particular common factors could explain what was driving the variability in the soil properties at each site. Data were graphed using biplots from principal components analysis using a correlation matrix. These graphs enabled us to investigate visually whether or not the relationships between variables were consistent between sites or within each of the soil layers. They also showed how soil ECa and yield could relate (i.e. correlated or independent) to soil properties.

Crop yield was also regressed against soil ECa to determine if the yield could be predicted from the shallow or deep ECa values. Linear and curvilinear relationships were investigated using linear and exponential regression.

4.5.2.3 Paddock elevation

Exponential regressions were used to determine the relationship between soil ECa and RTK-GPS elevations at sites H2 and B1. Elevation from a Lidar survey was available for site M1, but the data were collected at a time of heavy weed cover over the soil surface, and were not considered to be accurate enough for use in statistical analyses.

4.5.3 Levels of significance

Results were reported as significant at a 95% confidence level ($p < 0.05$). Correlation coefficients (r) have been used to indicate the strength of linear association between two variables. This quantity is independent of the units of measurement, and values can range from -1 to +1. A positive value indicates that as the values of one variable increases, so do the values of the other. A negative association means as the values of one variable increases the values of the other variable tend to decrease. Values between 0.8 and 1 or between -0.8 to -1 indicate strong associations. Values close to zero mean there is no association.

Adjusted R^2 statistics have also been used to indicate the amount of variability within the data that is explained by regression models. This value (expressed as a percentage) is calculated as

$$\text{Adjusted } R^2 = 100 \times (1 - \text{Residual Mean Square}) / \text{Total Mean Square.}$$

Values can range from 0 to 1 (or 0 to 100%). The closer the value is to 1 or 100%, the better the model, as more of the variability within the data set is explained. Ideally R^2 values should be 0.8 (80%) or above. Being the percentage of variance accounted for, the adjusted R^2 is usually a better guide to the fit of the model than the unadjusted R^2, which is the percentage of the sum of squares, or the square of the linear correlation coefficient (r) between response and explanatory variates (Payne *et al.* 2009).

Chapter 5

UNDERSTANDING PADDOCK VARIABILITY: THE SOIL GIS LAYER

5.1 INTRODUCTION

In this and the following chapter, we have set out the findings that have led us to an understanding of the three main data sets, or GIS layers, that underpin paddock variability. One of the important conclusions arising from Project BPS001 is that no one GIS layer, by itself, can be used to describe and explain the variability in crop growth that is observed within sugarcane paddocks. A number of different data sets are needed to define paddock zones that may be used to manage the variability in crops. We found that the most important of the indicators of crop growth variability within a paddock (defined by yield monitors on harvesters or processed satellite imagery) were the positions of contrasting soil properties (defined by soil ECa mapping patterns) within the topographic landscape of the property (defined by digital elevation information).

From a precision agriculture perspective, soil maps are generally not available in sufficient detail to contribute significantly to resolving the origin and management of crop variability within specific sugarcane paddocks across the industry in Australia. If soil ECa maps are to be used as surrogates for detailed soil maps, it is important to know that the ECa maps are stable with time and that repeated ECa mappings of the same paddock produce closely similar maps. The present chapter of this report addresses this issue, and the relationships of soil ECa signals to the actual soil patterns in the field and to the physical and chemical properties of the soils. The combination of paddock elevation and contrasting soil properties as drivers of within-paddock variability in crop growth are discussed in the following chapter.

5.2 STABILITY OF SOIL ECA MAPPING PATTERNS

In order to evaluate the stability of soil ECa maps over time, and to explore the effects of cultivation and subsequent soil settlement on the stability of ECa map patterns, we carried out multiple ECa mappings on sites M1 and B1 during the fallow phase of the cropping cycle using the protocols set out in Section 4.1.1, above.

- *Site M1:* underlain predominantly by poorly drained yellow duplex soils and grey clays, was ECa mapped on:
  - 12 December 2007 on compacted, dry soils after a wet harvest;
  - 24 December 2007 following deep ripping and offset discing to plough out the previous ratoon crop.
  - 18 June 2008 following 1940 mm of rain in 17 significant rainfall sequences including 720 mm in a single event. Multiple discing and spring-tyne cultivations were carried out during the fallow period to control weeds and to disrupt soil crusts prior to the third ECa mapping.

- *Site B1:* underlain predominantly by well drained dark coloured sandy soils and poorly drained dark clays, was ECa mapped on three separate occasions:
  - 15 December 2007 immediately after harvest of the last ratoon crop before plough out;
  - 24 March 2008 during the fallow period after double discing, bed forming, and herbicide applications;
  - 19 July 2009 after harvest of the plant cane crop.

5.2.1 Shallow soil ECa instability over a fallow period

The shallow soil ECa mapping events at site M1, six months apart at the start and end of the fallow period, produced generally similar patterns: low signals from the sandy topsoils of the duplex soils in the eastern parts of the paddock, and more variable responses from the rest of the paddock (compare Figs 5.1a and 5.1b). A linear regression of the shallow ECa values from corresponding georeferenced 7 x 7 m cells of the 2007 and 2008 mapping events was highly significant ($p < 0.001$), but the adjusted R^2 value was only 0.35 (Fig. 5.2a), thus showing that only one third of the variability in the observations could be explained by this regression.

Analysing the spatial stability of soil ECa patterns over time has been facilitated by the preparation of 'ECa difference maps', using an approach akin to, but different from that of Diker *et al.* (2003), where all the grid cell values within a specific contour interval, such as those of Figs 5.1a and 5.1b, have been allocated the same integer value; values within increasing contour intervals have been allocated increasing values from 1 (very low) to 5 (very high). Subtracting the integer values related to the first mapping in 2007 from corresponding, spatially matched values from the second mapping in 2008 shows where there has been nil, little (1 unit), or much (2 or 3 units) change between the soil ECa maps (Fig. 5.1c). In this manner, the differencing technique is capable of illustrating the repeatability of the delineation of zones from soil ECa measurements, and the stability of those zones over time.

The shallow soil ECa difference map (Fig. 5.1c) shows that the shallow soil ECa values over only 32% of the paddock remained unchanged between the two ECa surveys six months apart. A similar, poor correlation was evident in shallow soil ECa signals from the two mappings just over 3 months apart (Table 3.1) at the start and end of the fallow period at site B1 in the Burdekin District (adjusted $R^2 = 0.14$; n= 2,584).

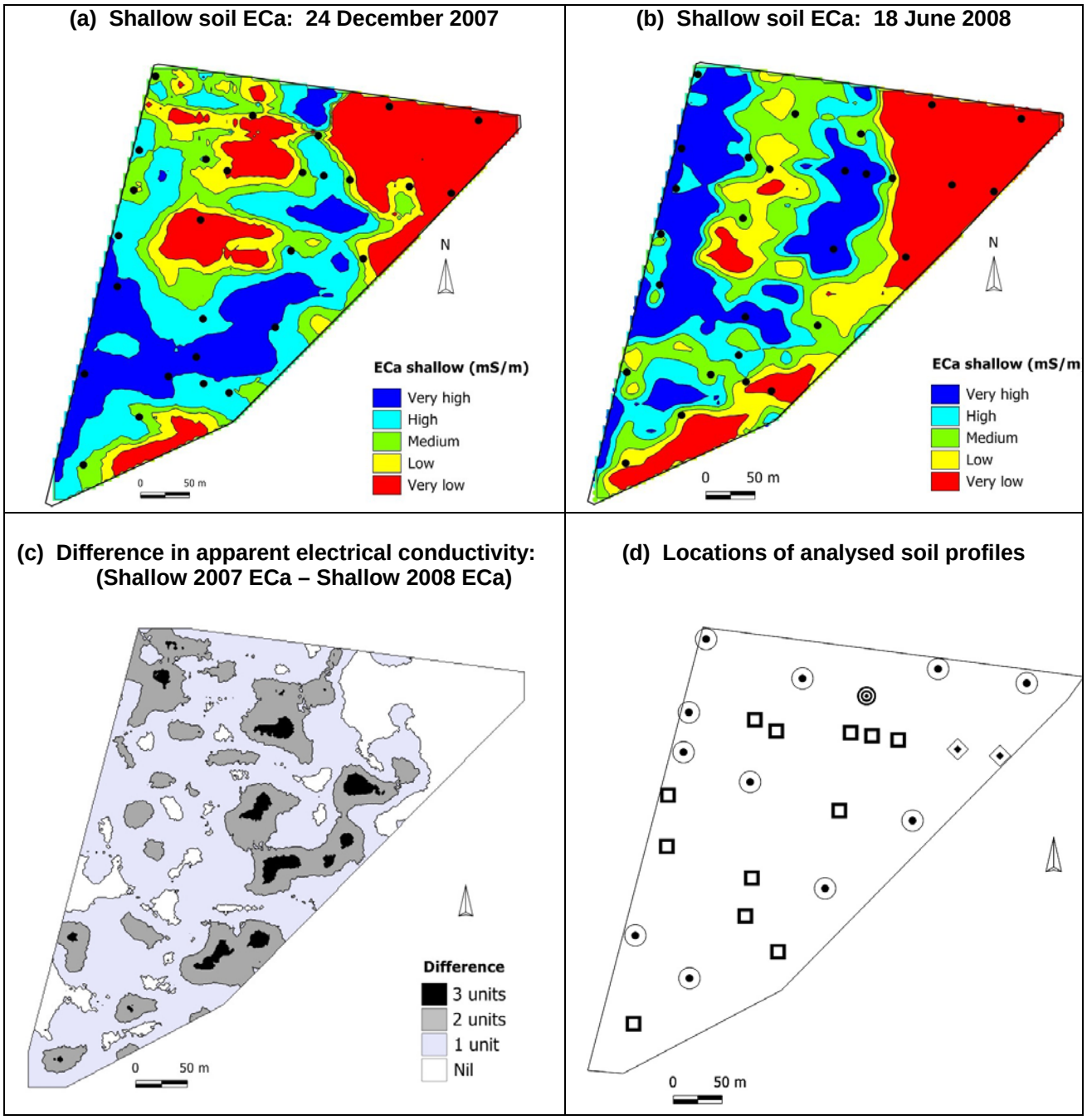


Figure 5.1. Site M1, Homebush: shallow (0-300 mm) soil ECa patterns, soil profile validation sites, and soil types.

(a) patterns produced by shallow ECa mapping carried out after harvest on 24 December 2007.

(b) patterns produced by shallow ECa mapping carried out 6 months later on 18 June 2008, before planting.

(c) areas of difference in spatial patterns of mapping units between the two shallow ECa mapping events.

(d) locations of analysed soil profiles.

Generalised soil profile characteristics (after Northcote 1979) are shown as:

◘ non-structured clay (Uf 6), ◈ yellow earth (Gn 2.4), ⦿ yellow duplex soil (Dy 5), ◎ dark coloured duplex soil (Dd 4).

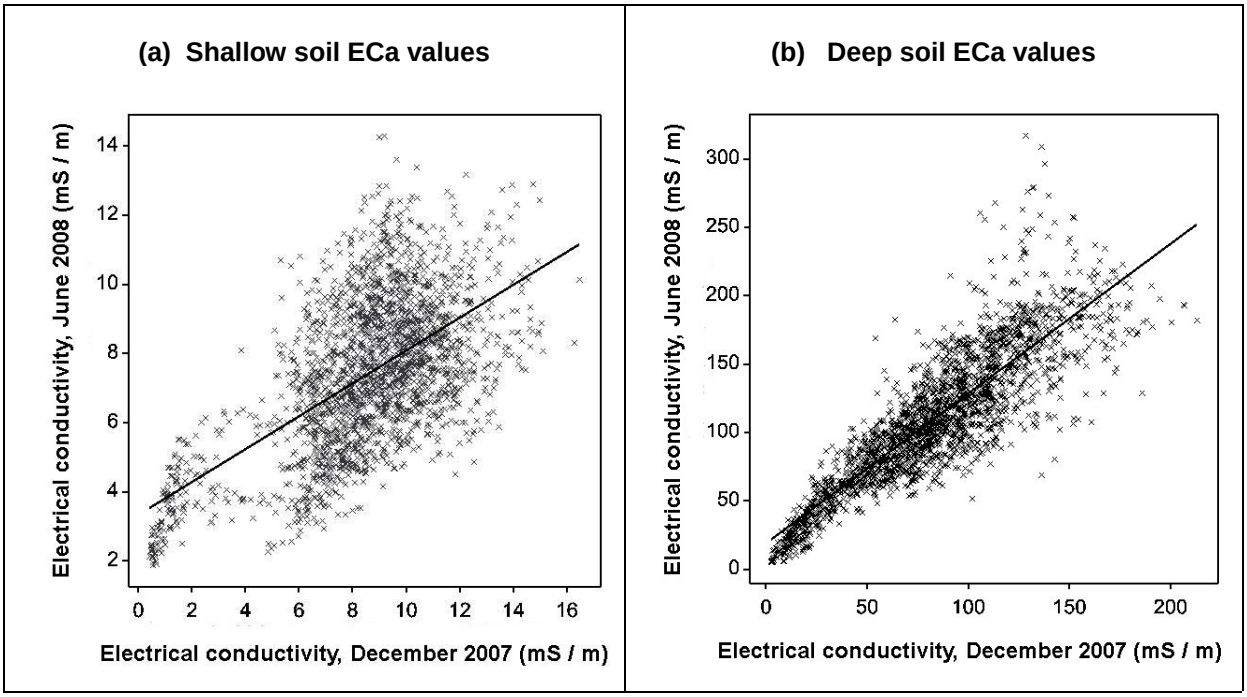


Figure 5.2. Relationships between shallow and deep soil ECa signals from corresponding georeferenced 7 x 7 m cells recorded in two Veris 3100 mapping events within a fallow period at study site M1, Homebush.

Soil ECa mapping was carried out at the start of the fallow period on 24 December 2007 and six months later, just before planting, on 18 June 2008.

(a) Poor relationship between shallow (0–300 mm) soil ECa signals (adjusted $R^2 = 0.35$, n = 2312).

(b) Much better relationship between deep (0–900 mm) soil ECa signals (adjusted $R^2 = 0.75$, n = 2312).

5.2.2 Deep soil ECa stability within a cropping cycle

5.2.2.1 Site M1, clayey duplex soils, Central District

The deep soil ECa patterns, reflecting the nature of the soil properties that lie largely below the cultivation layer in the paddock, varied between the mapping events much less than the shallow patterns did. The deep ECa maps prepared for site M1 at the start and end of the 6 month fallow period have delineated the yellow earth and yellow duplex soils of the northern parts of the paddock, and have highlighted the distribution of the grey clay soils defined by the pattern of high soil ECa readings through the middle of the paddock (Figs 5.3a, 5.3b). The deep soil ECa difference map (Fig. 5.3c) indicates that 59% of the area of the paddock showed no change between ECa mapping events, and that only 6% of the area changed by more than 1 unit.

The relationship between the 2007 and 2008 deep ECa data for site M1 was much stronger than that of the shallow ECa data (Figs 5.2a, 5.2b). A linear regression for deep ECa values was highly significant (adjusted $R^2 = 0.75$, $p < 0.001$; Fig. 5.2b). There was minimal improvement in the adjusted R^2 value when the data were log transformed to stabilise the variance of the data across the data range (Fig. 5.2b), or when a curvilinear relationship was fitted.

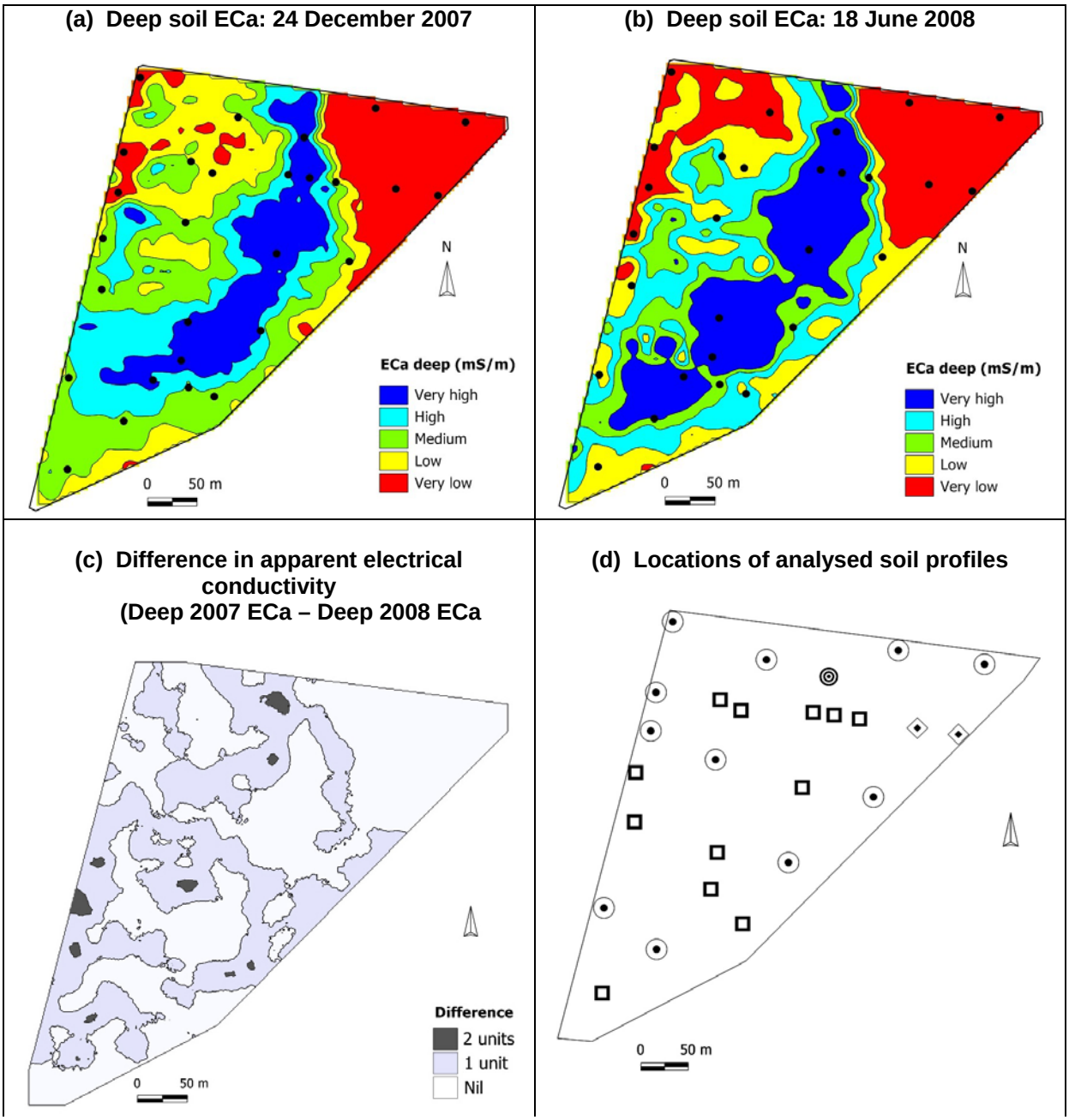


Figure 5.3. Site M1, Homebush: stable, deep (0-900 mm) soil ECa patterns, soil profile validation sites, and soil types.

(a) patterns produced by deep ECa mapping carried out after harvest on 24 December 2007.

(b) patterns produced by deep ECa mapping carried out 6 months later on 18 June 2008, before planting.

(c) areas of difference in spatial patterns of mapping units between the two deep ECa mapping events.

(d) locations of analysed soil profiles.

Generalised soil profile characteristics (after Northcote 1979) are shown as:

◘ non-structured clay (Uf 6), ◈ yellow earth (Gn 2.4), ⊙ yellow duplex soil (Dy 5), ◎ dark coloured duplex soil (Dd 4).

5.2.2.2 Site B1, sandy and clayey soils, Burdekin District

The general similarity of the deep soil ECa readings was reflected in three successive soil ECa surveys at site B1 (mapping events at the start and end of the fallow period in 2008; a subsequent ECa mapping event following harvest of the plant cane crop in 2009). The strong correlations between corresponding georeferenced 7 x 7 m cells of each of the pairs of deep ECa maps convincingly reinforce the concept of stability of deep soil ECa map patterns with time (Fig. 5.4). The strongest correlation in the soil deep ECa maps (adjusted $R^2 = 0.92$; n = 2740) was between the 2008 and 2009 data sets that related to soils that had been allowed to settle after cultivation and to allow good contact between the coulters and the non-compacted soil.

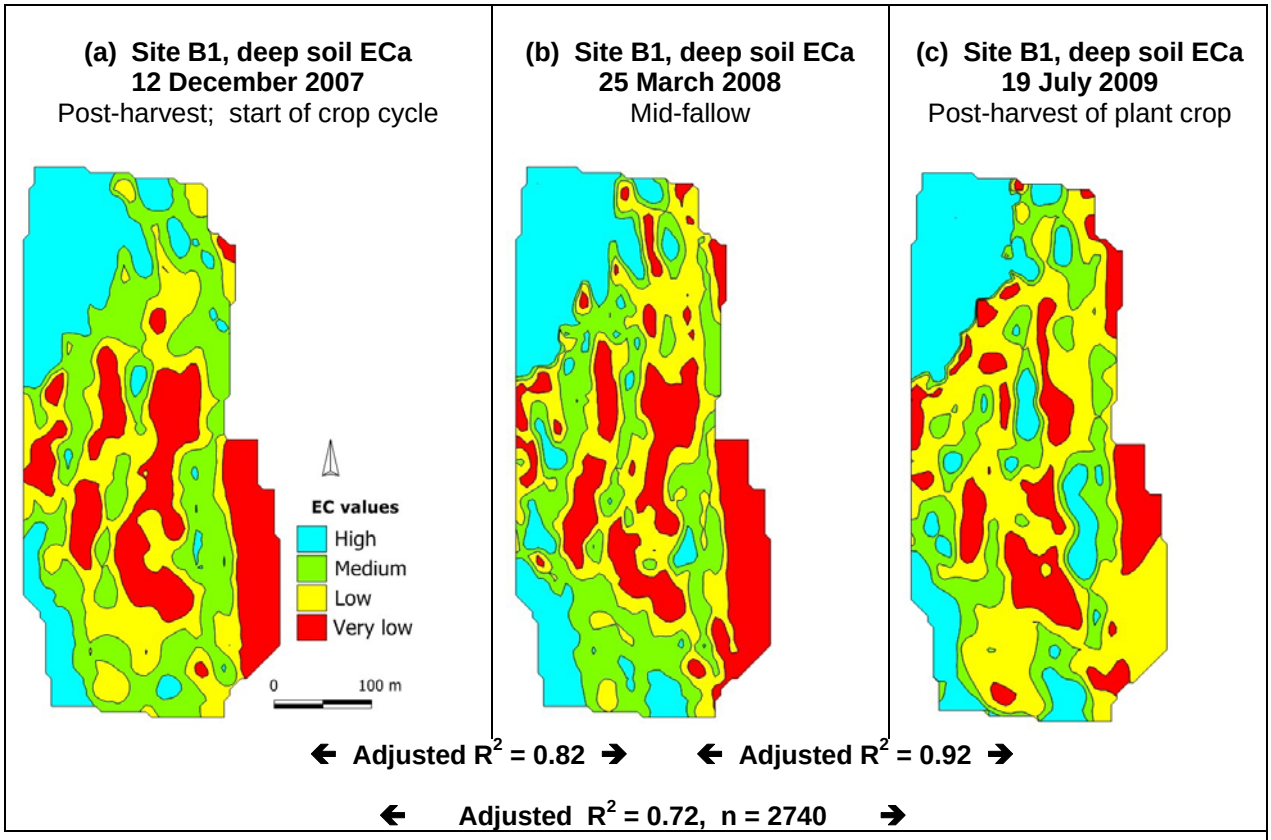


Figure 5.4. Stable, deep (0-900 mm) soil ECa patterns in the fallow and plant crop at Site B1, Brandon.
The correlation coefficients (adjusted R^2 values) are indicated for pair-wise comparisons.

The strong correlations for the deep soil ECa data from site B1 accord with the findings from site M1 that the soil properties influencing the deep ECa values had changed little between the surveys during the fallow period. As with site M1, however, variability occurred in the shallow ECa patterns between repeat mapping events, possibly in response to tillage activity, significant rainfall occurrences, and their influence on Veris 3100 readings through variable coulter penetration.

5.2.2.3 Deep soil ECa stability over a cropping cycle

Commercial soil ECa mapping by Veris 3100 machines began in the Australian sugar industry in 2001, but no repeat ECa mappings of the same paddock had been attempted prior to Project BPS001 (A.J. Crowley, pers. comm.). Therefore, in May 2008 we specifically re-mapped a fallow sugarcane paddock situated 5.4 km west of site M1, Homebush. The entire 8.2 ha paddock had been designated as a Calen Soil (deep, alkaline, sodic, yellow-grey duplex soil) in the 1:100,000 scale soil survey of Holz and Shields (1985). The paddock had been soil ECa mapped five years previously in March 2003 during the fallow phase of the preceding crop cycle.

The shallow soil ECa map patterns were found to have varied considerably in the five years between the March 2003 and May 2008 mapping events. Linear regressions for log transformed data explained only a small proportion of the variability (adjusted $R^2 = 0.25$, $p < 0.001$); the logarithmic transformation was required for the data to meet normality assumptions.

In contrast, however, the deep soil ECa patterns were found to be remarkably stable between the two separate surveys five years apart (compare Figs 5.5a, 5.5b). There was a very strong linear relationship between the log transformed values from corresponding georeferenced 7 x 7 m cells of the 2003 and 2008 mapping events (adjusted $R^2 = 0.86$, $p < 0.001$, $n = 1633$). Again, the trend was for repeatable patterns of zones derived from the deep soil ECa data that are linked to soil conditions.

Hence, we conclude that deep (0 - 900 mm) soil ECa maps produced from the same paddock are likely to show closely similar, stable spatial patterns whether the data has been collected:

- after short intervals (4 - 6 months) during the fallow period between crops,
- at mid-term intervals (16 months) within a cropping cycle, and
- at long intervals (5 years) between cropping cycles.

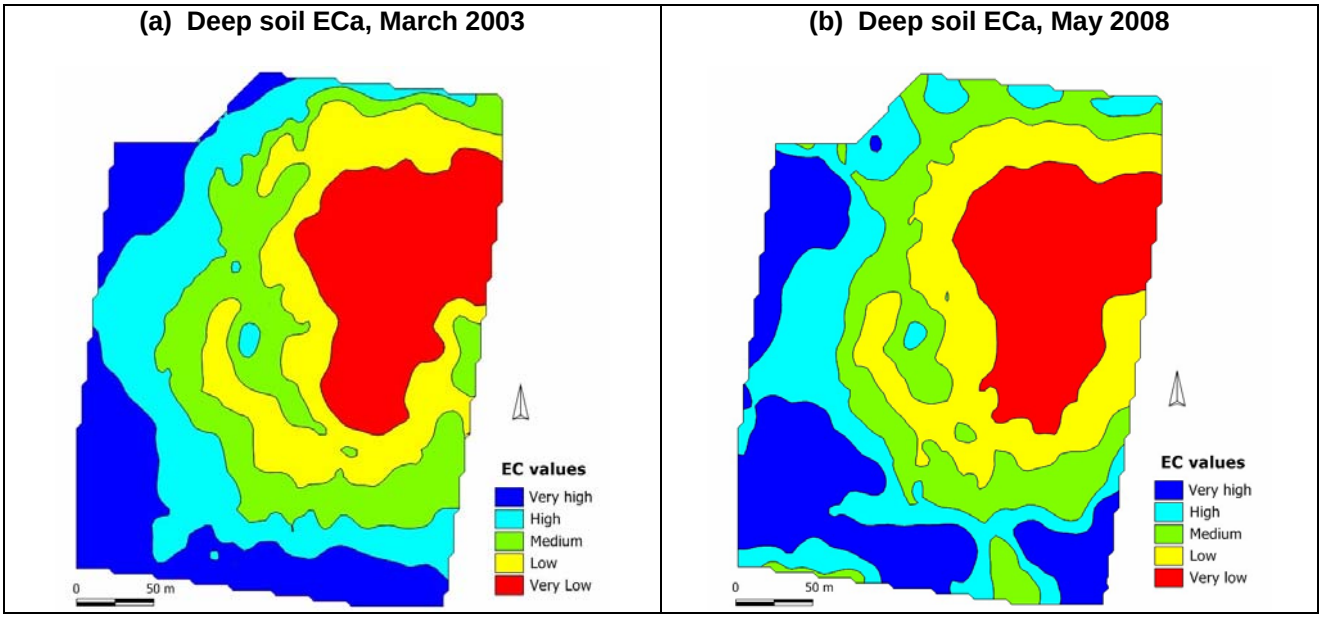


Figure 5.5. Stable, deep soil ECa patterns collected five years apart from the same sugarcane paddock that is located 5.4 km southwest of site M1, Homebush.

(a) Deep soil ECa patterns at the start of a cropping cycle (March 2003).

(b) Deep soil ECa patterns five years later at the start of the next cropping cycle (May 2008). The GPS coordinates for the centroid of the paddock are: (x) 715393.06 (y) 7648516.58, projection MGA94 (55).

5.3 ECa MAP PATTERNS AND SOIL PATTERNS

5.3.1 Soils of contrasting texture at site B1

5.3.1.1 Nature of the site

Site B1 is located on part of an alluvial plain deposited by an ancestral Burdekin River system and is underlain by interbedded sediments that vary in particle size from sandy gravels, to well-sorted sands and fine clays. The site lies about 500 m east of Sheep Station Creek which, in the relatively recent geological past, has been the source of abundant medium – fine aeolian sand that has been blown out of the creek bed and over the pre-existing, heavy textured, alluvial plain. This produced a slightly hummocky topography that has been smoothed by land planning to produce the current topography of the paddock. There is a low, east-west ridge across the middle of the paddock and it forms the headland from which furrow irrigation water is provided to the sugarcane crop (Fig. 4.2a).

Some of the older alluvial clays are evident in the seasonally cracking and non-structured clay soils on the western side of the paddock (soil BUga; Fig. 5.6a) mapping unit where the alluvial plain has not been completely covered by the younger aeolian sands (mapping unit BUfa; Fig. 5.6a). Several soil profiles in this part of the paddock continue to below a depth of 1 m as strongly alkaline (pH 9 – 9.5), medium – heavy clays (Soil profiles 1, 2, 3, 4, 7, 14, 17; Fig. 5.6c); two other soils with heavy clay subsoils occur at sites 14 and 17 (Fig 5.6c). Elsewhere in the paddock, all of the other soil profiles passed at depths of 60 – 85 cm into well-sorted coarse sands with occasional rounded gravel pebbles indicative of an alluvial origin.

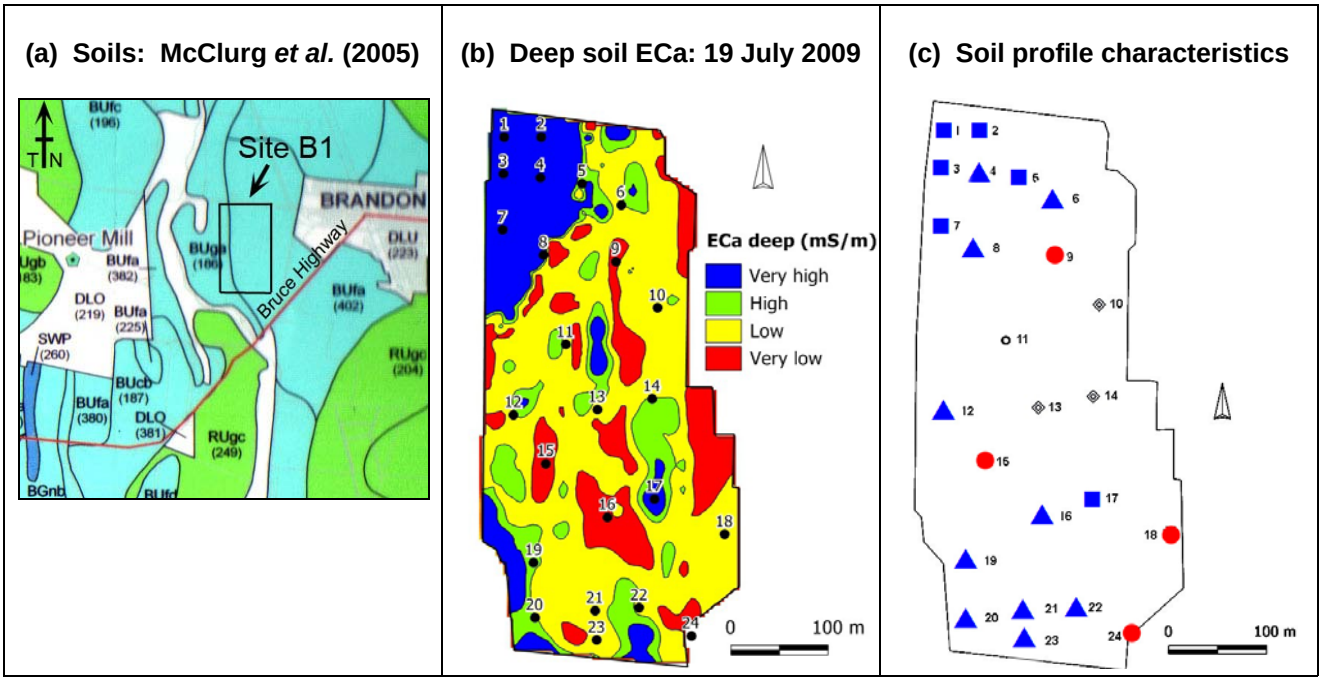


Figure 5.6 The soils of site B1, Brandon.
(a) The most detailed published soil map (1 : 50,000 scale) for the site. Source: McClurg *et al.* (2005).
(b) Deep (0 – 900 mm) soil ECa patterns (17 July 2009) after the plant cane harvest.
(c) Locations of the analysed soil profiles.
Generalised soil profile characteristics (after Northcote 1979) are shown as:
■ cracking clay (Ug 5), ▲ non-structured clay (Uf 6), ● well drained red sand (Uc 5),
◈ dark coloured massive earth (Gn 2.0), O red duplex soil (Dr 4).

The very well-sorted, medium – fine aeolian sand forms a low north-south ridge on the eastern side of the southern half of the paddock in the vicinity of site 18 (Fig 5.6c) where the uniform brown sand continues to below 1 m depth. A similar soil occurs at site 15. The dark coloured massive earth and red duplex soils occur at sites where the aeolian sands overlie the older alluvial clays and there is a gradual (massive earth) or sharp (duplex soil) transition between the sandy topsoil and clayey subsoil.

5.3.1.2 Soil ECa mapping and deep soil ECa patterns

There were strong spatial associations between the patterns of occurrence of the clay soils, especially those of medium – heavy clay at depths of 90 – 100 cm, and high soil ECa responses (compare Figs 5.6b and 5.6c). Another strong association linked the deep sandy soils with very low soil ECa responses. The bulk of the soils in the paddock had a deep sandy substrate that represents a sandy layer (or layers) in the underlying alluvial sediments. These deep sands were moist to wet at the time of ECa mapping and soil sampling, and their depth and moisture characteristics appear to have dominated the low to medium signals of the deep ECa responses of the soils.

Although spatial associations are suggested from a visual inspection of the maps of Figure 5.6, there are too few soil profile descriptions from the paddock to allow statistical correlations to be drawn between the soil profile characteristics and their deep soil ECa signals.

5.3.2 Self-mulching soils at Site B2

5.3.2.1 Nature of the site

Site B2 is located close to Collinsons Lagoon in an area of clay soils that are typical of the heavy textured soils of the older alluvial sediments that underlie the Burdekin River Irrigation Area. The soil profiles of the site bear evidence of three cycles of clay deposition, weathering and soil formation, and erosion which are summarised in Fig. 5.7.

The soils of the first phase (called here, for convenience in the following discussion, the ‘Old Soils’) have formed in a layer of clay (medium to heavy clay field texture; Fig. 5.7a). The clay has weathered to form soils generally found in the western part of the paddock with strongly crusting, hard-setting, non-cracking surface soils with neutral pH and 5% of small (2 – 6 mm) ferromanganiferous (ironstone) nodules; they were underlain by alkaline, strongly mottled brown, red, and grey subsoils. The Old Soils were eroded by shallow streams that incised channels less than 1 m deep (Fig. 5.7b). Ironstone nodules, weathered out of the Old Soils, accumulated on the exposed surface of the truncated, mottled subsoils and were buried by the deposition of a second layer of clay-rich alluvial sediments of light medium clay to medium heavy clay field texture (Fig. 5.7c). The soils that formed in these sediments, the ‘Intermediate Soils’, presented a variety of hard-setting, non-structured and seasonally cracking, neutral surface soils that were generally only weakly crusting (if at all); they were underlain by weakly mottled (brown and grey) subsoils with neutral pH. A subsequent phase of stream downcutting and channel filling resulted in the deposition of sediments of light clay field texture in narrow channels across the floodplain (Fig. 5.7d). These sediments exceed a depth of 1 m and their depth is unknown. Weathering produced soils with uniformly coloured, dark grey, non-mottled profiles, the ‘Young Soils’, with an increasing abundance of lime nodules with depth in alkaline subsoils. The topsoils, like those of the other two soil groups,

were of neutral pH but, unlike the other clay soils at the site that had coarse blocky structure, they displayed a very strongly developed self-mulching surface soil condition, which means that when the topsoil dries out, it tends to form a soft, loose mass of small polyhedral aggregates, like match heads, up to 4 mm in diameter.

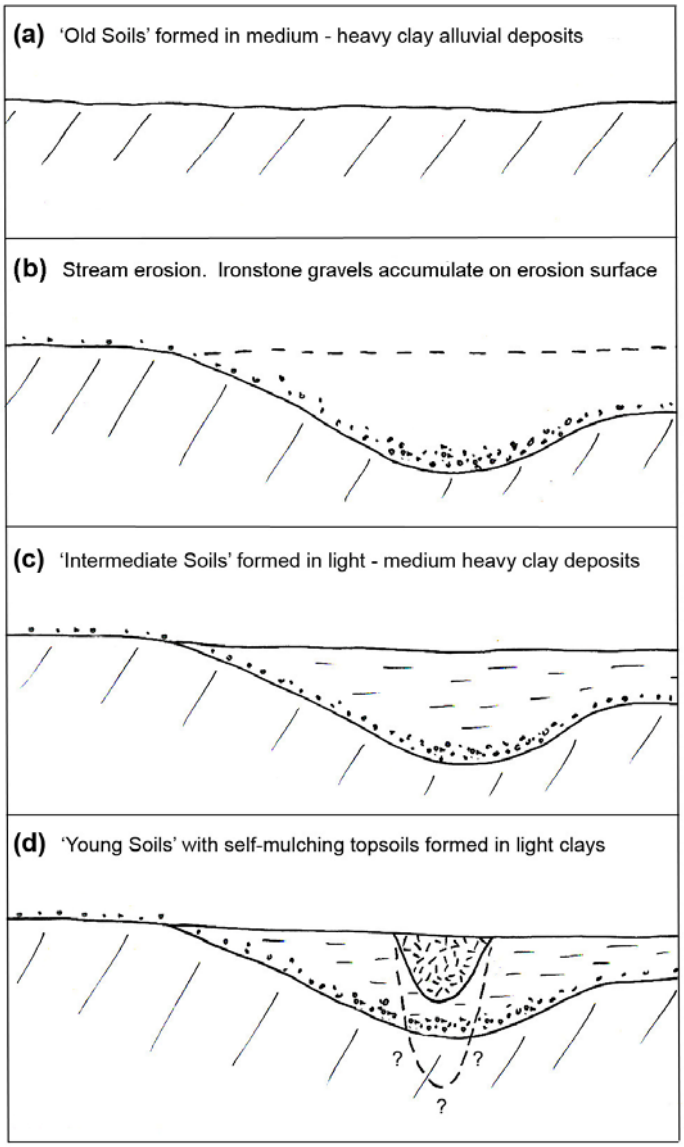


Figure 5.7. Diagrammatic illustration of the main sediment deposition, weathering, soil formation, and erosion events in the geomorphic history of site B2, Brandon.
The sequence begins with the oldest event for which there is evidence in the landscape (a) to the present day (d). Not to scale.

5.3.2.2 Soil ECa mapping and self-mulching soils

The self-mulching Young Soils all lie in a southwest-northeast trending zone, up to 50 m wide, that is evident on satellite imagery (Fig. 3.3b) that represents a young, clay-filled channel that was cut into older alluvial sediments in much the same manner that the stream draining the nearby Collinson's Lagoon has cut into the adjacent, modern alluvial plain. The self-mulching soils react to seasonal rainfall and heavy irrigation events by swelling and creating a low barrier to water movement down the irrigation furrows that run east-west, parallel with the northern and southern paddock boundaries, and across the linear band of self-

mulching soils. A recurring farm management chore is the need to re-grade the slightly raised area of the swelling, self-mulching topsoils to remove the barrier they present to flood irrigation and to sustain the efficiency of the water furrows.

The soil ECa values reflect the distribution of the three soil groups: the Old Soils, exposed at the ground surface on the western side of the paddock, relate to the very low to low signals on both the shallow and deep soil ECa maps (Figs 5.8a, b); the Intermediate Soils found on either side of the band of the self-mulching soils, generally produced medium to high soil ECa responses. The Young Soils displayed very strong shallow soil ECa signals in a relatively poorly differentiated southwest-northeast spatial pattern across the paddock (Fig. 5.8a), and very strong deep soil ECa responses that match the spatial pattern of the self-mulching soils (Fig. 5.8b).

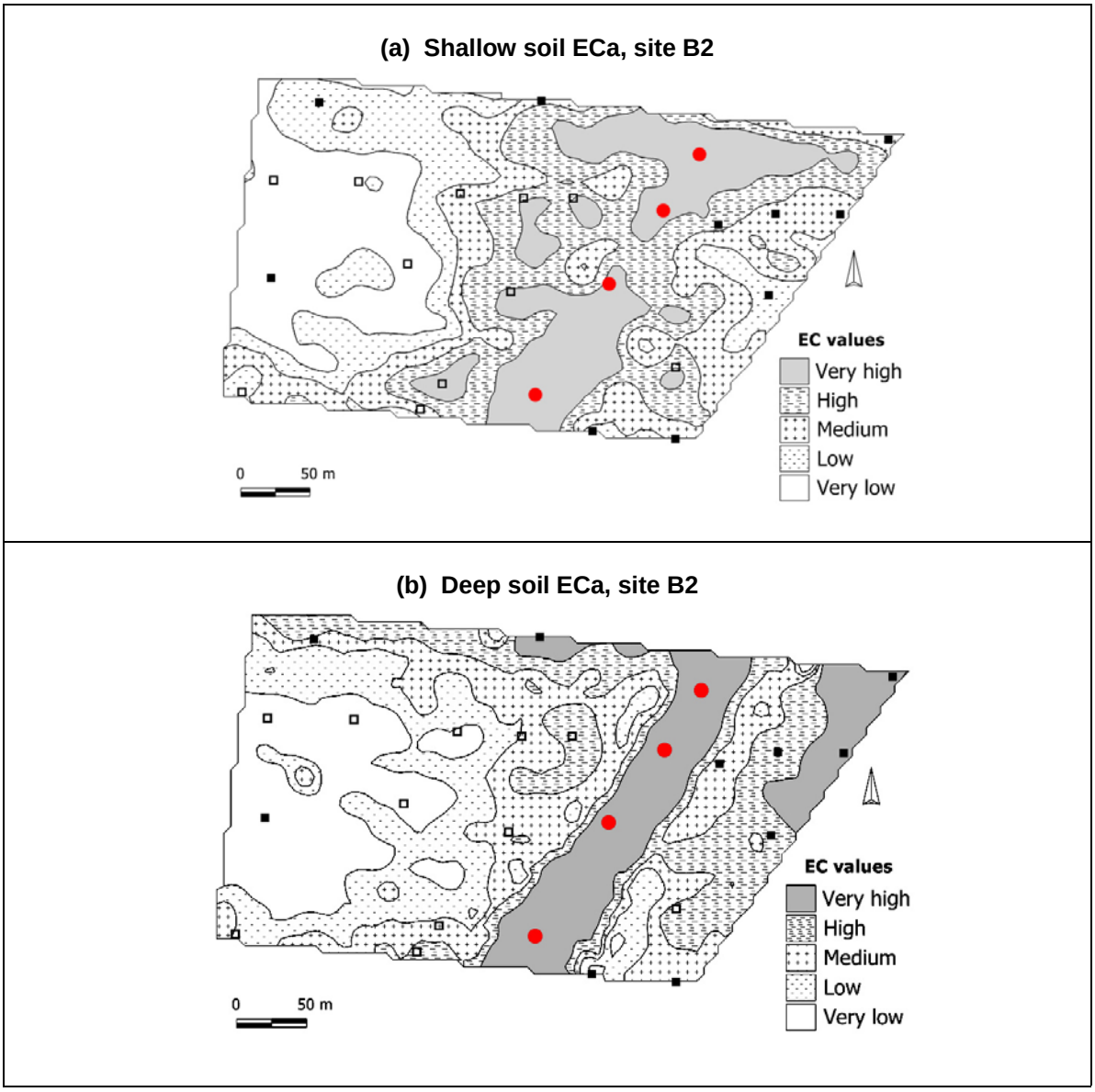


Figure 5.8. Soil ECa patterns and soils of site B2, Brandon; soil ECa data collected on 31 March 2009.
(a) Shallow apparent soil electrical conductivity.
(b) Deep apparent soil electrical conductivity.
Generalised soil profile characteristics (Northcote 1979):
□ non-structured clay (Uf 6), ■ cracking clay (Ug 5), ● self-mulching, cracking clay (Ug5).

The relationship between the field distributions of the soils and the patterns of their ECa responses may be driven by two main factors at this site. First, the regular re-grading of the water furrows in the vicinity of the self-mulching soils has spread some of their distinctive topsoils over the adjacent parts of the paddock, spreading and diluting the influence of the self-mulching soil properties on the shallow soil EC signals (Fig. 5.8a). Second, enhanced sugarcane crop growth on the self-mulching soils (evident on satellite imagery in the paddock adjacent to site B2 in Fig. 3.3b) has responded to the soil properties that are more strongly related to the soil ECa responses within the undisturbed subsoil, and not so much to the properties of the disturbed, cultivated surface soils. The uniform grey colours, strong swell-shrink characteristics, and light clay textures to a depth of at least 1 m in the self-mulching soil profiles suggest that these soils may be saturated more frequently, or for longer periods than the other clay soils at site B2. It is likely that these subsoil properties are driving both the stronger deep soil ECa signals and associated plant growth on the self-mulching clays.

5.3.3 Sodic soils at Site H1

Site H1, Mutarnee, is located on the gently sloping levee bank and floodplain of Crystal Creek which lies adjacent to the northwestern boundary of the paddock. The levee carries well drained, non-sodic, red earth and red duplex soils (with gradual and sharp increases in field texture between the topsoil and subsoil, respectively) that merge down a gentle slope into almost flat-lying, poorly drained, brown and yellow duplex soils with light textured, crusting topsoils and strongly mottled, strongly sodic subsoils (Fig. 3.3c). As in most well fertilised plant cane crops, the crop yield from the harvest on 12 June 2009 was relatively uniform and moderately high over the whole paddock (yield of 563 t, or 103 tonnes of cane / ha). Nevertheless, there were distinctively different growth responses in the following ratoon crop that appeared to be related to patches of soil sodicity scattered through the paddock.

Soil sodicity is evaluated in terms of the fraction of exchangeable basic cations in the soil that is accounted for by sodium, and is measured by soil chemical analysis. Non-sodic soils have exchangeable sodium contents that are less than 6% of the cation exchange capacity of the soil; ‘sodic soils’ have exchangeable sodium percentages of 6–15%, and ‘strongly sodic’ soils have exchangeable sodium percentages exceeding 15% (Isbell *et al.* 1983). Nelson (2001) showed that the sodicity of the 25–50 cm soil layer (corresponding with the upper subsoil sampling interval 40–60 cm of the present study), is crucial to the growth of sugarcane, especially in ratoon crops, with crop yields diminished by 1.5–2.1 t/ha for every 1% increase in exchangeable sodium percentage.

The areas of soil sodicity at site H1 are patchy: for example, the six red soils analysed from the levee of Crystal Creek at the northwestern end of site H1 were non-sodic, as were two other profiles found in a grey earth soil in coarse sandy sediments deposited in a former stream channel crossing the lower part of the site (Fig. 5.9).

There was a clear association of sodic and strongly sodic soils with the higher values of the deep soil ECa signals at site H1 where five of the six strongly sodic soils were found in the areas that returned deep soil ECa values with the highest values (Fig. 5.9). Except for one yellow duplex soil profile found in association with the non-sodic grey earths in a coarse stream channel sand, all of the sodic or extremely sodic soils were found in areas of medium to very high deep soil ECa responses; none were found in the areas of low deep soil ECa signals.

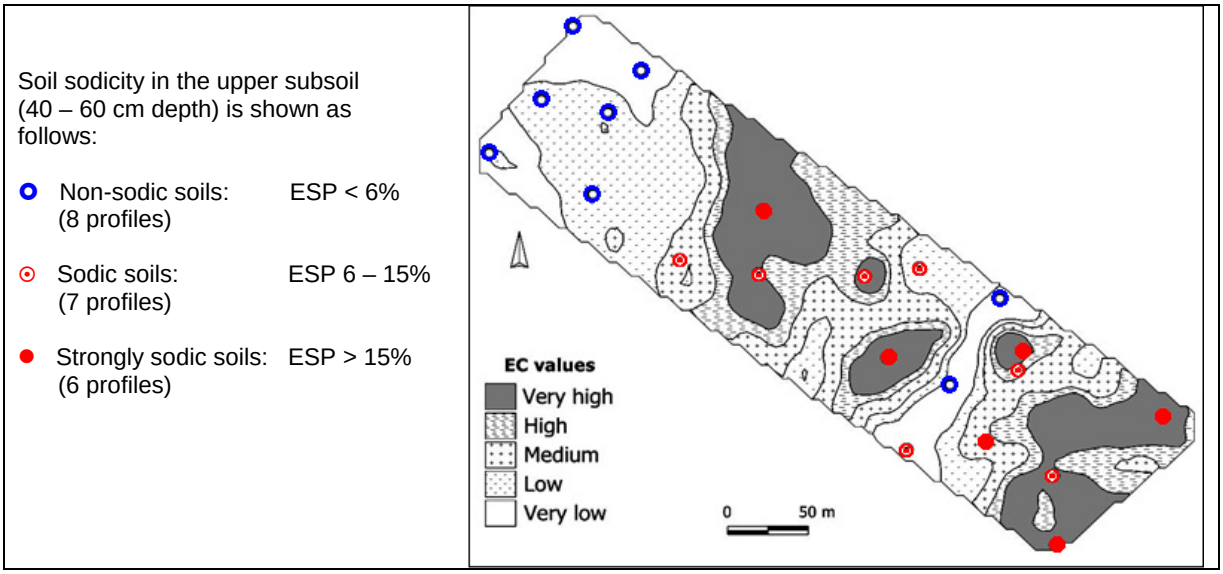


Figure 5.9. Deep apparent soil electrical conductivity and the severity of soil sodicity in the upper subsoil (40–60 cm depth) of the 21 analysed soil profiles at site H1.

Field observations made 10 weeks after the plant cane harvest (22 August 2009) confirmed vigorous ratoon growth (tillers 60–80 cm long) in the non-sodic, red levee soils and grey earths. Extensive areas of diminished growth (such as bare patches, or tillers, if evident, rarely longer than 30 cm) were restricted to the sodic and extremely sodic soils that lay at elevations of 1.0 – 1.5 m below the crest of the stream levee. Very high exchangeable sodium percentages of 24–29% were found in the upper subsoils of the areas of highest deep soil ECa (Fig. 5.9); extremely high exchangeable sodium percentage values of 36 – 52% were found in the deep subsoils (75–100 cm depth) at these sites.

While the poor ratooning of the crop may be attributed to other causes such as cane grub damage, the high exchangeable sodium percentages of the underlying soils demonstrate a link between the deep soil EC map patterns, field properties of soils, and crop variability.

5.3.4 Partly stripped and buried soils at Site H2

5.3.4.1 Nature of the site

Site H2, is located in the Lannercost area, Ingham, on an ancestral floodplain of the Herbert River. A low, red, sandy ridge, which is probably a remnant of an old channel sand deposited by a stream traversing the clayey soils of the floodplain, lies close to the southwestern side of the sugarcane paddock (Fig. 5.10a). Medium–heavy clay soils lie to the northeast of the ridge, in an area that had been a shallow, poorly drained depression under cattle grazing, prior to tree clearing and development of the land for sugar cane production within the last 20 years. The topography has been significantly modified by laser-leveling. A substantial part of the topsoil of the sandy ridge has been removed and spread nearby in the paddock, and the former depression has been infilled, mainly by using heavy clay soils from an adjoining paddock.

The spatial pattern of the shallow soil ECa responses in the topsoils was variable, but there was an identifiable spatial matching with the northern margin of the infilled depression evident on the satellite image (Figs 5.10a and 5.10c). The pattern of the deep ECa signals was quite strongly related to the distribution of the sandy and clay soils, as detected by 1:5,000

scale conventional mapping (Figs 5.10b and 5.10d), which were both related to the shape of the infilled depression evident on a high resolution satellite image (Figs 5.10a and 5.10d). The match in soil patterns has been confirmed by detailed description and analysis of 32 soil profiles in the paddock (Fig. 5.10d).

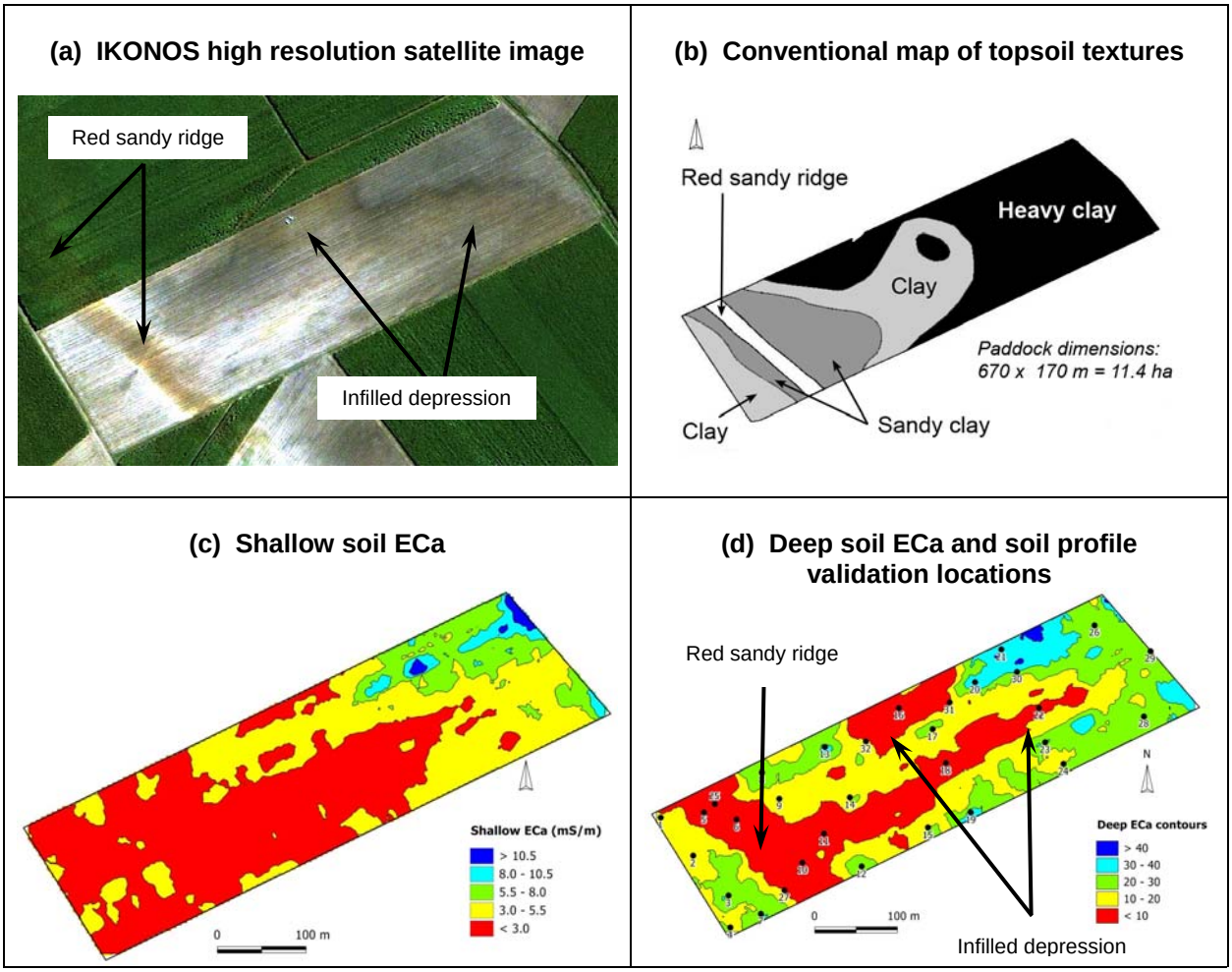


Figure 5.10. Satellite imagery, conventional soil mapping, and soil ECa mapping at site H2, Lannercost.

(a) High resolution IKONOS satellite imagery (1 m resolution; captured on 13 June 2008 after cultivation and before planting) showing the red sandy ridge and infilled drainage depression.
(b) Extract from a conventional soil map at 1:5,000 scale showing the distribution of topsoil textures (source: A.W. Wood, Sucrogen Ltd, Macknade).
(c) Shallow (0 – 300 mm) soil ECa responses to Veris 3100 mapping on 12 May 2008.
(d) Deep (0 – 900 mm) soil ECa responses to Veris 3100 mapping on 12 May 2008 showing the locations of soil profile verification sites (•).

5.3.4.2 ECa mapping and paddock history at site H2

As recently as July 1977, site H2 was poorly drained cattle grazing land whose soils became waterlogged in most wet seasons. The area was unsuitable for sugarcane cropping which was a prominent land use to the west and southeast of the site; the natural drainage of the whole farm was towards the southeast through the eastern part of the site (Fig. 5.11a). Aerial photography in September 1988 shows that a drain had been installed to the north of site H2, and farm drainage was through a systems of drains and a wetland to the southeast (Fig. 5.11b). Part of the land underlying site H2 was still a shallow depression and an ephemeral swamp in most wet seasons.

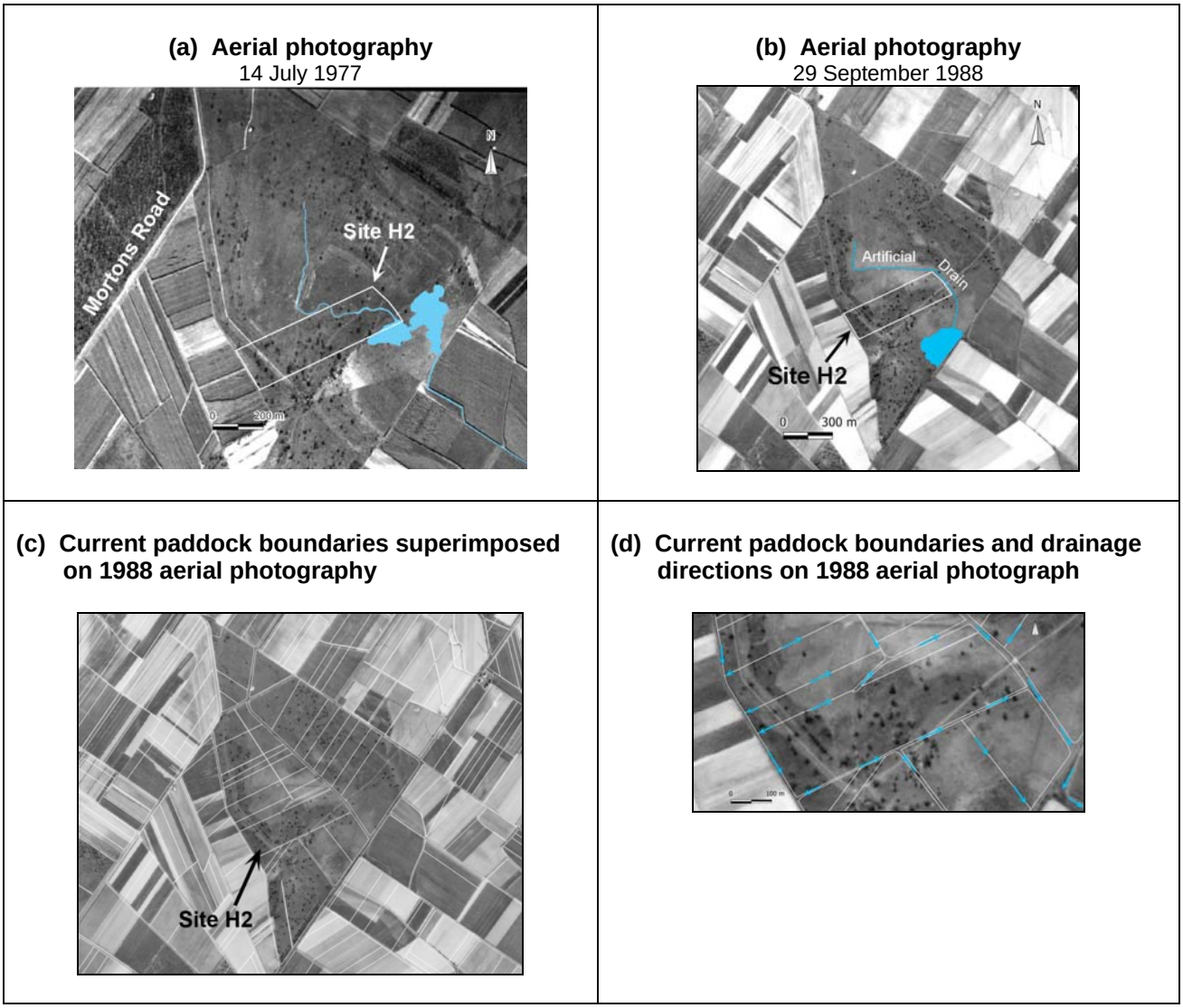


Figure 5.11 The land around Site H2 was cattle grazing land and too wet for growing sugarcane until shallow depressions were infilled and an integrated farm drainage system was developed in the early 1990s.

Aerial photographs supplied by the Queensland Department of Environment and Resource Management.

(a) Sugarcane land surrounding grazing land at site H2 as on 14 July 1977. The ephemeral drainage of the area is shown in pale blue.

(b) Farm drainage patterns over the land near site H2 as on 29 September 1988. The ephemeral drainage of the area is shown in pale blue.

(c) Current paddock boundaries have been superimposed over the georectified 1988 aerial photograph.

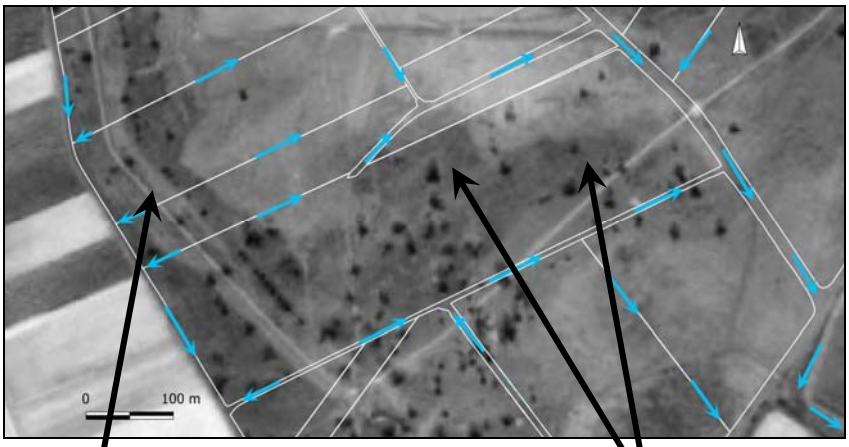
(d) Current drainage (blue arrows) is confined largely to the paddock headlands.

The grazing land around site H2 was cleared during 1993 – 1994, extensively land-formed, shallow depressions infilled, red sandy ridges scalped, an integrated farm drainage system developed, and sugarcane planted into new paddocks. The current paddock boundaries have been superimposed over a georectified 1988 aerial photograph in Fig. 5.11c. Drainage still remains towards the southeast and southwest by way of shallow drains in headlands along most paddock margins (Fig. 5.11d).

An enlargement of part of the 1988 aerial photograph over site H2, with the current paddock boundaries superimposed, is shown in Fig. 5.12a. The deep soil ECa map patterns detected on 12 May 2008 are superimposed over the same image in Fig. 5.12b.

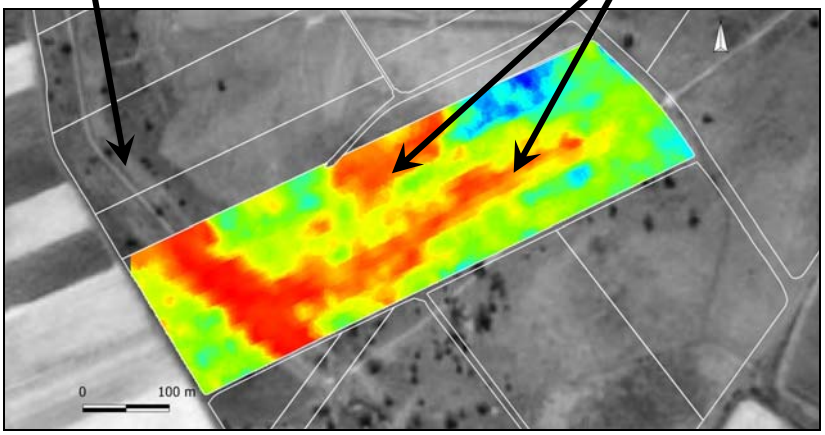
The soil ECa mapping has drawn out details of the fundamental nature of the soils that relate to land characteristics that predate the conversion of the study site from cattle grazing to sugarcane production. Some of the soils have undergone significant modification (partial scalping or burial) in the ensuing land use changes, yet the broad features of their profile characteristics, probably reflecting their pedogenetic processes, were still evident in the patterns of the deep soil ECa signals collected 20 years after the major land disturbance had occurred. It is likely, then, that Veris 3100 mapping has the potential to generate farm maps incorporating aspects of landscape history relevant to current land management decision making.

(a) Current paddock boundaries and drainage directions superimposed on 1988 aerial photograph



Road on crest of red sandy ridge

Infilled former drainage line or ephemeral swamp



(b) Deep soil ECa patterns superimposed on 1988 aerial photography

Figure 5.12. Spatial patterns of geomorphic features evident in the landscape before extensive land-forming operations to develop grazing land for sugarcane production are associated with spatial patterns in deep soil ECa collected after 20 years of sugarcane production at site H2.

(a) Current sugarcane paddock boundaries and drains have been superimposed on a geo-rectified aerial photograph taken on 29 September 1988. Short blue arrows indicate current drainage directions.

(b) Deep soil ECa mapping on 12 May 2008 reveal lower responses on the red sandy ridge and in the sandier subsoils of the infilled depression, compared with higher signals from the surrounding clay soils. The colour code for the ECa map units is the same as that in Fig. 5.10.

5.3.4.3 ECa mapping and soil profiles at site H2

Non-saline, heavy textured duplex and clay soils with fairly similar, medium to high soil ECa responses occur over much of site H2. The low ridge towards the south-western margin of the site represents a remnant of a former channel sand deposited by a past stream which traversed the heavier soils of the Herbert River floodplain. The low relief of the site has been significantly modified by land-forming operations over the last 20 years to aid site drainage under sugarcane. The surface soil of a substantial part of the sandy ridge has been removed and spread nearby in the paddock as a fill, producing or enhancing the duplex soil profile trends (Fig. 5.13).

The main morphological and chemical characteristics of the topsoils and subsoils of four soil profiles (two duplex soils and two non-structured clays) from the same deep soil ECa mapping unit are summarised in Tables 5.1 and 5.2. The contrasting topsoil properties have been shaped largely by the thickness and texture of the fill over the undisturbed clayey subsoils. All of the subsoils are remarkably similar, and the soil profiles differ mainly in the thickness of the lighter textured topsoil (or fill) that overlies the clayey subsoils (Table 5.2). The uniformity of the heavy subsoils is reflected in the similarity of their deep soil ECa signals (Table 5.2).

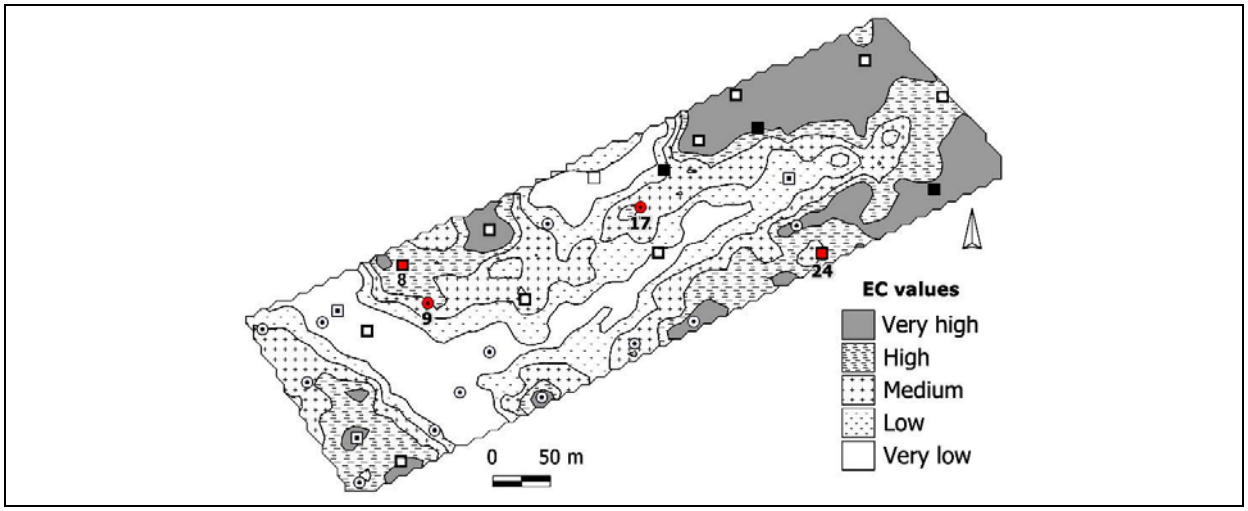


Figure 5.13. Deep soil ECa patterns and soil profile characteristics at site H2, Lannercost, showing locations of analysed soil profiles.
Generalised soil profile characteristics (after Northcote 1979) are shown as:
☐ uniform sand (Uc 5), ⊡ uniform loam (Um 5), ◘ non-structured clay (Uf 6), ■ cracking clay (Ug 5), ⦿ yellow duplex soil (Dy 3 or Dy 5).
The properties of soil profiles 8, 9, 17, and 24 (coloured symbols) are listed in Table 5.1 (topsoils) and Table 5.2 (subsoils).

Figure 5.13 shows that different soils may occur in areas with dissimilar soil ECa mapping units. For example, the yellow duplex soils are the main soil type in the area of low soil ECa responses while the non-structured clays are common in the areas of deeps soil ECa signals that are very high.

On the other hand, however, Tables 5.1 and 5.2 demonstrate that while soils with similar deep ECa readings may have similar soil profile morphologies and properties (e.g. profile 9 compared with profile 17, and profile 8 compared with profile 24), it is also possible for soils with different profile morphologies to produce similar deep soil ECa signals (e.g. profiles 9 and 17 compared with profiles 8 and 24). In our experience, this is a common occurrence in soils modified for agriculture through earthworks, and strongly reinforces the point that the

interpretation of a soil ECa map requires verification of the field characteristics of the soils at strategically chosen locations within soil ECa mapping units.

Table 5.1. **Properties of selected topsoils (0–25 cm depth) from site H2, Lannercost.**
The profiles are located on Fig. 5.13.

Profile number (Fig. 7)	Profile type (Northcote (1979)	Veris Deep ECa (mS / m)	Thickness of fill over undisturbed soil (cm)	Field texture *	pH (1:5 water)	CEC (meq/100g)	Organic carbon (%)	P (BSES) (mg/kg)	Exch Ca (meq/100g)	Exch Mg (meq/100g)	Exch K (meq/100g)	Exch Na (%)	Clay (%)
Yellow duplex soils													
9	Dy	18	25	SL	5.1	2.6	1.0	11	1.0	0.5	0.15	2	14
17	Dy	18	28	SL	4.9	4.6	1.1	5	1.4	0.8	0.22	1	28
Uniform, non-structured clays													
8	Uf 6	23	0	LC	5.3	4.2	0.8	7	1.9	1.0	0.14	2	24
24	Uf 6	19	0	LMC	5.1	6.8	1.9	11	3.1	1.3	0.35	1	36

* SL: sandy loam, LC: light clay, LMC: light medium clay.

Table 5.2. Properties of selected upper subsoils and deep subsoils (40–60 cm and 75–100 cm depths, respectively) from site H2, Lannercost.
The profiles are located on Fig. 5.13.

Profile number (Fig. 7)	Profile type (Northcote (1979)	Veris Deep ECa (mS / m)	Depth to clay textured subsoil (cm)	Upper subsoil (40 – 60 cm)					Deep subsoil (75 – 100 cm)				
				pH (1:5 water)	CEC (meq/100g)	Exch Na (%)	Clay (%)	Field texture *	pH (1:5 water)	CEC (meq/100g)	Exch Na (%)	Clay (%)	Field texture *
Yellow duplex soils													
9	Dy	18	45	5.8	5.9	5	3	LMC	6.8	10.7	9	39	MHC
17	Dy	18	45	5.7	10.0	7	12	s LC	6.4	11.7	9	41	HC
Uniform, non-structured clays													
8	Uf 6	23	0	6.2	9.8	1	45	MHC	7.1	13.0	12	46	HC
24	Uf 6	19	0	6.8	4.3	3	29	g LMC	6.8	9.3	7	41	g LMC

* LC: light clay, LMC: light medium clay, MHC: medium heavy clay, HC: heavy clay, s: sandy, g: gritty.

This conclusion reinforces the major finding of Project BPS001 that spatial patterns in one GIS layer by itself (e.g. a soil-related layer) must be interpreted in the light of other site data such as topography, soil profile drainage, and crop yield estimates in improving the processes involved in the selection of strategic sites for the verification of soil characteristics. Such soil verification field work may be carried out at relatively few sites and the choice of their locations will be greatly aided by the patterns derived from a soil ECa survey. If the soil verification work incorporates a stable, deep ECa map layer, it should be quicker and require much less effort and expense to obtain soils information at a spatial resolution comparable to that produced by conventional soil mapping on a closely spaced grid of boreholes across the paddock.

5.3.5 Soils and ECa patterns at Site M1

5.3.5.1 Soil mapping

Most of the northern part of Site M1 (Homebush) had been mapped as the Sandiford Soil (Fig. 3.11), which is a deep, acid to neutral, bleached, mottled yellowish brown, moderately sodic, duplex soil (Hardy *et al.* 2000). In the northwestern corner, however, Holz and Shields (1985) mapped an occurrence of the Mirani Soil, which has profile characteristics similar to those of the Sandiford Soil but the yellow and grey mottled subsoil colour is predominantly grey and has a higher exchangeable sodium content leading to its classification as a Grey Subnatric Sodosol (Hardy *et al.* 2000). The site had previously been laser-leveled to produce a very gentle slope (< 1%) to the west to aid surface drainage (Figs 4.8e, 4.8f).

Eighteen exploratory boreholes, located within 75 m of a 370 m long transect across the pattern of ECa responses (between Profiles 6 and 13; Fig. 5.14), were drilled to a depth of 1 m; another eight boreholes were drilled elsewhere in site M1 (Fig. 5.1d). The field morphological characteristics of the soil profiles, and the results of chemical analysis of their topsoils, upper subsoils, and lower subsoils revealed five distinctly different soil groups. In the absence of data from more soil profiles in the detailed study area, the boundaries between the five soil groups are shown as straight lines on Fig. 5.14. The soil profile characteristics and selected analytical results are listed in Table 5.3.

5.3.5.2 Nature of the topsoils at site M1

The soils changed systematically from east to west down the topographic transect and the characteristics of each groups of soils are summarised in Table 5.3. Their topsoils, however, were remarkably uniform: they were all dark coloured ('black' in the broad colour groupings of Isbell 1996) soils of loam or silty loam texture (as determined by use of a texture triangle; see Section 4.2.1.1, above). The topsoils were all strongly acidic (pH 5.3 – 5.7), were non-sodic (exchangeable sodium percentages less than 6%), had low exchangeable cation contents (1.4 – 8.9 me / 100 g), and had low electrical conductivities (5 – 8 mS / m = 0.05 – 0.08 dS/m). Note that the laboratory-determined electrical conductivities reported in Table 5.3 are in the same units as those used for the apparent soil electrical conductivities determined by the Veris 3100 instrument. The topsoils were of generally low fertility with low organic carbon and exchangeable cation contents, and with marginal plant-available phosphorus contents. It is only the topsoils of Group A that stand out: they contained much more abundant coarse sand (46%) giving these soils a much coarser, almost gritty field texture compared with the other soil groups that contained only a quarter to half this amount of coarse sand.

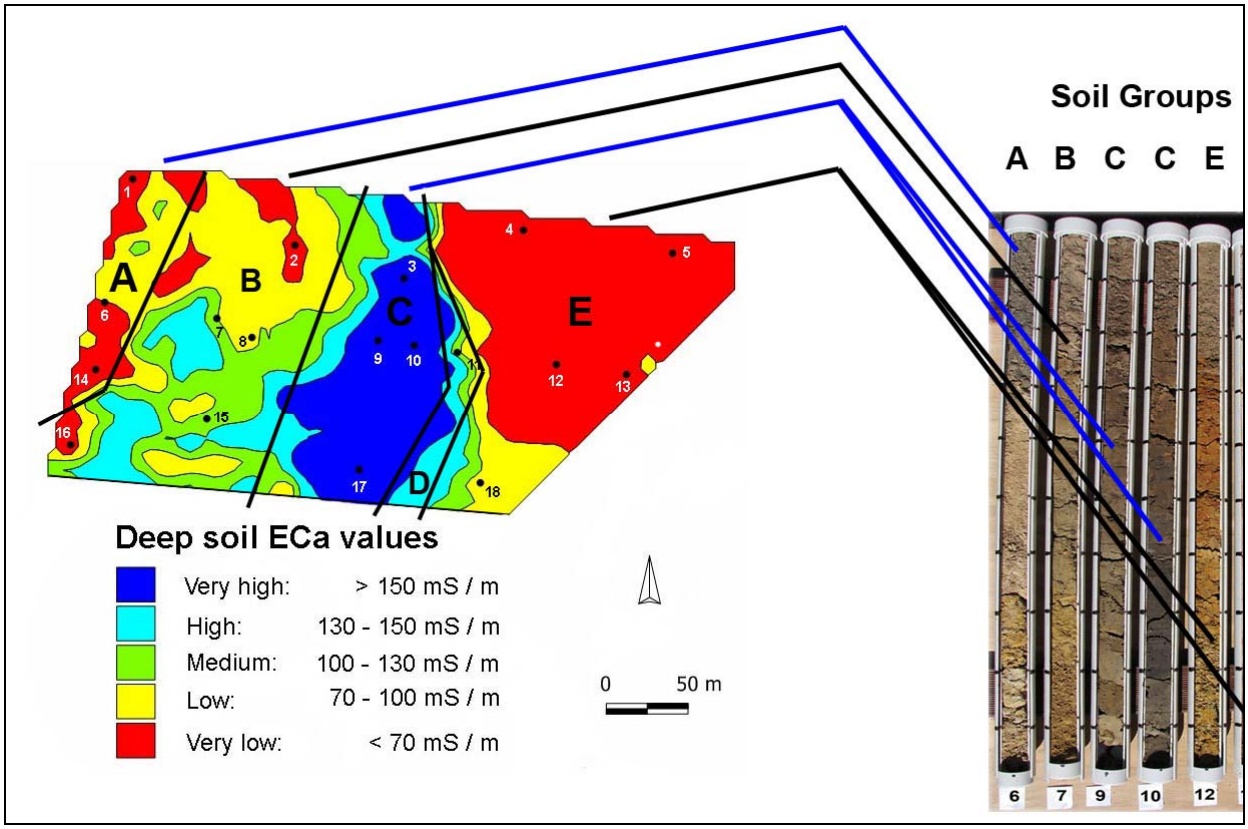


Figure 5.14. Soil profile groups (A – E), based on the field morphology of individual soil profiles and their chemical analysis, are superimposed over a deep (0 – 900 mm) soil ECa map derived from Veris 3100 mapping carried out on 17 June 2008 in the northern part of Site M1, Homebush.
The characteristics of the five soil groups are based on profile descriptions made at the 17 sites shown and are summarised in Table 5.3. The morphology of the soils of Group D is very similar to that of the soils of Group C, but with much higher pH and minor lime nodules in the deeper subsoils.

5.3.5.3 Nature of the subsoils at site M1

The mottled, grey, brown, and black upper subsoils of the transect had similar low electrical conductivities, but were less acidic than the overlying topsoils with soil pH (6.1 – 7.1) ranging from weakly acidic to neutral. The clay-textured upper subsoils contained considerably more clay than the topsoils and were linked with higher cation exchange capacities (up to 21.8 me / 100 g) and greater soil moisture retention at the time of soil sampling (17 – 20 June 2008). The upper subsoils of Groups B and C were weakly sodic (exchangeable sodium contents of 5.7 – 6.3).

The lower subsoils were weakly to strongly alkaline (soil pH 7.2 – 8.4) and lime nodules were evident in the deeper parts of each soil profile included in Group D. Only one Group D soil was found in the detailed study area (Fig. 5.14), but similar soils with lime nodules occurred in a broad arc on the eastern side of, and within the area of high soil ECa signals (Fig. 5.3b), and their analytical data were included in the averaged values for Group D in Table 5.3. The mottled lower subsoil horizons of all of the soil groups were predominantly grey or brown clays with 42 – 51% clay evident in Groups C and D. The higher clay contents were associated with elevated cation exchange contents (up to 27.5 meq / 100 g). The soils of Groups A, B, and C, corresponding with the occurrence of Mirani Soils, all had sodic lower subsoils (exchangeable sodium contents of 9.2 – 11.5%).

Table 5.3. Mean values for selected characteristics of soil profile groups in the Sandiford and Mirani Soil mapping units at Site M1, Homebush.

Soil sampling depths in some profiles may have varied slightly from the standard depths shown.

	Soil Group Properties		Group A	Group B	Group C	Group D	Group E
	Profile numbers included in the soil group (Profile locations are shown on Fig. 5.6)		1, 6, 14	2, 7, 15, 16	3, 9, 10, 17	11, 21, 24 ,25	4,5,12,13,18
	Soil mapping unit (Holz & Shields 1985; Fig. 4.12)		Mirani	Mirani	Mirani	Not mapped	Sandiford
	Shallow (0 – 300 mm) ECa, 17/6/2008	(mS/m)	9	8	10	7	4
	Deep (0 – 900 mm) ECa, 17/6/2008	(mS/m)	53	84	208	127	44
	Drainage status		Very poor: throttle at 1.6 m	Poor	Imperfect	Imperfect	Good
TOPSOIL *0 – 25 cm depth*	Colour	(Isbell 1996)	Black	Black	Black	Black	Black
	Texture - from particle-size analysis (Nat. Comm. Soil & Terrain 2009)		Loam	Loam	Silty loam	Silty loam	Loam
	Coarse sand	(%)	46	12	17	10	16
	Clay	(%)	11	12	25	22	6
	Gravimetric moisture at sampling	(%)	11	14	7	16	12
	Electrical conductivity (1:5 soil:water suspension, mS/m)		7	6	8	5	5
	pH	(1:5 soil:water suspension)	5.7	5.3	5.4	5.3	5.5
	Organic carbon	(%)	0.7	0.9	1.1	1.0	0.7
	Phosphorus	(BSES, mg/kg)	56	53	42	24	30
	Cation exchange capacity	(meq/100 g)	3.4	6.5	8.9	1.7	1.4
	Exchangeable sodium	(%)	2.2	2.3	2.3	1.7	1.4
	Exchangeable aluminium	(%)	7	14	7	16	12
UPPER SUBSOIL *40 – 60 cm depth*	Colour	(Isbell 1996)	Mottled: brown	Mottled: grey	Mottled: black, brown	Mottled: grey, brown	Mottled: brown
	Texture - from particle-size analysis (Nat. Comm. Soil & Terrain 2009)		Sandy loam	Clay	Clay	Clay	Clay
	Coarse sand	(%)	31	9	6	4	9
	Clay	(%)	27	22	53	53	22
	Gravimetric moisture at sampling	(%)	17	14	31	29	13
	Electrical conductivity (1:5 soil:water suspension, mS/m)		4	6	9	5	4
	pH	(1:5 soil:water suspension)	7.0	6.2	6.6	7.1	6.1
	Cation exchange capacity	(meq/100 g)	5.7	13.0	21.8	21.3	9.2
	Exchangeable sodium	(%)	4.6	6.3	5.7	4.3	2.9
	Exchangeable aluminium	(%)	0	6.0	0.4	0.2	7.0
LOWER SUBSOIL *75 – 100 cm depth*	Colour	(Isbell 1996)	Mottled: brown, grey	Mottled: brown	Mottled: grey, brown	Mottled: brown	Mottled: red
	Texture - from particle-size analysis (Nat. Comm. Soil & Terrain 2009)		Clay	Sandy clay loam	Clay	Silty clay	Clay
	Coarse sand	(%)	36	17	5	3	10
	Clay	(%)	30	20	51	42	21
	Gravimetric moisture at sampling	(%)	16	12	30	23	13
	Electrical conductivity (1:5 soil:water suspension, mS/m)		7	5	16	13	5
	pH	(1:5 soil:water suspension)	7.2	7.2	7.5	8.4	7.3
	Cation exchange capacity	(meq/100 g)	8.1	13.5	27.5	26.3	13.1
	Exchangeable sodium	(%)	11.5	9.3	9.2	4.9	5.3
	Exchangeable aluminium	(%)	0	0.8	0	0	0

5.3.5.4 Soils and deep soil ECa patterns at site M1

Deep soil ECa maps of the paddock showed a pattern of soil responses that trended in a broad arc over the block (Fig 5.14). The deep soil ECa signals recorded in the vicinity of the detailed transect showed similar, very low levels (44 – 53 mS / m; Table 5.1) in the sandier soils at both ends of the transect, but much higher levels (127 – 208) in much heavier textured clay soils of Groups C and D (Fig. 5.14).

These results were consistent with those from the extensive field validation of deep soil ECa mapping patterns at the various Project BPS001 sites: low soil ECa values were generally associated with lighter textured soils while the higher soil ECa values indicated heavier texture soils with relatively higher exchangeable cation properties, poorer subsurface drainage characteristics, and the highest gravimetric moisture contents measured immediately after soil description and sampling. Nevertheless, the patterns of occurrence of the actual soils, exposed by site validation boreholes drilled in the field over the three days immediately after the Veris 3100 survey, matched closely with the deep soil ECa patterns detected by the Veris mapping unit in less than an hour's survey in the bare fallow land.

Bulk density and gravimetric soil moisture samples were collected at the intersections of a 40 x 40 m grid at each of the sites immediately after the Veris 3100 survey (Section 4.1.1, above). The processing of these data from site M1 provided valuable insights into the relationships between moisture distribution patterns at the site, bulk density, soil ECa mapping patterns, and paddock topography, all of which have the capacity to seriously influence the variability of the crop yield. Samples for surface (0 - 10 cm depth) bulk density measurements were collected from the 40 m grid intersection locations in loose, cultivated soil as well as from adjacent locations in the wheel tracks formed after one pass of a Toyota Hilux utility, as shown in the foreground of Fig. 3.6c.

To facilitate the comparison of the 40 x 40 m grid data sets with soil ECa data, the raw point data were all transformed into data surfaces and then into contour mapping layers using Manifold GIS software (Fig. 5.15). The 40 x 40 m moisture and bulk density contour layers were very coarse in appearance due to their high content of interpolated data.

Visual assessment of the shallow soil ECa mapping patterns showed very little relation to the surface soil moisture map (data not shown). However, the deep soil ECa patterns (0 – 900 mm) closely resembled the patterns displayed in the soil moisture map (compare Figs 5.15a and 5.15b), despite the fact that the moisture samples were extracted from the soil surface (0 - 100 mm). This may be attributed to capillary action drawing moisture from deeper in the profile. The close matching of patterns between these two data layers supports the notion that soil ECa values are largely driven by soil texture properties, and changes in soil texture properties through the soil profile strongly influence soil moisture content and soil-water availability (Hillel 1998).

A practical outcome from the strong relationship between contrasting moisture patterns and deep soil ECa patterns is the possibility of estimating sub-surface drainage characteristics through soil ECa mapping. This would provide, in turn, an indication of the propensity for compaction in spatially-defined areas of the paddock. However, caution needs to be exercised as soil sodicity and salinity will significantly influence soil ECa readings, and will influence the integrity of a derived sub-surface drainage mapping layer in areas with inherent soil sodicity or salinity issues.

The soil bulk density mapping patterns closely resembled both the deep ECa and soil moisture patterns with the lighter textured soils displaying higher bulk density readings compared to the heavier textured soils (Fig. 5.15c). There was a significant change in bulk density mapping patterns with one pass of a light utility vehicle with different textured soils responding differently to paddock traffic (Fig. 5.15d). This represents yet another factor that may influence within-paddock variability of crop yield, especially in paddocks where vehicle movement is not restricted to GPS-controlled traffic lanes.

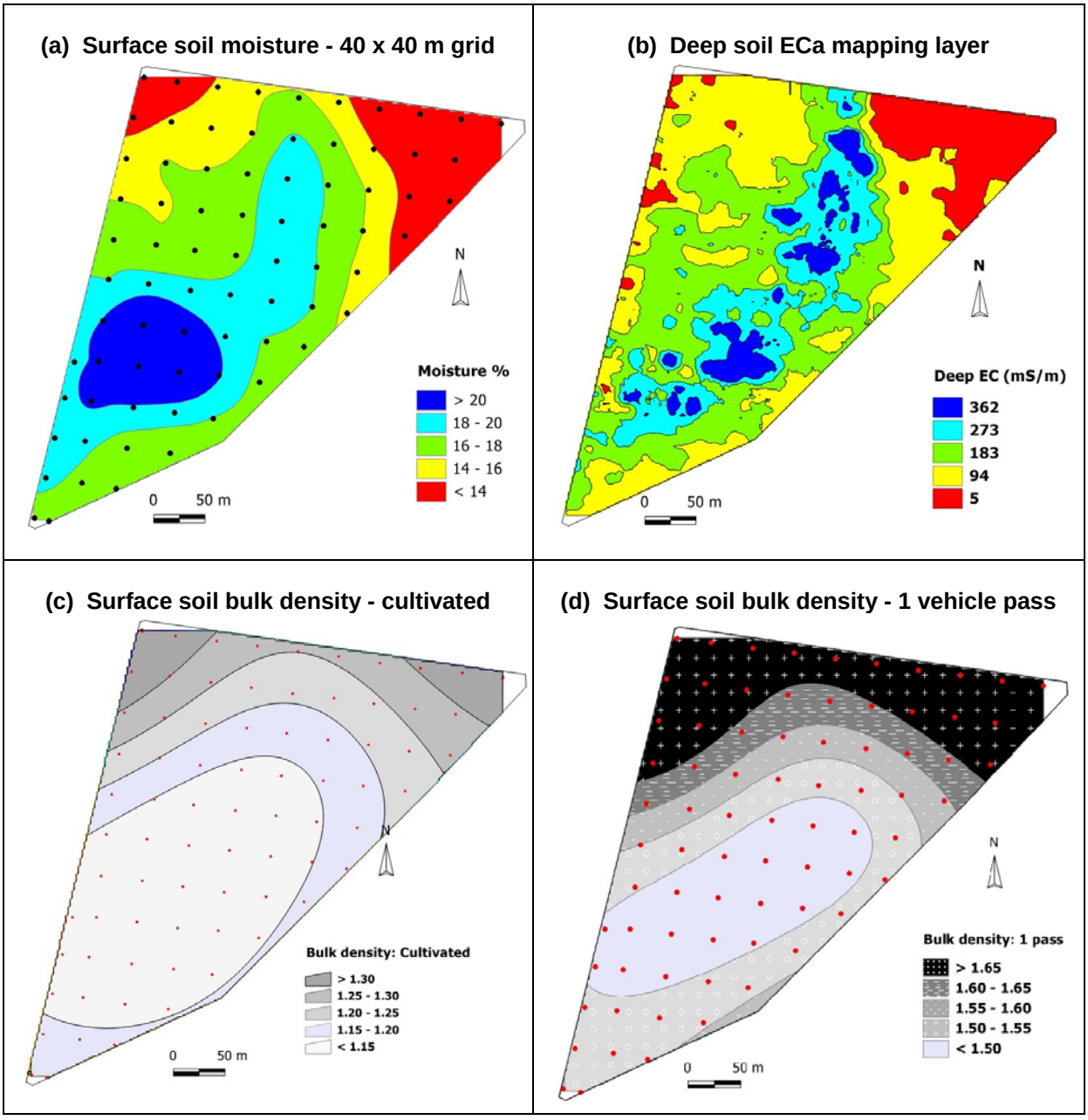


Figure 5.15. Surface soil (0 – 10 cm depth) moisture and bulk density maps made from data collected from intersections of the 40 x 40 m grid superimposed over site M1 at the time of soil ECa mapping (18 June 2008).

(a) Gravimetric soil moisture determined from samples collected on a 40 x 40 m grid over the site on 18 June 2008.

(b) Deep soil ECa survey made on 18 June 2008.

(c) Bulk density of loose, uncompacted samples of cultivated surface soil (0 – 10 cm depth) collected on 19 and 20 June 2008.

(d) Samples collected on 19 and 20 June 2008 from wheel ruts produced by one pass of a Toyota Hilux utility at locations less than 1 m from the loose, uncompacted samples used to prepare part (c) of this figure. Note the difference in scales on parts (c) and (d).

5.4 SOIL ECa DATA AND ACTUAL SOIL PROPERTIES

Components of the very extensive soil analytical data set (130 soil profiles x 3 sample depths x 16 soil chemical analytes, gravimetric soil moisture analyses from 10 soil profile depths, 4 particle-size fractions from 3 soil depths, and surface soil bulk density) were analysed statistically to determine which soil properties were most closely related to the shallow and deep soil ECa signals, and also to the crop yield, at 130 map validation locations across the five study sites. The details of the data set are described in Section 4.2, above.

The stronger associations between soil ECa patterns and the occurrence of soils with particular properties in the field are unlikely to be mere coincidences. In this section we present and discuss some of the more striking statistical relationships that became evident between soil properties and either shallow or deep soil ECa responses.

5.4.1 Soil ECa and soil properties

A large number of statistical analyses were carried out in order to draw out significant associations between soil ECa responses (shallow and deep) and soil properties at each of the soil profile validation locations at each of the study sites. The relationships between shallow soil ECa values and soil properties are summarised in Table 5.4, and between deep soil ECa values and soil properties in Table 5.5.

Data were entered into these tables using the following protocols:

- *strong relationships:* correlation coefficients are shown in shaded cells and bold fonts where the *r* value was greater than 0.8;
- *weak to moderate relationships:* correlation coefficients are shown where the *r* value was between 0.6 and 0.8;
- *poor relationships:* correlation coefficients are shown as x if the *r* value was less than 0.6.

In the tables, we have considered 21 topsoil (0 – 25 cm depth) properties, 14 upper subsoil (40 – 60 cm depth) properties, and the same 14 deep subsoil (75 – 100 cm depth) properties. Data from the three Veris 3100 ECa mapping events for site B1 have been included because each ECa mapping produced consistent, deep soil ECa map patterns that were closely related to one another.

Over 700 correlation coefficients are listed in Tables 5.4 and 5.5, and there is only one soil variable (the **laboratory-determined electrical conductivity of the upper subsoil**) that was moderately to strongly correlated with **deep soil ECa values** across all of the study sites.

5.4.1.1 Shallow soil ECa relationships

The strongest correlations between shallow soil ECa values and soil properties (*r* greater than 0.9) occurred with the laboratory-determined electrical conductivity of the upper and lower subsoils, and with the extractable silicon and exchangeable magnesium contents of the topsoil (Table 5.4).

Table 5.4. Correlations of soil properties with shallow soil ECa values at each soil profile validation site at each study site.

Shaded cells show correlation coefficients (*r*) greater than 0.8, those less than 0.6 are shown as 'x'.

	Study site		B1	B1	B1	B2	H1	H2	M1
	Year of ECa survey		2007	2008	2009	2009	2008	2008	2008
	Median rainfall (mm)		968	968	968	968	1831	2340	1619
Depth	**Soil property**	**Units**							
Topsoil:	pH (1:5 soil:water)		0.79	0.63	0.76	x	x	x	x
0 – 25 cm	Electrical conductivity (lab)	dS/m	0.71	x	x	0.62	x	x	0.60
	Chloride	mg/kg	x	x	x	x	x	x	x
	Organic carbon	%	0.60	x	x	x	x	x	x
	Nitrate nitrogen	mg/kg	x	x	x	x	x	x	x
	Available phosphorus (BSES)	mg/kg	x	x	x	x	x	x	x
	Potassium reserve (Nitric acid)	meq/100g	**0.84**	x	0.61	x	x	x	x
	Sulphate sulphur	mg/kg	x	x	x	x	x	x	x
	Extractable silicon (BSES)	mg/kg	**0.92**	0.65	0.75	x	x	x	x
	Cation exchange capacity	meq/100g	**0.89**	0.66	0.69	0.66	x	0.74	x
	Exchangeable calcium	meq/100g	**0.86**	0.64	0.67	0.66	x	0.76	x
	Exchangeable magnesium	meq/100g	**0.91**	0.66	0.72	0.66	x	**0.84**	x
	Exchangeable potassium	meq/100g	**0.82**	x	x	x	x	x	x
	Exchangeabe sodium	%	0.73	x	0.61	x	x	x	x
	Bulk density	g/cm^3	-0.62	x	x	x	x	x	x
	Gravimetric moisture	%	**0.82**	0.63	0.62	x	x	x	x
	Coarse sand	%	**-0.83**	-0.63	-0.64	-0.71	x	x	x
	Fine sand	%	x	x	x	x	x	x	-0.64
	Silt	%	x	x	x	x	x	x	x
	Clay	%	**0.81**	0.69	0.71	0.64	x	0.61	x
	Silt + clay	%	0.78	0.61	0.64	0.64	x	x	x
Upper	pH (1:5 soil:water)		**0.84**	x	0.78	0.66	x	x	x
subsoil:	Electrical conductivity (lab)	dS/m	**0.96**	x	**0.84**	x	x	x	x
40 – 60 cm	Chloride	mg/kg	x	x	x	x	x	x	x
	Cation exchange capacity	meq/100g	**0.89**	0.60	0.64	0.69	x	x	x
	Exchangeable calcium	meq/100g	**0.84**	x	x	0.72	x	x	x
	Exchangeable magnesium	meq/100g	**0.89**	0.61	0.65	0.63	x	x	x
	Exchangeable potassium	meq/100g	**0.82**	x	x	0.63	x	x	x
	Exchangeable sodium	%	**0.80**	0.60	**0.80**	x	x	x	x
	Gravimetric moisture	%	**0.80**	x	x	x	x	x	x
	Coarse sand	%	**-0.82**	x	-0.62	x	x	x	x
	Fine sand	%	x	x	x	x	x	x	x
	Silt	%	0.78	x	0.61	x	x	x	x
	Clay	%	0.76	x	0.60	x	x	x	x
	Silt + clay	%	**0.80**	x	0.63	x	x	x	x
Lower	pH (1:5 soil:water)		**0.89**	0.55	0.71	0.69	x	x	x
subsoil:	Electrical conductivity (lab)	dS/m	**0.92**	x	0.71	x	x	x	x
75–100 cm	Chloride	mg/kg	0.66	x	x	x	0.60	x	x
	Cation exchange capacity	meq/100g	**0.82**	x	x	x	x	x	x
	Exchangeable calcium	meq/100g	0.79	x	x	0.60	x	x	x
	Exchangeable magnesium	meq/100g	**0.80**	x	x	x	x	x	x
	Exchangeable potassium	meq/100g	0.76	x	x	x	x	x	x
	Exchangeable sodium	%	**0.86**	x	0.79	x	x	x	x
	Gravimetric moisture	%	0.69	x	x	x	x	x	x
	Coarse sand	%	-0.71	x	x	x	x	x	x
	Fine sand	%	x	x	x	x	x	x	x
	Silt	%	0.73	x	x	x	0.63	x	x
	Clay	%	0.78	x	x	x	x	x	x
	Silt + clay	%	0.78	x	x	x	x	x	x

Table 5.5. Correlations of soil properties with deep soil ECa values at each soil profile validation site at each study site.

Shaded cells show correlation coefficients (*r*) greater than 0.8, those less than 0.6 are shown as 'x'.

	Study site		B1	B1	B1	B2	H1	H2	M1
	Year of ECa survey		2007	2008	2009	2009	2008	2008	2008
	Median rainfall (mm)		968	968	968	968	1831	2340	1619
Depth	**Soil property**	**Units**							
Topsoil:	pH (1:5 soil:water)		0.68	0.74	0.67	x	x	x	x
0 – 25 cm	Electrical conductivity (lab)	dS/m	0.71	0.74	0.65	x	x	x	x
	Chloride	mg/kg	x	x	x	x	0.63	x	x
	Organic carbon	%	x	x	x	x	x	x	0.77
	Nitrate nitrogen	mg/kg	x	x	x	x	x	x	x
	Available phosphorus (BSES)	mg/kg	x	0.62	x	x	x	x	x
	Potassium reserve (Nitric acid)	meq/100g	**0.84**	**0.86**	**0.82**	x	x	x	x
	Sulphate sulphur	mg/kg	x	x	x	x	x	x	0.70
	Extractable silicon (BSES)	mg/kg	**0.91**	**0.95**	**0.88**	x	x	x	0.71
	Cation exchange capacity	meq/100g	**0.85**	**0.90**	**0.83**	x	x	x	0.76
	Exchangeable calcium	meq/100g	**0.81**	**0.86**	0.78	x	x	x	0.69
	Exchangeable magnesium	meq/100g	**0.90**	**0.93**	**0.88**	x	x	x	0.77
	Exchangeable potassium	meq/100g	**0.81**	**0.81**	0.79	x	x	x	x
	Exchangeabe sodium	%	0.67	0.78	0.66	x	0.67	x	x
	Bulk density	g/cm^3	x	-0.62	x	x	x	x	-0.64
	Gravimetric moisture	%	**0.86**	**0.88**	**0.81**	x	x	x	0.66
	Coarse sand	%	**-0.81**	**-0.85**	-0.78	x	x	x	x
	Fine sand	%	x	x	x	x	x	x	x
	Silt	%	0.63	0.60	0.63	x	x	x	0.63
	Clay	%	0.75	0.77	0.71	x	x	x	0.70
	Silt + clay	%	0.78	0.77	0.76	x	x	x	0.77
Upper subsoil:	pH (1:5 soil:water)		**0.80**	**0.85**	**0.80**	0.67	x	x	x
40 – 60 cm	Electrical conductivity (lab)	dS/m	**0.93**	**0.97**	**0.91**	0.76	0.74	0.74	0.70
	Chloride	mg/kg	x	0.65	x	x	0.70	x	x
	Cation exchange capacity	meq/100g	**0.85**	**0.90**	**0.83**	**0.83**	x	0.71	0.77
	Exchangeable calcium	meq/100g	0.78	**0.84**	0.76	**0.81**	x	**0.80**	0.73
	Exchangeable magnesium	meq/100g	**0.89**	**0.92**	**0.87**	0.78	x	0.62	0.78
	Exchangeable potassium	meq/100g	0.76	0.78	**0.80**	0.75	x	x	0.75
	Exchangeable sodium	%	0.79	**0.86**	0.72	x	0.74	x	x
	Gravimetric moisture	%	**0.81**	**0.84**	**0.80**	**0.67**	x	**0.80**	**0.81**
	Coarse sand	%	**-0.81**	**-0.84**	-0.78	x	x	-0.69	x
	Fine sand	%	x	x	x	-0.62	x	x	x
	Silt	%	0.79	**0.81**	0.78	x	x	x	x
	Clay	%	0.72	0.74	0.67	x	x	0.64	0.65
	Silt + clay	%	0.78	**0.81**	0.75	0.64	x	0.76	0.66
Lower subsoil:	pH (1:5 soil:water)		**0.88**	**0.93**	**0.89**	0.73	x	x	x
75–100 cm	Electrical conductivity (lab)	dS/m	**0.91**	**0.93**	**0.95**	0.60	**0.82**	x	0.68
	Chloride	mg/kg	x	0.64	0.62	x	**0.80**	x	0.72
	Cation exchange capacity	meq/100g	**0.87**	**0.90**	**0.89**	x	x	**0.82**	0.79
	Exchangeable calcium	meq/100g	**0.84**	**0.87**	**0.87**	**0.82**	x	**0.84**	0.68
	Exchangeable magnesium	meq/100g	**0.87**	**0.89**	**0.89**	0.74	x	0.74	**0.81**
	Exchangeable potassium	meq/100g	**0.84**	**0.84**	**0.85**	0.75	x	x	0.65
	Exchangeable sodium	%	**0.87**	**0.94**	**0.84**	x	0.79	x	x
	Gravimetric moisture	%	**0.80**	**0.81**	**0.83**	x	x	0.70	0.73
	Coarse sand	%	-0.78	**-0.80**	**-0.80**	x	x	-0.61	x
	Fine sand	%	x	x	x	x	x	x	x
	Silt	%	0.77	0.79	**0.86**	x	x	x	x
	Clay	%	**0.83**	**0.87**	**0.85**	x	x	**0.80**	0.71
	Silt + clay	%	**0.83**	**0.86**	**0.88**	x	0.67	0.76	0.66

At site B1, where three ECa surveys had been made, the following soil properties were most strongly related to the shallow ECa signals in all three of the ECa surveys:

- *topsoil characteristics:* pH, extractable silicon, cation exchange capacity, contents of exchangeable calcium, magnesium, potassium and sodium, gravimetric moisture, clay %, and silt + clay %;
- *upper subsoil characteristics:* cation exchange capacity, contents of exchangeable magnesium and sodium;
- *lower subsoil characteristics:* pH.

There were no strong correlations between shallow soil ECa values and any soil properties at site B2 where there was an association with the cation characteristics of the topsoil and upper subsoil.

Remarkably few correlations were found to exist between shallow ECa values and actual soil properties from any depth at the three wetter sites (H1, H2, and M1). The only strong correlation was with the exchangeable magnesium content of the topsoil and shallow ECa values (Table 5.4).

Where correlations occurred between shallow ECa values and the coarse sand content of the topsoils, and sporadically with the subsoils, they were all negative, indicating that the shallow ECa values were more closely associated with the finer components of the soil.

5.4.1.2 Deep soil ECa relationships

Deep soil ECa values were correlated with few, if any, topsoil properties at sites B2, H1, and H2; Table 5.5). On the other hand, however, the deep soil ECa values were moderately to strongly correlated in six out of the seven ECa mapping events (Table 5.5) with:

- *upper subsoil properties:* laboratory-determined electrical conductivity (in all seven ECa surveys), gravimetric soil moisture, silt + clay %, cation exchange capacity, and contents of exchangeable calcium and magnesium;
- *deep subsoil properties:* silt + clay %, exchangeable calcium content, and laboratory-determined electrical conductivity.

The strongest correlations (*r* greater than 0.9) of deep soil ECa values with laboratorty-determined soil electrical conductivity, cation exchange capacity, and exchangeable magnesium and sodium contents in the upper and lower subsoils at site B1 (Table 1). Except for the chloride content and fine sand % of any of the three soil layers analysed at site B1, and for the soil fertility characteristics of the organic carbon, nitrate nitrogen, BSES phosphorus, and sulphate sulphur, all of the other soil properties at each soil depth at site B1 were moderately to strongly correlated with the deep soil ECa signals (Table 5.5).

None of the topsoil properties were correlated with deep soil ECa signals at sites B2 and H2, although the chloride content and exchangeable sodium contents of the topsoils were weakly correlated with deep soil ECa values from the sodic soils of site H1 (Table 5.5). Topsoil moisture, silt %, clay %, and cation characteristics of the topsoils were weakly correlated with the deep soil ECa values at site M1 (Table 5.5).

5.4.2 Multivariate analyses: soil ECa and soil properties

Soil compaction, as represented by physical properties bulk density and coarse sand % emerged from a principal components analysis as the major, overall soil property driving variability in the data. This is due to the separation in values seen on the principal component 1 (PC1) axis of Fig. 5.16. For the PC2 axis, the values were separated by various depths, hence PC2 seems to be related to a sample depth factor.

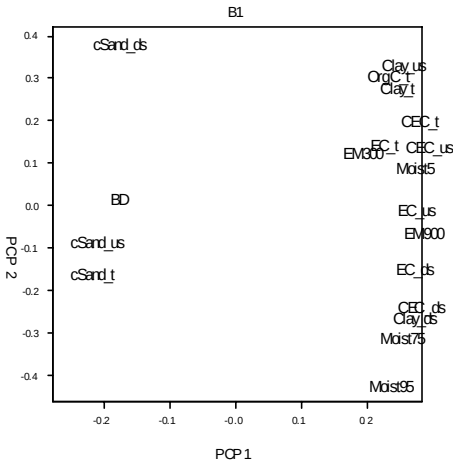
The percentage of variability explained by principal component 1 and by component 2 for each of the sites is given in Fig. 5.16f where the two components explain between 44% of the variability in the data set for site H1, up to 84% of the variability of the data at site B1.

5.5 CONCLUSIONS

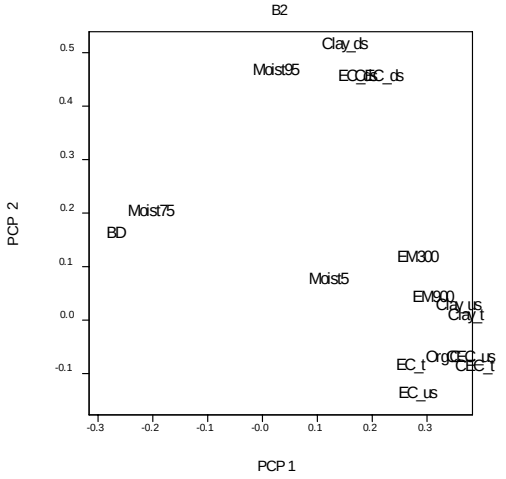
The field validation process at each study site has shown that deep ECa mapping can provide a rapid and reliable method for identifying the paddock-scale variations in the patterns of soils. Soil ECa mapping may be used a tool that allows the delineation of variations in soils with different morphological properties. The relative stability of deep soil ECa signals over time allows their use, in conjunction with strategically-located soil profile assessments, as surrogates for soil properties that are much more time-consuming and costly to measure directly.

The patterns found by a soil ECa survey, however, will assist in the necessary soil validation field work by reducing the number of sites to be investigated and the assisting in the choice of their locations; site selection is likely to be improved with access to additional spatial layers such as those related to crop growth and paddock topography and are discussed with reference to sites H2 and M1 in Section 7.3 (below). The supplementary mapping layers may also be used to help to determine where to apply site-specific inputs within paddocks, and are likely to be of greatest value in areas where detailed soil maps of paddocks are not available.

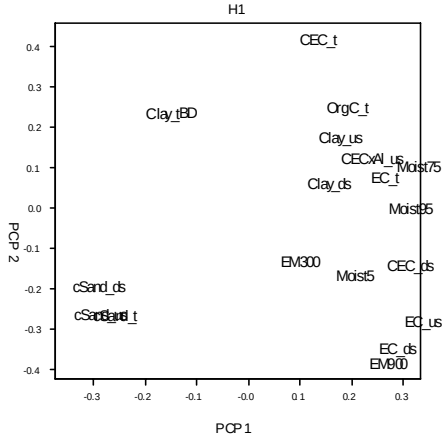
(a) Site B1



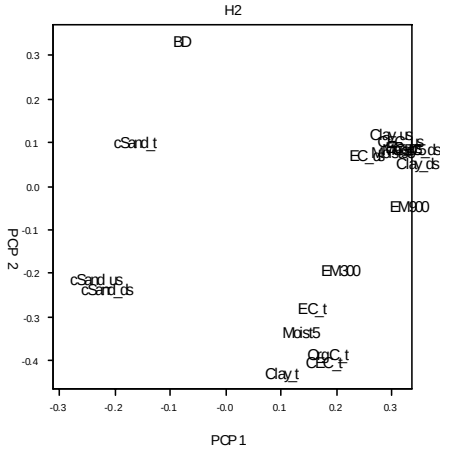
(b) Site B2



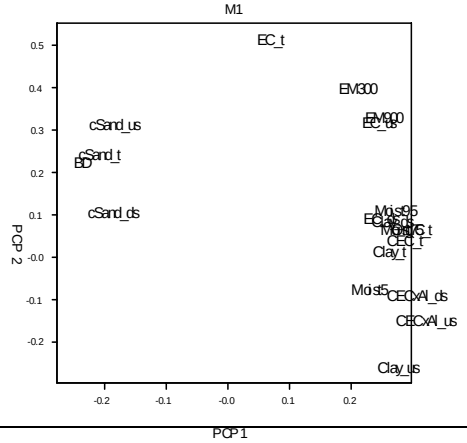
(c) Site H1



(d) Site H2



(e) Site M1



(f) Percentage of variability explained by principal components 1 and 2

Site	PC1	PC2
B1	73	11
B2	46	21
H1	33	11
H2	48	22
M1	63	12

Figure 5.16. Principal components analysis of selected data from each study site.
The variables included are:
cSand = coarse sand content, Clay = clay content, BD = bulk density of the topsoil, EC = laboratory determined electrical conductivity, EMS = shallow ECa, EMD = deep ECa, Moist = gravimetric soil moisture at a given soil depth (5, 15, 25, … cm), OrgC = organic carbon, CECAl = effective cation exchange capacity (basic and acidic cations). Postscripts _t, _us, and _ds indicate topsoil, upper subsoil, and lower subsoil samples respectively.

Chapter 6

UNDERSTANDING PADDOCK VARIABILITY: CROP YIELD AND PADDOCK TOPOGRAPHY GIS LAYERS

6.1 INTRODUCTION

In this chapter, we have set out the project findings that have led us to an understanding of variations on crop yield and paddock topography data that underpin paddock variability. First, we have discussed a method of calibrating the Normalised Difference Vegetation Index (NDVI) satellite image processing that was developed by Project BPS001 and was used at site H2 in 2009 for the first time to map and quantify the variations in yield of a sugarcane crop (Section 4.4.2.2, above). Variations in crop yield were detected and estimated from the processed imagery and then related to patterns in yield of the same crop that had been detected by a harvester-mounted, Techagro^{TM} yield monitor (Section 4. 4.1.1, above).

The BPS001 project team had intended to apply the new methodology across all of the study sites during the 2010 harvest, but was seriously hampered by prolonged, heavy rainfall throughout the harvesting season. One site (H2, Lannercost) was too wet to allow access to any harvesting equipment in 2010, and only part of site M1, Homebush, was sufficiently dry to allow harvesting; the unharvested sugarcane from these sites has been stood over to the 2011 harvest. A manual harvest calibration exercise was conducted at site M1 in 2010 to validate the variability evident in processed IKONOS imagery of the first ratoon crop. At this site, the collaborating grower introduced two harvesters to accelerate the cutting of the crop because of the wet harvesting conditions and the threat of further rain; while this facilitated the harvesting of most of the site, the value of the partial Techagro^{TM} yield monitor data was limited.

The plant cane crop at site B2 was harvested early in the 2010 harvesting season under good weather conditions (Table 3.1). The first ratoon crops at sites B1 (Brandon) and H1 (Mutarnee) were both harvested at the same time later in the season during an opportunistic break in the sustained wet weather. Hence, field calibration of processed IKONOS imagery by manually harvesting of small plots at both sites (150 km apart) was logistically impossible. Manual harvest calibrations were successfully completed during commercial harvesting operations at sites B1 and B2. In this way, Project BPS001 has acquired a limited set of field-calibrated, crop yield data upon which to base general conclusions.

6.2 MAPPING VARIATIONS IN THE YIELD GIS LAYER

6.2.1 Calibration of NDVI yield mapping: Site H2, plant cane crop 2009

The following example from site H2 in the Herbert District demonstrates how the interaction of spatial data layers related to crop yield (satellite imagery, yield monitoring, yield sampling) can be used effectively to identify the spatial variability of crop production, and to predict lost production resulting from underperforming areas within a paddock. The processed infrared reflectance images of sugarcane crops, derived from high resolution satellite images captured

just before harvest, identified in-season crop variability that related well with the expected variability driven by contrasting soil properties portrayed through soil EC mapping (see Section 5.3.4, above).

A 5-zone NDVI image of site H2 (Fig. 6.1a) was produced by the satellite image processing methods described in Section 4.4.2 (above). To assess the nature of the relationship between NDVI values and yield variability in the plant cane crop, ten small plots of sugarcane, each a row 5 m long, were manually cut from areas with a range of NDVI values (Fig. 6.1b), counted, and weighed on a portable weigh trailer. These cane samples were collected on 21 August 2009, 19 days after image capture and three days before the commercial harvest of the crop on 24 August 2009.

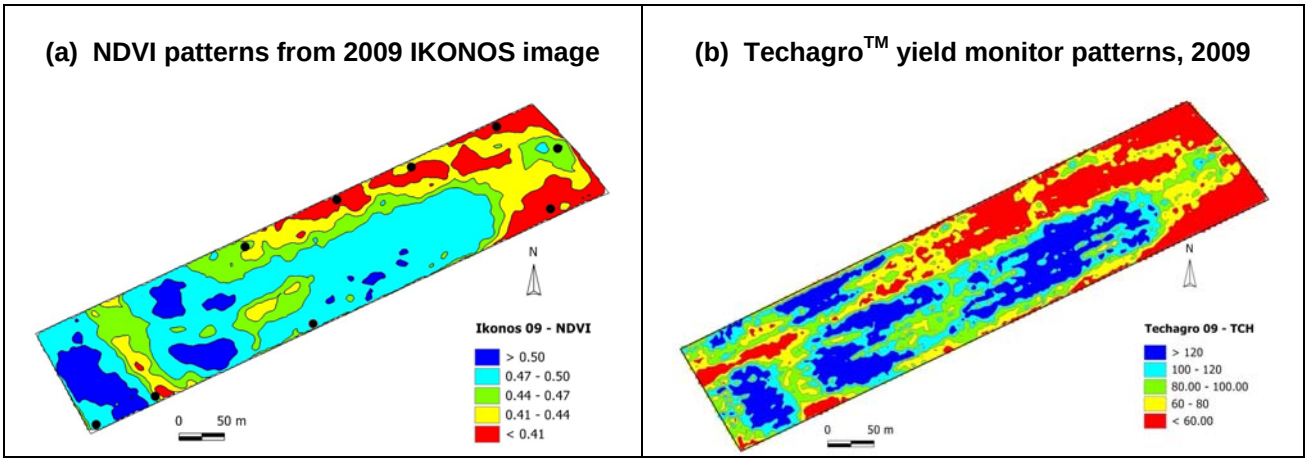


Figure 6.1. NDVI patterns derived from IKONOS satellite imagery captured on 2 August 2009 and Techagro™ harvester-mounted yield map, site H2, Lannercost.

(a) A 5-zone normalized difference vegetation index (NDVI) derived from the 2009 IKONOS satellite image. The nine locations shown by black dots are where 5 m rows of sugarcane were manually harvested and weighed just before commercial harvesting operations on 21 August 2009.

(b) A 5-zone yield map derived from Techagro™ data collected on the day of harvest: 24 August 2009.

6.2.2 Comparison of crop yield monitoring methods at Site H2, 2009

Site H2 was harvested using a Techagro™ yield monitor on 24 August 2009, 22 days after capture of the IKONOS image upon which the NDVI crop yield estimates were based. The commercial yield monitor data generously provided by Techagro Pacific, was georeferenced, set to the same
7 x 7 m grid as that of the NDVI image, classified, and is shown in Fig. 6.1b. The yield patterns were generally similar between the satellite image analysis and harvester yield monitor approaches (compare Figs 6.1a and 6.1b).

The Techagro data processing protocol links the yield measured by the harvester to the tonnes of sugarcane delivered over the weighbridge at the sugar mill. In the case of the plant cane crop harvested at site H2 in 2009, 594 tonnes were received by the mill.

The satellite image processing method of yield analysis, used for the first time at site H2, was based on the strong regression (adjusted R^2 value = 0.79, n = 9) of the yields of the nine manually harvested small plots with the NDVI values determined from spatially matched 7 x 7 m pixels of the processed satellite image (Fig. 6.2). The average value from all of the pixels

across the NDVI image (Fig. 6.1a) was found to be 0.465747. Substituting this value into the regression equation of Fig. 6.2 indicated an average yield across the 8.2 ha site of 87.36 t / ha, which equates to a total paddock yield of 716 t. The over-prediction of paddock yield of 20% by the mathematical model may be related to harvest losses, inaccurate consignment records, or insufficient small plot yields against which the NDVI values were calibrated.

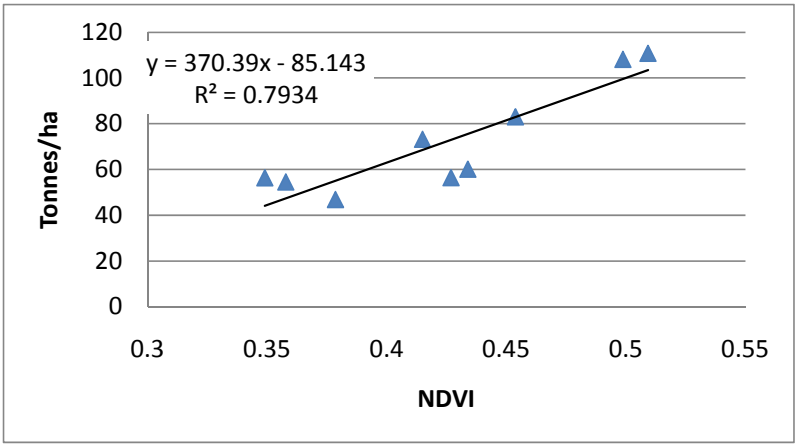


Figure 6.2. Regression relationship between Normalised Difference Vegetation Index (NDVI) values and manually harvested crop yield estimates, 2009 harvest at Site H2, Lannercost.

The infrared reflectance images of plant cane crops, derived from high resolution satellite images captured just before harvest, identified in-season crop variability that related well with the expected variability driven by contrasting soil properties portrayed through soil EC mapping. Robson *et al.* (2010) suggested that the regression between NDVI values with strategically located manually harvested yield samples produced a reasonable predictor of spatial variability as well as total crop yield when compared to final harvest weights, and harvest results obtained from a yield monitor on a commercial sugarcane harvester.

The preliminary results indicated that the spatial variability of cane yield can be predicted using satellite imagery, but needs to be validated with either accurate yield monitor data or strategically located, manually harvested samples. Robson *et al.* (2011) have begun to explore the influence of crop variety and geographic location (12 varieties and 15 planting stages at Bundaberg) on the reproducibility of sugarcane crop yield prediction from multispectral satellite imagery. Further research is required, however, to identify if accurate algorithms can be developed to predict yield without the need for intensive manual sampling in the field, as well as the optimal timing for satellite image capture.

6.2.3 Calibration of NDVI yield mapping: Site M1, first ratoon crop 2010

An IKONOS satellite image of the first ratoon crop was successfully captured over the M1 site on 21 June 2010 in the expectation that the commercial harvest was imminent. But rain delayed the harvest until 1 November 2010. Twelve 5 m rows of sugarcane were selected for manual harvesting to calibrate the NDVI patterns displayed in a 5-zone, equal count, colour coded surface mapping layer generated by Manifold GIS software from the IKONOS image (Fig. 6.3a). The manual sampling of the small plots was coordinated with the passage of the commercial harvester to facilitate access of a vehicle-drawn weigh trailer to the vicinity of the sampling sites. After the manual sampling exercise, the locations of the associated NDVI

values, transformed to a 7 x 7 m grid, were related to the georeferenced, manually harvested, small plot locations using the Manifold package. A strong correlation was evident (adjusted $R^2 = 0.78$) between the actual yield from the 12 small plot samples and the matched NDVI values (Fig. 6.3b)

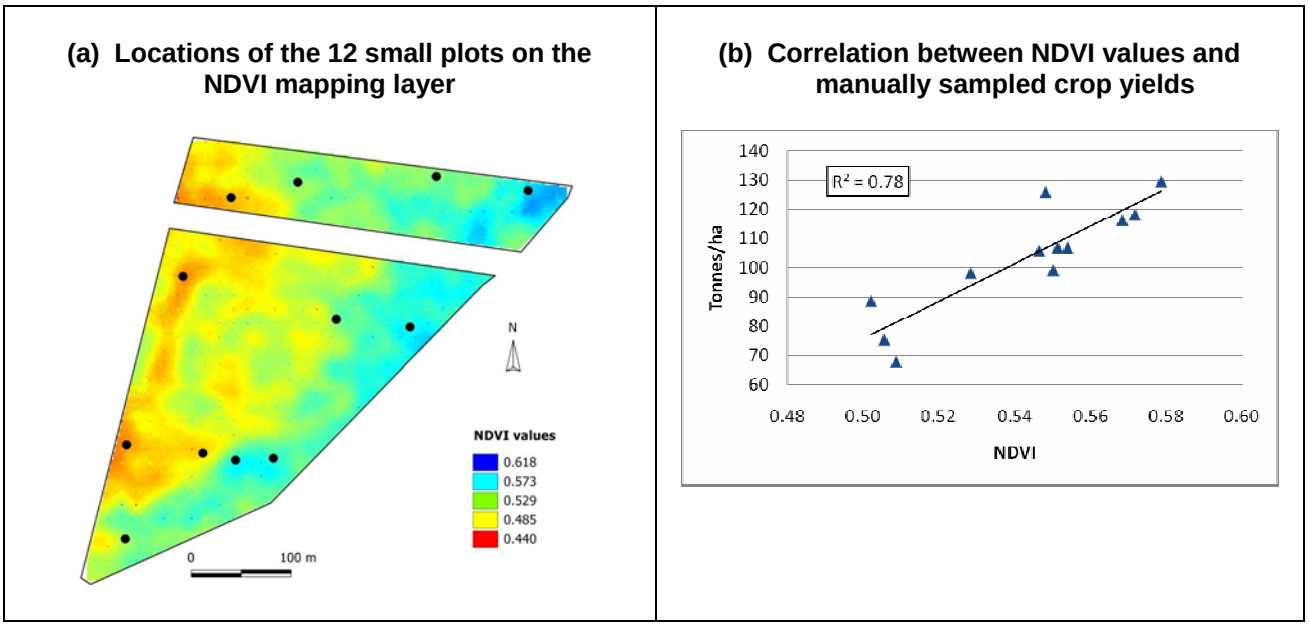


Figure 6.3. Manually sampled yield calibration locations and the regression relationship between Normalised Vegetation Difference Index (NDVI) values from processed IKONOS satellite imagery captured over the first ratoon crop at site M1, Homebush, on 21 June 2010.

(a) Location of the 12 x 5 m rows of manually sampled sugarcane laid over an NDVI map derived from IKONOS imagery.

(b) Regression relationship between Normalised Difference Vegetation Index (NDVI) values and crop yield estimates from matching paddock locations, 2010 harvest of the first ratoon crop at site M1.

Field observations during the NDVI calibration exercise showed that there was very little lodging of the first ratoon crop although the heavier yielding areas along the eastern side of site M1 displayed some stalk bending in response to the winds of Cyclone Ului (20 March 2010). This was validated by examination of a false colour infra-red satellite image (near infrared, red, green) generated by ENVI software from the IKONOS image which indicated subtle variability in crop reflections but no evidence of breaks in the canopy associated with crop lodging (Fig. 6.4a). Generally, sugarcane production along the western, poorly drained side of the paddock was relatively low; the crop was short and erect, and no within-crop weedy patches were observed.

After the 2010 harvest calibration exercise, concerns were raised about the possible impact of flowering of sugarcane varieties on the integrity of NDVI map patterns. A field inspection of the second ratoon crop at site M1 was carried out on 3 June 2011 to determine the variability in flowering along a transect between the regions of different crop growth, similar to those evident in the first ratoon crop (2010) discussed above. In 2011, good crop growth was still evident in the well drained, elevated northeastern section of the paddock and contrasted with low crop production in the poorly drained, low-lying area of the northwestern part of the block. Active flowering was observed in the well drained and elevated zones in contrast to the poorly drained, low-lying areas where flowering had not commenced (Figs 6.4b, 6.4c). Despite the variability in flowering, there appeared to be little impact on the integrity of a false colour image generated from an IKONOS satellite image captured over the site on the 23 May 2011 (Fig. 6.4a).

The gradual reduction in yield and flowering from east to west is matched by soil ECa mapping patterns, consistent variations in the NDVI yield layer, and in paddock topography (*i.e.* the digital elevation layer). These relationships are discussed in detail in Chapter 7, below.

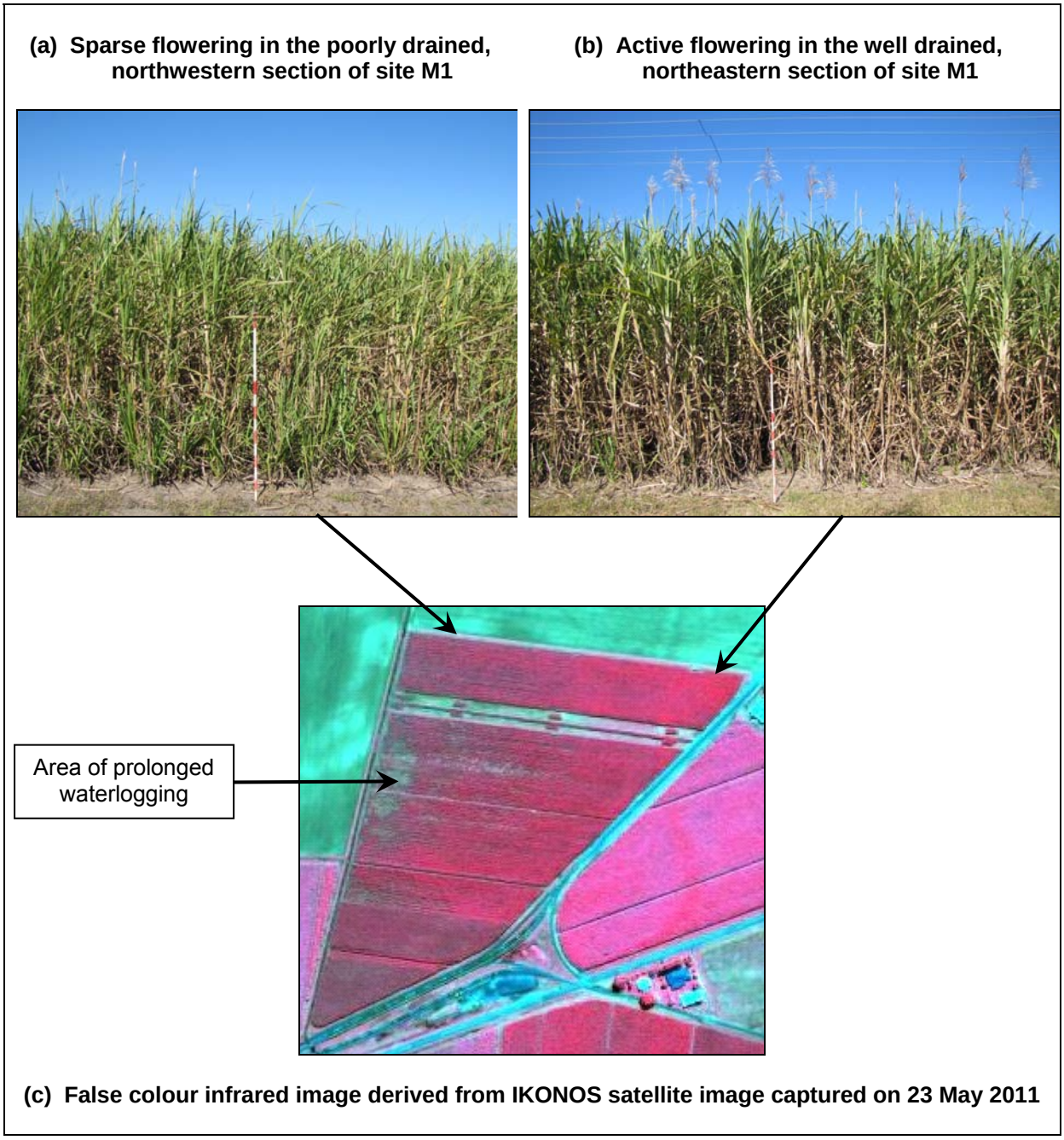


Figure 6.4. Contrasting sugarcane growth patterns at site M1, Homebush.
(a) Stunted growth and sparse flowering in the poorly drained northwestern section of the site. Note the active suckering in response to stress from waterlogged conditions. Photograph facing south taken on 3 June 2011.
(b) Vigorous growth and active flowering in the well drained, northeastern section of the site. Photograph facing south taken on 3 June 2011.
(c) Relative positions of the sparsely flowering and flowering sites (a) and (b), above, shown on a false colour infrared image generated from an IKONOS satellite image captured on 23 May 2011.

6.2.4 Calibration of NDVI yield mapping: Site B1, first ratoon crop 2010

Following the successful IKONOS satellite image capture over site B1 on the 11 June 2010, 27 small plots were selected for manual harvesting on the basis of contrasting patterns in a 5-zone, colour coded, NDVI surface map derived from the satellite image (Fig. 6.5a). The manual sampling regime was coordinated with the commercial harvesting on 15 - 17 September 2010. The scale of the yield calibration exercise was large because the crop was to be burnt prior to harvest providing improved access to georeferenced, small plot sampling locations and 'comfortable' manual cane cutting conditions. In addition, the cane bin supply was restricted so an extended harvesting period was available for the manual harvesting of the large number of sampling sites.

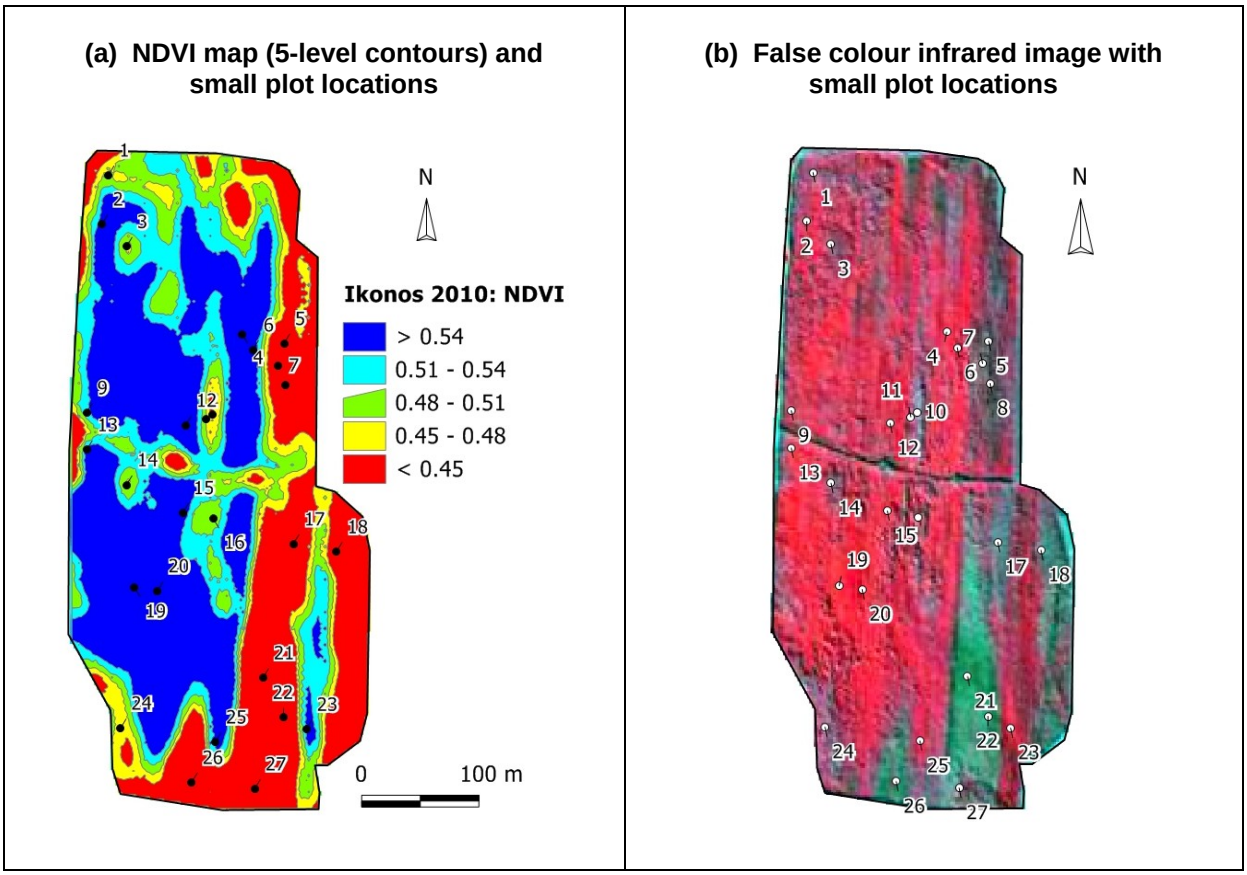


Figure 6.5. Site maps derived from the IKONOS satellite image captured on 11 June 2010 and 3 months before harvest of the first ratoon crop at site B1, Brandon.

(a) Normalised Difference Vegetation Index (NDVI) map generated from a high resolution IKONOS satellite image captured on 23 May 2011.

(b) False colour infrared image of site B1 showing an uninterrupted canopy and no evidence of crop lodging. Locations of the manually harvested small plots (5 m rows of sugarcane) are shown; they were used to calibrate yield estimates derived from the NDVI image.

Differences in crop growth characteristics and related agronomic issues are listed in Table 6.1 for each of the 27 georeferenced small plots, with their NDVI values and spatially matched, manually harvested, sugarcane yields (tonnes of cane per hectare, TCH). In contrast to the strong correlations between NDVI values and spatially-matched yield data from georeferenced, manually harvested small plots at sites H2 and M1, site B1 displayed much more variable crop growth responses to the impact of agronomic and paddock management inputs on vegetative reflectances detected in the satellite imagery.

Table 6.1. Variations in crop growth across site B1 observed at the time of commercial harvest of the first ratoon crop in September 2010.

Data from the shaded cells were removed from the regression of NDVI on sugarcane yields from manually harvested, small plots because of the influence of early lodging that was evident as disruptions to the continuity of the crop canopy shown on a false colour, infrared satellite image (Figure 6.5b) captured
three months before harvest.

Site no.	Canopy continuity * 11/06/2010	Lodging at harvest ** 15/09/2010	Weed status	Stool tipping	Stalks (per m²)	Stalk length (m)	NDVI value	Manually harvested yield (TCH)
1	Continuous	9	Nil		8.7	2.6	0.4823	71
2	Broken	3	Nil		13.2	2.9	0.5657	148
3	Continuous	1	Nil	Tipped	11.1	2.8	0.4849	88
4	Continuous	8	Nil		13.9	3.0	0.5900	124
5	Broken	1	Guinea grass		1.0	1.6	0.4070	2
6	Broken	3	Nil		12.6	3.2	0.5563	142
7	Continuous	1	Nil	Tipped	10.9	1.6	0.3929	50
8	Broken	6	Guinea grass		4.3	1.6	0.4070	19
9	Continuous	7	Nil		12.8	2.8	0.5166	118
10	Broken	3	Guinea grass	Tipped	5.8	2.3	0.4656	34
11	Continuous	3	Nil		11.2	2.7	0.4684	89
12	Continuous	10	Nil		11.6	2.7	0.5717	92
13	Continuous	10	Nil		11.0	2.8	0.5284	86
14	Broken	1	Guinea grass	Tipped	10.8	2.8	0.4926	92
15	Continuous	8	Nil		13.2	2.7	0.5705	103
16	Broken	2	Nil	Tipped	13.7	2.9	0.4976	130
17	Broken	10	Guinea grass		4.8	2.0	0.3658	17
18	Broken	3	Guinea grass		3.6	1.8	0.3437	10
19	Continuous	8	Nil		10.0	2.7	0.6200	100
20	Continuous	8	Nil		11.4	2.7	0.6056	101
21	Continuous	10	Nil		10.7	1.7	0.1924	56
22	Continuous	10	Nil		10.8	1.9	0.2352	53
23	Continuous	10	Nil		11.8	3.0	0.5288	117
24	Broken	4	Nil		10.1	2.8	0.4579	102
25	Continuous	3	Nil		13.0	2.8	0.5509	116
26	Continuous	10	Nil		10.6	2.0	0.2267	58
27	Continuous	2	Nil		10.9	2.7	0.3643	83

* Determined from a false colour infrared IKONOS image captured 11 June 2010.

** Determined by visual inspection of the small plots at the time of commercial harvest on 15 – 17 September 2010. Crop lodging scale: 1 = fully lodged, 10 = fully erect.

As is the case on all Burdekin sugarcane farms, production at site B1 relied on flood irrigation to achieve yield targets. Topographic constraints to flood irrigation at site B1, coupled with areas of freely draining sandy soils, resulted in stressed sugarcane plants in specific areas of the paddock. During the small plot harvesting exercise it was noted that significant areas of cane had stool-tipped as a consequence of pest (nematode) damage in sandy soils, or shallow planting with a double disc opener planter into permanent beds with uneven heights. Hill-height issues are known to be a fairly common occurrence when permanent beds are formed in paddocks with contrasting physical soil properties. The crop in parts of the paddock was heavily lodged (Fig. 6.6a) while other areas were erect (Fig. 6.6b). Weed issues were evident in parts of the paddock with Guinea grass *(Megathyrsus maximus)* growing prolifically in many of the stool-tipped zones and low yielding areas (Fig. 6.6c and 6.6d). In addition,

variability in flowering across the site was evident prior to burning of the crop for harvesting, which suggests yet another possible factor impacting on crop reflectance and compromising the NDVI values.

(a) Harvesting of heavily lodged crop

(b) Poor yielding sugarcane, erect growth

(c) Guinea grass invasion

(d) Stool-tipped, low yielding zone

Figure 6.6 Agronomic and management issues resulting in variable sugarcane crop production across site B1, Brandon.
All of the photographs were taken during the commercial harvest 15 – 17 September 2010.
(a) Harvesting of a heavily lodged part of the crop in the vicinity of small plot 24 (Fig. 6.5b).
(b) Poor yielding area of the crop with erect growth habit at small plot 20 (Fig. 6.5b).
(c) Invasion of Guinea grass (foreground) into an area of very poor crop growth at small plot 5 (Fig. 6.5b).
(d) Stool tipping and no crop production as a consequence of pest damage or shallow planting into permanent beds at small plot 7 (Fig. 6.5b).

In the light of these drivers of crop variability, it is not surprising that a poor correlation (adjusted $R^2 = 0.43$, n = 27) emerged between the georeferenced NDVI values and the spatially matched sugarcane yields from the manually harvested small plots (Fig. 6.7a).

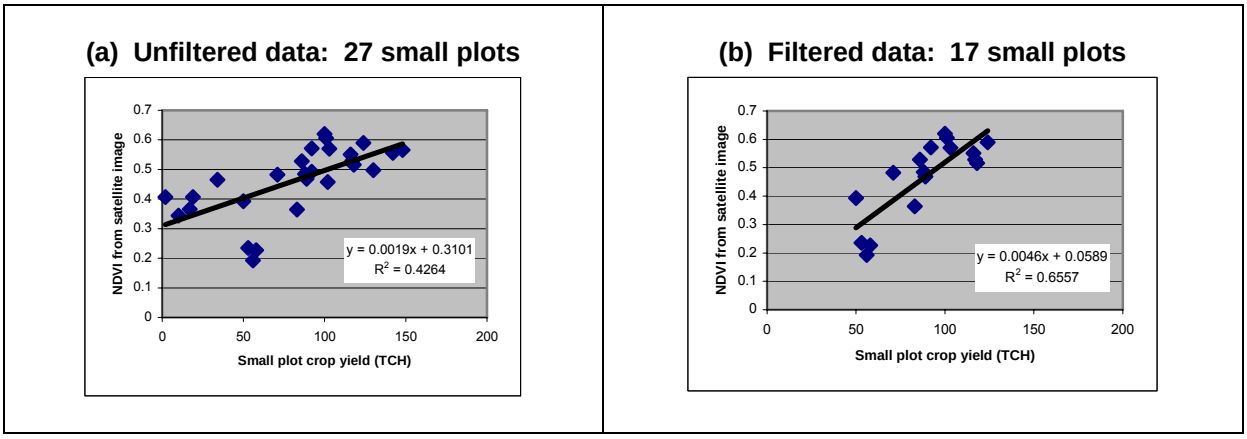


Figure 6.7. Regression relationships of NDVI values on sugarcane yields from matching, georeferenced, manually harvested small plots in the first ratoon crop (2010 harvest) at site B1.
(a) Regression of NDVI values on small plot, manually harvested, sugarcane yield: data from all 27 small plots listed in Table 6.1.
(b) Regression of NDVI value on small plot, manually harvested, sugarcane yield: data from 17 small plots, excluding the plots with an early break in the crop canopy (including all of the grass-invaded and most of the stool-tipped plots) highlighted as shaded cells in Table 6.1.

Access to an IKONOS false colour infrared satellite image (Fig. 6.5b) provided a critical link in understanding the poor relationships between sugarcane yields from the small plots and their NDVI values. The NDVI values were derived from crop reflectance differences some three months before commercial harvest (satellite image capture: 11 June 2010) and were influenced by early crop lodging and stool tipping that broke up the continuity of the crop's canopy cover, and allowed grass and weed invasion of particular small plots. The plots displaying evidence of early lodging (*i.e.* those with broken crop canopies in Fig. 6.5b) are highlighted by the shaded rows in Table 6.1.

Small plots with relatively erect, non-lodged sugarcane before harvest (Plots 12, 15, 19, and 20 of Table 6.1) were found to have higher NDVI values and lower matching plot yields than the highest yielding plots (Plots 2, 6, and 16) which displayed early lodging patterns evident in the false colour satellite image (Fig. 6.5b). Erect sugarcane characteristics were evident throughout sites H2 and M1 discussed above (Sections 6.2.1 and 6.2.3, above) and have contributed to the strong correlations between spatially matched NDVI values and small plot yield data at those sites.

The high NDVI values in plots 5, 8, 10, 14, 17, and 18 at site B1 (Table 6.1) were most likely a consequence of the reflectance of the high Guinea grass biomass in the grass-infested plots and contributed to the poor correlation between spatially matched NDVI and sugarcane yields. The sporadic occurrence of Guinea grass throughout the paddock was caused by the lack of crop competition as a consequence of poor sugarcane growth and reduced stalk numbers (*e.g.* plots 17 and 18; Table 6.1). The poor growth relates to crop management issues such as uneven watering, pest (nematode) infestations, stool tipping because of shallow planting depths, or harvester damage of stools in the previous harvest.

Plots 2, 6, 16, and 24 (Table 6.1) displayed low NDVI values matched to plot yields. This can be attributed to reduced crop reflectance caused by early lodging at the time of the satellite image capture (Fig. 6.5b). Plots 21, 22, and 26 are situated in an area of the paddock where the paddock topography has interfered with flood irrigation resulting in temporary water stress on the crop. Table 3.2 shows that the paddock had received little to no rainfall in the 2 – 3 months prior to the satellite image capture date and the collaborating grower confirmed that temporary stress in this particular zone was likely. Water stress explains the low NDVI values relative to yield for these three plots, and they were retained in the NDVI regression on small plot yields. The small plot growth responses highlight the possible impact of irrigation management practices and timing on the integrity of NDVI mapping patterns.

The correlation of NDVI values on matching sugarcane yields from small plots was improved significantly by removing data for the plots with reduced NDVI values as a result of early lodging (shaded cells of Table 6.1), which included all of the small plots invaded by Guinea grass and most of the plots where stool tipping was evident during the commercial harvest. The adjusted R^2 value increased from 0.43 for the regression relationship that included all of the 27 small plots (Fig. 6.7a), to 0.65 for the filtered data set of the 17 remaining plots (Fig. 6.7b). Thus, the filtered small plot data from site B1 provided a similar NDVI - crop yield relationship to that from sites H2 and M1 where strong relationships had been established between NDVI values and sugarcane yields from spatially matched, manually harvested small plots (Sections 6.2.1 and 6.2.3, above).

The improved correlation at site B1 highlights the crop growth factors that compromised the integrity of NDVI yield mapping layer at this site. This is directly relevant to determining optimum satellite capture times to minimize agronomic or site management factors that reduce the quality of NDVI yield patterns, which is a research issue currently being addressed in the SRDC-funded Project CSE022 and has not been taken any further by Project BPS001.

6.2.5 Calibration of NDVI yield mapping: Site B2, plant cane crop 2010

Two satellite images were available for the plant cane crop at site B2: a Spot 5 image with 10 m resolution captured on the 14 May 2010, and an IKONOS image with 0.8 m resolution captured on 11 June 2010. The site was scheduled for commercial harvest on 17 June 2010 and, as the IKONOS data had not been received from the image provider during preparations for manually calibrating the crop yield during the harvest, a decision was made to use the SPOT 5 data as a basis for processing and calibrating NDVI values.

The SPOT 5-derived, raw NDVI point data were processed onto a georeferenced 7 x 7 m grid and transformed into a 5-zone, equal count, surface layer using the Manifold GIS package. A total of 14 small plot sites was selected across the range of NDVI zones for manual harvesting and weighing. The IKONOS spatial data was subsequently received and processed in the same way for analysis and comparison with the NDVI values derived from the SPOT 5 image.

Field observations prior to, and during the manual harvesting calibration exercise at site B2 revealed a number of factors that may have influenced the relationship between the crop yield determined from the small plots and the corresponding NDVI values derived from the SPOT 5 and IKONOS images:

- strong variability was observed in flowering intensity at the time of the IKONOS image capture;
- crop lodging was variable across the paddock;

- the plant cane crop was reasonably uniform and high yielding with the yields from the 14 manually harvested plots ranging from 114 to 181 tonnes/ha (average 139 tonnes/ha);
- the possibility of pixel saturation induced by the high-yielding crop may have influenced the integrity of the NDVI-related yield patterns;
- the two month drying off period (cessation of scheduled flood irrigation) prior to harvest may have resulted in variability in crop reflectance due to non-uniform induced crop stress across the clay soils of the site (Section 3.3.1.2, above).

These factors appear to have influenced the poor correlations found between NDVI values derived from either the SPOT 5 (adjusted $R^2 = 0.03$, n = 14) or IKONOS images (adjusted $R^2 = 0.08$,
n = 14) and the spatially matched sugarcane yields from the manually harvested small plots (Fig. 6.8). In addition, the correlation between spatially matched NDVI point data from the SPOT 5 and IKONOS imagery was also very poor (adjusted $R^2 = 0.02$, n = 2084). These results appear to be consequences of differences in flowering intensity, changes in crop lodging status, or variability in crop stress that occurred in the month between the two image captures.

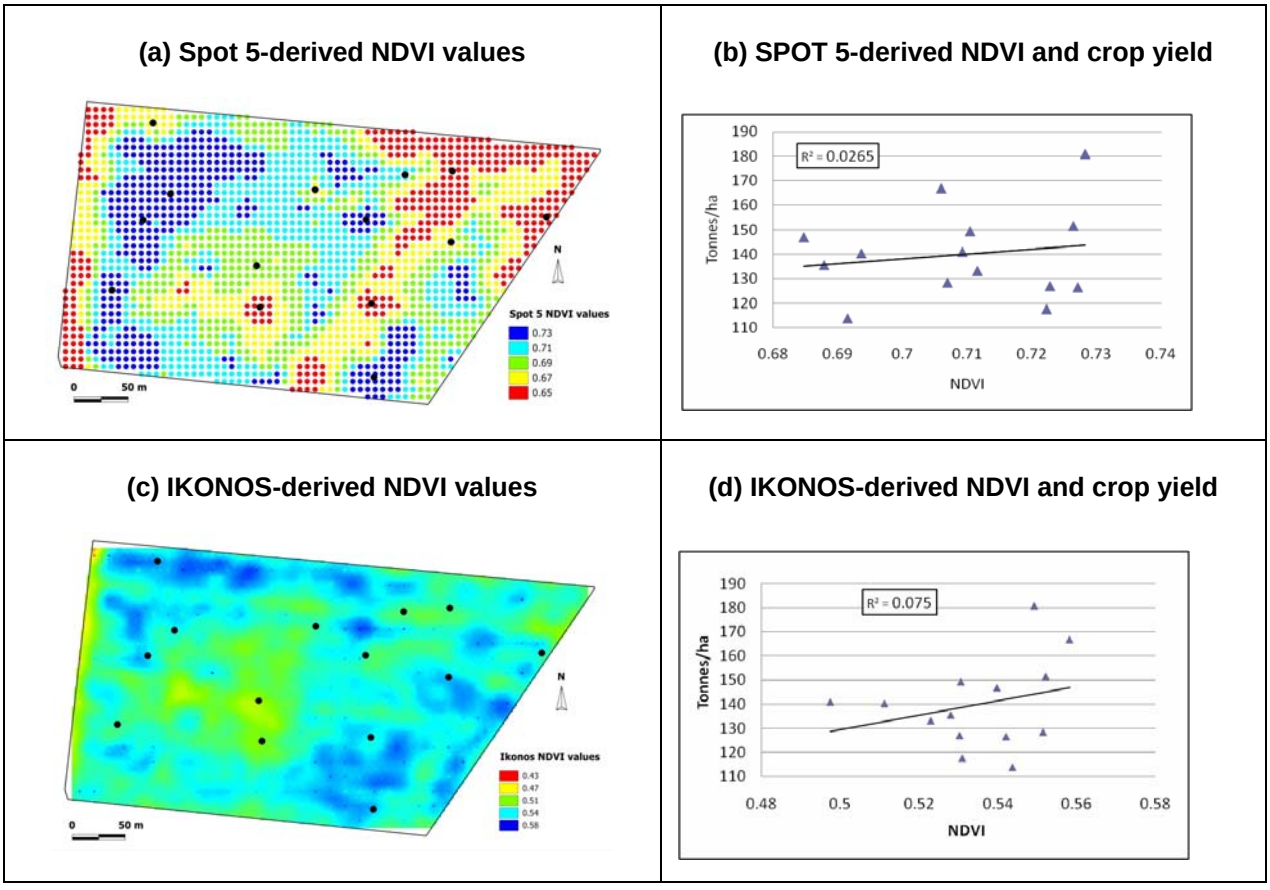


Figure 6.8. IKONOS and SPOT 5 satellite images captured over the plant crop at site B2, 1 and 4 weeks before harvest on 17 June 2011.

(a) Spot 5-derived NDVI values (5-coded, 7 x 7 m point data) from an image captured on 14 May 2020 and the locations of the 14 manually harvested small plots (black dots).

(b) Relationship between NDVI values from SPOT 5 imagery and sugarcane yields from the small plots.

(c) IKONOS-derived NDVI values (5-coded, 7 x 7 m point data) from an image captured on 11 June 2010, and the locations of the 14 manually harvested small plots.

(d) Relationship between NDVI values from IKONOS imagery and sugarcane yields from the small plots.

6.3 CROP YIELD MONITORING METHODS: CONCLUSIONS

Satellite imagery has been successfully used for the last decade by Mackay Sugar Ltd to streamline harvesting schedules across the Central Region and for estimating the district's overall yield on an annual basis (Markley *et al.* 2003; Markley and Fitzpatrick 2004). The NDVI calibration protocol based on sugarcane yields from manually harvested small plots established by Project BPS001 provides some indication of the value of satellite imagery in determining crop growth variability, and in predicting crop yields at a highly detailed spatial scale. It has provided a basis for the approach of Robson *et al.* (2011) who are developing algorithms based on multispectral satellite imagery for crop yield estimation across a number of sugarcane varieties and regions.

It is evident from the NDVI-crop yield calibration exercises conducted at sites H2 and M1 that processed satellite imagery can accurately predict variability in crop yield provided specific growth patterns exist. In contrast, sites B1 and B2 presented a number of growth pattern and agronomic variables that compromised the reliability of interpretations of NDVI-based crop yield patterns. It is notable that the two satellite images over site B2 (IKONOS and SPOT 5), captured within a month of each other, produced very poorly correlated NDVI values from the same 7 x 7 m georeferenced pixels ($R^2 = 0.02$, n = 2084). While current image processing methods and well-timed satellite image captures may provide the sugar industry with a valuable resource for regional yield prediction, they currently fall short in providing a reliable crop yield mapping layer for precision agriculture purposes.

The data collected during the limited yield calibration work undertaken by Project BPS001, suggest that consideration of the following points may improve the reliability and accuracy of yield maps generated from processed satellite imagery:

- In the Burdekin region, satellite image captures brought forward to a November - January time may avoid some of the factors compromising the accuracy of processed yield maps, namely:
    - sugarcane crop lodging,
    - flowering of specific sugarcane varieties,
    - early lodging, stool tipping, and subsequent infestation of affected areas by weeds,
    - induced crop stress from pre-harvest dry-down periods.

- In the wetter central and northern cane growing regions of Queensland, satellite image captures between March and early May would minimize the impact of flowering on the integrity of NDVI mapping layers.

- NDVI processing of satellite imagery involves a simple combination of pixel data from only the visible red and near infrared satellite sensor bands. Different mathematical combinations of these or other multispectral satellite sensor bands may offer an image processing strategy capable of minimising the effects of flowering on sugarcane crop reflectances. The issue of pixel saturation by heavy crop yields still remains.

Results from site H2 (Section 6.2.2, above) indicated that the Techagro™ system produced satisfactory yield maps, but further work may be required to achieve a consistent level of accuracy required for precision agriculture in sugarcane production. Apart from the initial study during the 2009 harvest at site H2, Project BPS001 has not pursued an assessment of

the accuracy or reliability of yield monitors on harvesters because the SRDC-funded Project CSE022 is committed to research in this field.

At this stage, access to an accurate and reliable harvester-mounted yield monitor system dovetails perfectly with a precision approach to improved sugarcane production. A good harvester monitor provides an annual snapshot of within-block yield variability on a paddock to paddock basis, and is not influenced by timing issues as is the case with satellite imagery. Data collected by many current yield monitors is stored on data cards that are manually transferred to data processors (Di Bella *et al.* 2009a), but this can be improved dramatically. There are systems available that are able to transfer the paddock information directly to an office for automated batch processing and analysis, which is a lot simpler than the post-processing requirement for yield data that is generated by satellite image analysis.

Both systems have inherent problems. Maintenance of yield monitor equipment is time-consuming, and equipment failure during the harvest period can result in the loss of critical crop data. Satellite capture is severely constrained by the weather, and the availability of other cloud-penetrating remotely sensed data sets such as radar and laser are currently too expensive or too restricted geographically for consideration.

With the reducing costs of satellite imagery it is probable that, in the future, this technology will be used in conjunction with harvester-mounted yield monitors for mapping crop growth patterns and for pest and disease detection throughout the sugarcane growing season.

6.4 RELATIONSHIPS BETWEEN CROP YIELD AND SOILS

Relationships between crop yield and soil properties and between crop yield and soil ECa values have been considered for sites B1, H1 and H2, which had yield data in 2009 collected from the first sugarcane harvest following the Veris mapping.

6.4.1 Relationships between crop yield and soil properties

Consistent, strong relationships between crop yield and particular soil property values at the soil profile validation sites were not evident at sites B1, H1 or H2. There were stronger correlations with crop yield and soil properties in the topsoil layer as compared to those with the two subsoil layers. There were no high correlations between yield and physical or chemical soil properties in the upper-subsoil layer. In the deep subsoil layer, there were only a few strong correlations between yield and the chemical soil properties. There were no strong correlations with physical soil properties in the deep subsoil layer.

For the physical soil characteristics of the topsoil layer, the highest correlations with yield were at site H1 with clay content (r = - 0.70) and at site H2 with total sand % (r = 0.6) and percent total fine fraction: r = - 0.6. For the chemical characteristics of the topsoil layer at site B1, the highest correlations were with organic carbon (r = 0.63) and BSES phosphorus (r =0.61). The correlation between exchangeable potassium % and yield was - 0.58. At site H2 this correlation was - 0.61. The only other noteworthy correlation at H2 was that with potassium reserves (nitric acid extractable potassium) and crop yield of - 0.72.

For chemical characteristics of the deep subsoil layer, the high correlations were with nitrate nitrogen, exchangeable calcium, and exchangeable magnesium (- 0.62, - 0.72 and 0.63 respectively).

Data was available for crop yield and bulk density at site M1 for 2005, 2006 and 2007. The correlations between these yield and bulk density were - 0.61, -0.68 and - 0.77 respectively for the three years. This negative correlation indicates a higher level compaction was associated with lower yields.

A high coefficient of variation (CV) in the values of a soil property may in turn relate to a display of spatial variability in crop yield. Thus, properties with high CVs could be potential variables to use to delineate management zones with in the paddock. When considering the average CV across sites B1, H1, H2 M1, the maximum CVs for the topsoil and upper subsoil were 51% and 72%, both for the total sand %. In the deep subsoil layer the highest CV was 86% for electrical conductivity measurements made in the laboratory.

6.4.2 Statistical relationships between crop yield and soil ECa

When considering the data from the soil profile validation locations, some significant relationships were attained in the regressions of crop yield against soil ECa values, but the adjusted R^2 values were not high enough to show a convincing relationship. However, they may highlight areas of further investigation.

At site B1, the exponential regression of crop yield versus shallow soil ECa was significant ($p = 0.027$) but with an adjusted R^2 value of only 23.4%. This was for the first of the three Veris 3100 mappings of site B1. The relationships for mappings subsequent soil ECa estimations were not significant ($p = 0.63$ and 0.21). At site H2 there was also a significant exponential relationship between crop yield and shallow soil ECa ($p = 0.002$) with a slightly higher adjusted R^2 of 35.7%. The relationship of crop yield with shallow soil ECa at site H1 was not significant ($p = 0.999$).

Site H2 had the only significant relationships between crop yield and deep soil ECa. For the exponential relationship, $p = 0.045$ and the adjusted R^2 was only 17%. The linear relationship was slightly better with $p = 0.013$ and adjusted R^2 of 27.1%. The relationships between crop yield and deep ECa were not significant at the B1 or H1 sites ($p > 0.05$).

6.4.3 Spatial relationships between crop yield and soil properties

6.4.3.1 Self-mulching soils, Site B2, 2001

An NDVI map of site B2 was derived from an IKONOS satellite image that was provided, fortuitously, on a demonstration disc by the image supplier. It had been captured on 30 October 2001 over a ratoon crop in the early stages of growth after harvest. While the date of capture of this image precludes its use in assessing crop yield, it demonstrates the outstanding correspondence between the patterns of poor plant growth depicted by low values on the NDVI map, the deep soil EC patterns, and the occurrence of self-mulching, cracking clay soils (Fig. 6.9).

In contrast, however, there was a much weaker association between the NDVI image and the shallow soil EC patterns (compare Figs 6.9 and 5.8a), despite the fact that the bulk of the

feeding roots of the sugarcane crop at that early growth stage would be in the cultivation layer of the soil, typically 0 - 25 cm deep, and corresponding with the depth of the shallow soil EC responses.

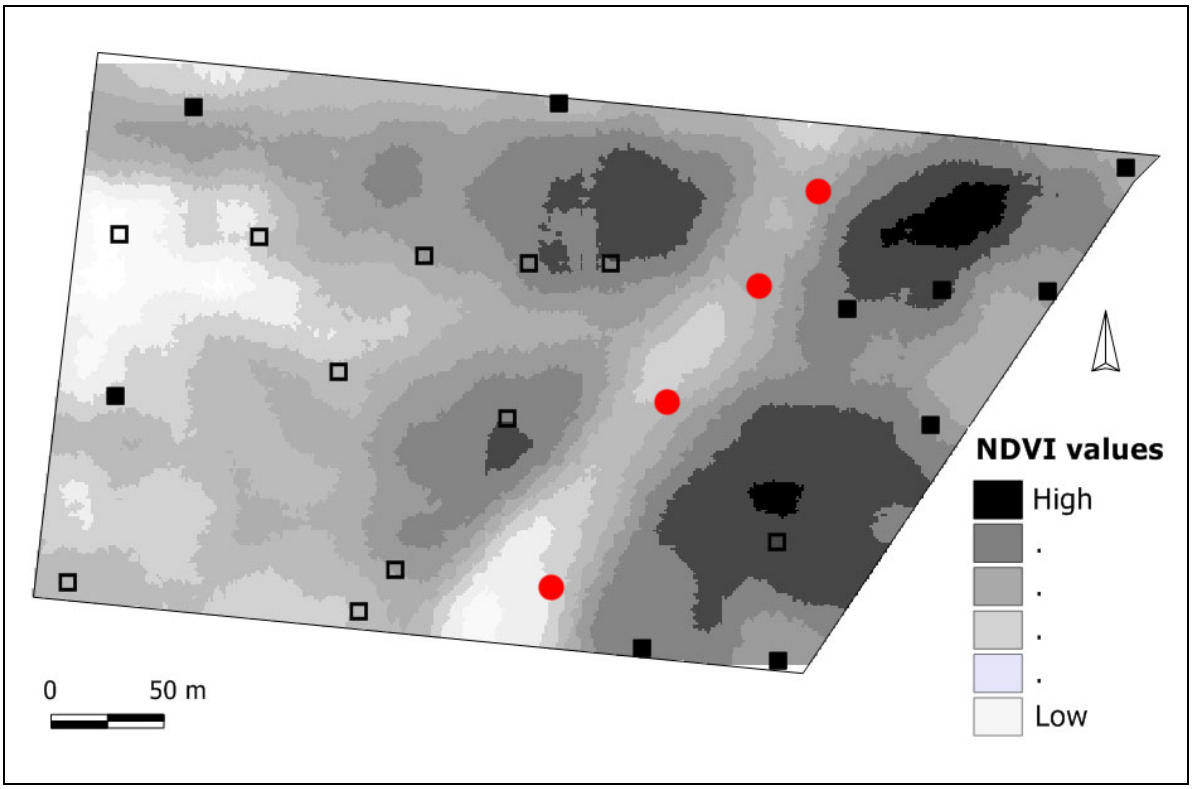


Figure 6.9. Normalized difference vegetation index (NDVI) map and the locations of different soil types at site B2, Brandon.
The NDVI map was derived from IKONOS satellite imagery captured on 30 October 2001. Generalised soil profile characteristics (Northcote 1979):
□ non-structured clay (Uf 6), ■ cracking clay (Ug 5), ● self-mulching, cracking clay (Ug5).

The self-mulching clays swell when wet and disrupt the flow of irrigation water along the paddock furrows that run across the zone of swelling soils. The paddock furrows are subjected to repeated clearing and the self-mulching clays have been mechanically mixed into the adjacent soils, thereby spreading their influence more widely in the shallow ECa signals, as discussed in Section 5.3.2 (above).

The deep soil ECa signals are derived largely from the part of the soil that lies below the cultivation layer, are relatively undisturbed by cultivation effects, and have retained spatial integrity and a strong relationship to the distribution of the self-mulching soils evident in Fig. 6.9.

6.4.3.2 Relationships between crop yield and soil ECa patterns

Variations in the crop planted in 2008 at site H2, determined by NDVI analysis of satellite imagery captured on 2 August 2009 just before harvest on 24 August 2009, are shown in Fig. 6.10a, adjacent to the patterns of deep soil ECa responses measured on 12 May 2008 (Fig. 6.10b), and patterns in crop yield determined by the Techagro™ yield monitor at harvest (Fig. 6.10c).

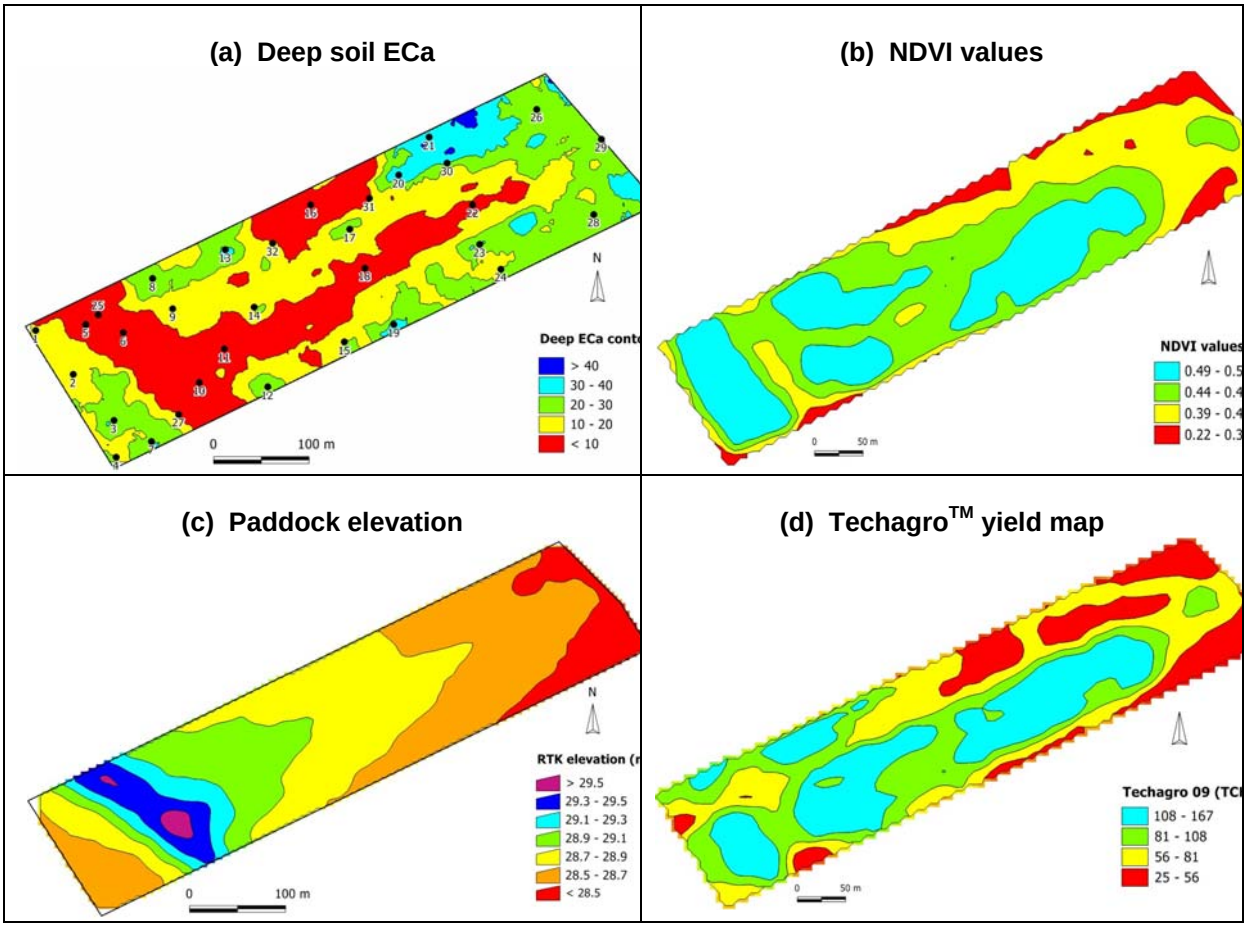


Figure 6.10. Patterns in deep soil ECa signals (May 2008), in the plant cane crop at harvest in August 2010, and in paddock elevation at Site H2, Lannercost.

(a) Deep soil ECa patterns determined on 28 May 2008, prior to planting the crop.
(b) Patterns in the normalized difference vegetation index (NDVI) determined from IKONOS satellite imagery captured on 2 August 2009, 22 days before harvest.
(c) Topography of the paddock determined by RTK-GPS methods by T. Parker, Northern Gulf Resources Management Group, Mareeba, as part of an EM38 survey across the site in September 2009. Locations of the soil validation sites are shown.
(d) Patterns determined by the TechagroTM harvester yield monitor on 24 August 2009.

There is a general visual association evident in Fig. 6.10 between low soil ECa values in the generally sandier, lighter textured soils and higher crop yield, and also between higher soil ECa values in the more clayey soils, and low crop yield (compare Figs 6.10a with 6.10b and 6.10d). Linear and exponential regressions were performed using the data for the soil ECa values from the 7 x 7 m pixels from the kriged data surface and the Techagro yield data, and the NDVI values, from the corresponding 7 x 7 m pixels. This was done for sites B1, H1, H2 and M1 with 2009 and 2010 data where available, with sample sizes of 2584, 1175, 1820 and

2312 respectively. Data from two Veris 3100 mappings at M1 and the three at B1 were analysed.

Relationships were found to be poor between crop yield and soil ECa with adjusted R^2 values for linear and exponential regressions mostly less than 20%. Only three analyses of matching 7 x 7 m pixels of crop yield and soil ECa data produced adjusted R^2 values greater than 45%:

- at site H2, the exponential regression of shallow ECa versus elevation was highly significant ($p<0.001$), but had an adjusted R^2 of only 45.8%;
- at site H2 again, the linear relationship of deep soil ECa versus elevation was also highly significant ($p < 0.001$) produced an adjusted R^2 value of 61.4%,
- at site B1, the exponential relationship between deep ECa and elevation was highly significant ($p < 0.001$) and had a similar adjusted R^2 of 60.2%.

It has been shown in the previous chapter that stable, deep soil ECa values are related to soil properties. Since soil properties are generally related to plant growth and crop yield, it is reasonable to assume that soil ECa values might similarly be related to crop yield. This was clearly not so in the foregoing case, even at site H2. Other factors such as external site drainage / site topography, internal soil profile drainage, soil compaction, seasonal growing conditions, and paddock management strategies confound the relationships. For example, in a dry year and all else being equal, the best yields are likely to come from poorly drained clay soils that better hold limited soil water supplies for plant use, and the poorer yields are likely from water-stressed crops on well drained sandy soils. But in a wet year the system may flip over with the clay soils becoming waterlogged and producing much poorer crops than those on better drained soils. This means that the soil-based GIS layer is inadequate, by itself, to define management zones within paddocks.

Nevertheless, the deep soil ECa GIS layer and the paddock boundaries do provide a stable base for displaying and analysing spatial patterns in a range of variables of significance to crop yield, including soil nutrient content, sodicity, and pH. Project BPS001 has shown that knowledge of relationships among a number of other spatial GIS layers is needed to progress precision agriculture in sugarcane. In addition to a soil-based GIS layer, other variables hold promise for explaining and managing paddock variability include: site topography, soil water properties *(infiltration, water-holding capacity, profile drainage),* and soil compaction *(bulk density, cone penetrometer resistance).*

6.5 CROP YIELD AND PADDOCK ELEVATION

As for the relationships between soil ECa data and crop yield, there are visual suggestions in Fig. 6.10 of possible relationships between paddock topography and crop yield. The NDVI values related to patterns of crop growth (derived from IKONOS satellite imagery) were transformed to tonnes of cane / ha using the manually harvested regression algorithms (Section 6.2, above) and Techagro^{TM} data, where available. Relationships were found to be poor between crop yield and paddock elevation with very few of the regressions of paddock elevation values versus NDVI- or Techagro^{TM}-based crop yields producing adjusted R^2 values greater than 20% for either linear and exponential regressions.

However, using Lidar elevation data at site M1, the regression of NDVI-derived crop yield on elevation produced an adjusted R^2 value of 76%; RTK-GPS elevation data at the same site was much more poorly related to NDVI-derived crop yields (adjusted R^2 = 37%).

The poor relationships between matching pixels of paddock elevation and crop yield data relate to the nature of the elevation data, which was derived from digital terrain models. The elevation dta points merely represent the height above a datum (often mean sea level) of each of the 1100 – 2500 pixels (7 x 7 m) within each study site. It is a crude estimator of the actual topography of a paddock that controls the drainage of surface water from sites that involves other geomorphological variables such as slope angle, slope length, flow directions of runoff water, depths and extent of closure of depressions that may retain runoff water on the slopes. The incorporation of soil data to give an indication of subsurface drainage of soil profiles is another area of refinement of the site hydrology that impacts on plant growth and crop variability (see Section 8.4.1.2, below). While it should be possible to combine such soil and site drainage parameters from the digital elevation models used in Project BPS001 and from detailed site descriptions and soil analyses, developing that methodology was beyond the time available to complete the project.

Although paddock elevation data by itself has been demonstrated to be poorly related to crop yield, when considered in conjunction with soil ECa data and patterns of crop growth, however, it has been found to be one of the key GIS layers that can be used to define spatial management zones within paddocks. These relationships are discussed in some detail in Chapter 7.

6.6 CROP YIELD AND SOIL MANAGEMENT PRACTICES

6.6.1 Soil compaction and tillage practices in the northern sugar industry

The bulk density of the soil is simply the mass of oven-dry (105^{o} C), undisturbed soil, including its air-filled pores, that fills a given volume. Recently cultivated soils contain more pores, and have a lower bulk density, than a soil that has settled naturally under the influence of the weather over a period of time. Soil compaction, the result of the passage of traffic (humans, animals, or vehicles) over the soil or dropping a heavy weight onto the soil, pushes the soil particles together, squashes the pores together reducing their volumes and connectivity, and increases the bulk density of the soil. Handreck and Black (2002) have discussed the ways in which soil compaction is detrimental to plant growth through its impact on:

- reduced infiltration rates of rain or irrigation water,
- reduced availability to plants of water stored in the soil profile,
- reduced air supply to plant roots,
- increased soil strength inhibiting plant root elongation,
- the development of shallow, perched water tables.

These impacts on plant growth are usually managed by tillage operations, but tillage can have both favourable and unfavourable effects on soils. If the soil is at an appropriate moisture content, tillage will break up dense soil layers, reduce the sizes of large clods, incorporate organic matter into the seedbed, kill weeds, and generally create a favourable seed bed into which the crop is planted. But too much tillage can also be detrimental to the structure of soils by promoting the entry of air into the soil and the oxidation and loss of soil organic matter, which then leads to a reduction in soil aggregate sizes, and a reduction in pore sizes and permeability, and a dramatic loss of pathways in the soil that allow the passage of air, water, and plant roots.

Until recently, most sugarcane crops in Australia have been established on 1.5 m row spacings, but the wheel centres of harvesting equipment are generally between 1.8 m and 2 m. The mis-match of row spacing and machinery wheel centres results in many cane paddocks being heavily compacted during wet harvests over a typical four to five year ratoon cycle. In particularly bad cases, the tyres of harvesters or haul-out units roll to the top of the row, and severely compact the moist soil over the top of the harvested cane stools from which tillers must emerge to establish the next ratoon crop (Fig. 6.11a). Multiple passes of heavy machinery over the moist soil compound the problem (Fig. 6.11b). Clayey soils usually become very hard and dense on drying out, and may present an almost impenetrable obstacle to the emerging sugarcane tillers, reducing stalk numbers and possibly also stalk diameters in the ratoon crop, and thereby lowering crop production.

In addition, poor control over the height of the base cutter on the cane harvester may result in scalping the soil along the top of the planted row, damaging the harvested stools, and also reducing the ability of the ratoon crop to develop tillers (Figs 6.11c, 6.11d).

Often the effects of poor harvesting practices are hidden below a thick green cane trash blanket and only become evident when the trash is burnt or removed, as in Fig. 6.11, but they have a very strongly detrimental influence on the yield of the ratoon crop.

Another hidden soil management problem is the effect of soil compaction arising from repeated passes of tractors, trucks, and haul-out units over paddocks where permanent planting beds and controlled traffic lanes have not been established. The soils may become compacted to a considerable depth (30 – 50 cm; Brady and Weil 2008), increasing the soil's bulk density, reducing its water transmission and water holding properties, and reducing plant root penetration and crop growth. The effects are pronounced in the formation of subsoil plough pans following traffic movement over even moderately moist soils (Fig. 6.12) and is dependent on the texture of the soil as well as the weight of the vehicle and its load, its tyre size, and tyre inflation pressure (Hillel 1998).

One of the important recommendations of the SRDC-funded Sugar Yield Decline Joint Venture Project (Garside and Bell 2006) for reducing soil compaction has resulted in the increasing adoption of permanent crop beds and a wider crop row spacing to match that of the harvesting vehicles. A significant decrease in the percentage of the paddock area that still becomes compacted is largely dependent on the fitting of GPS-controlled steering guidance systems on all of the farming machinery, including harvesters and haul-out units. Sugarcane growers generally utilise deep cultivation techniques during the fallow phase of the cane cycle to 'undo' compaction from the previous cropping cycle followed by a number of tillage operations, using tyned implements, offset discs, and/or rotary hoes, to break down dense blocks and clods of soil and to achieve a satisfactory tilth for the subsequent planting operation. Depending on soil type, these traditional deep tillage practices and subsequent clod breaking and seedbed tillage operations can significantly contribute to the destrction of soil structure and loss of organic matter. Surface crusting usually results and can be another impediment to the emergence of the primary tillers of the sugarcane plant. Further light cultivation may be required to break the surface crusting to enable tiller emergence

In the tropical and subtropical cane-growing regions of Queensland, traditional tillage and subsequent planting operations are determined by seasonal conditions and soil temperature. In the warmer wet tropical areas of north Queensland (Ingham, and the Cardwell to Mossman regions) the planting window can be very narrow as a result of extended wet conditions at the start of the season, and winter and early spring rainfall events later in the season. Growers in the northern, wetter regions generally plant as soon as conditions allow, and soil temperatures

do not normally influence the planting decision.

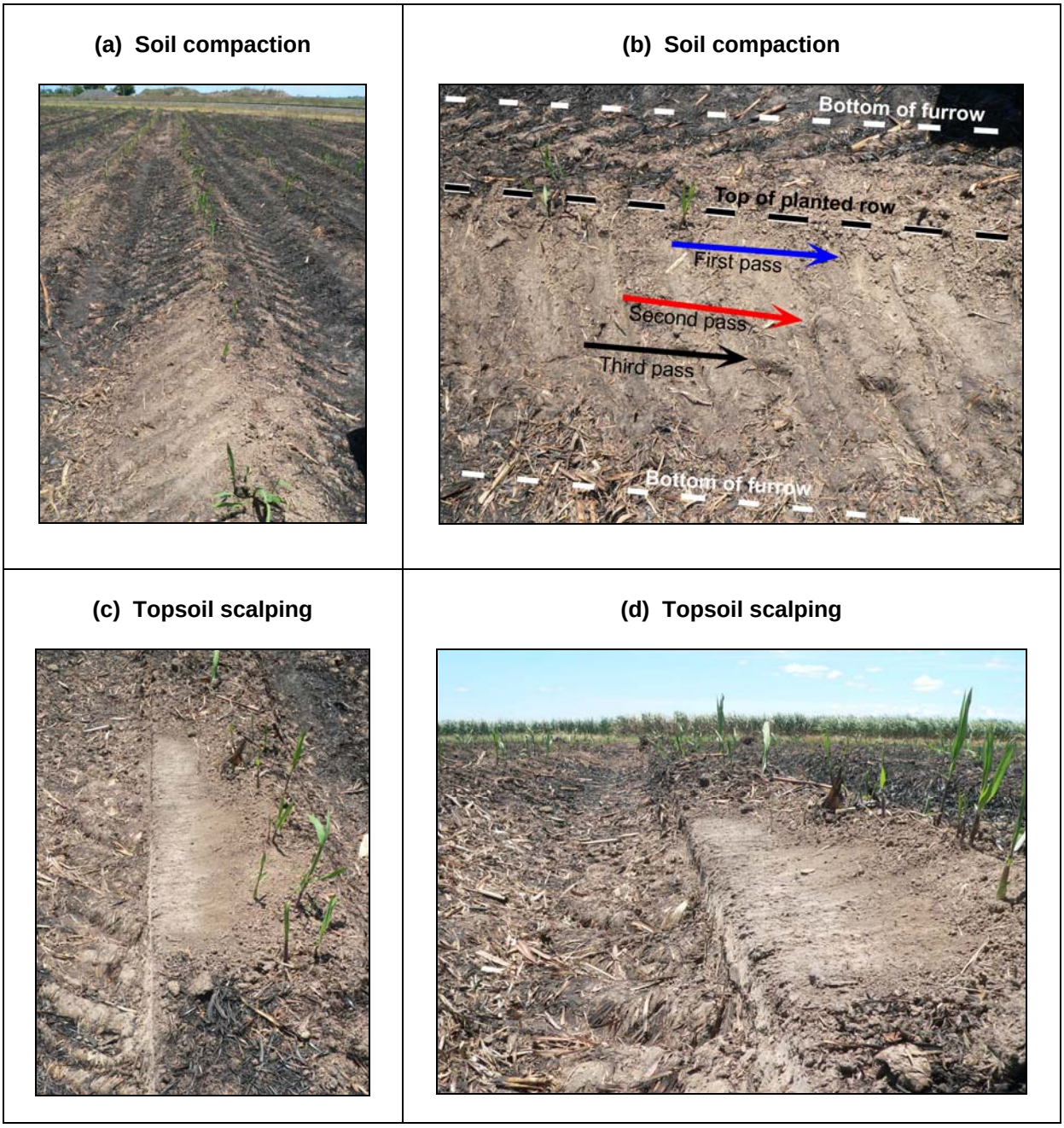


Figure 6.11. Impact of harvesting machinery on the growth potential of the ratoon crop. Site M1, 17 December 2007, prior to the adoption of BPS001 soil management recommendations.

(a) The soil has been compacted to the top of the row where the harvested sugarcane stools have begun to develop tillers as the first step in producing the ratoon crop.

(b) Evidence of at least three passes of farm machinery (sugarcane harvester and haul-out units) that have compacted the moist soil almost to the top of the row where ratoon crop tillering takes place. Subsequent drying of the clayey soil has produced a dense, hard-setting soil surface which is a significant barrier to the passage of the emerging tillers.

(c) The harvest trash has been removed to show that the soil of the row has been scalped, damaging the sugarcane stools, inhibiting tillering of the ratoon crop, and reducing its production potential.

(d) The base cutter of the sugarcane harvester has formed a steep slope on the top of the row, enhancing stormwater runoff and inhibiting water infiltration into the rootzone of the ratooning crop. Multiple passes of harvesting machinery over the paddock has produced an effective, sealed drain in the furrow, further inhibiting water entry into the root-zone of the rain-fed crop.

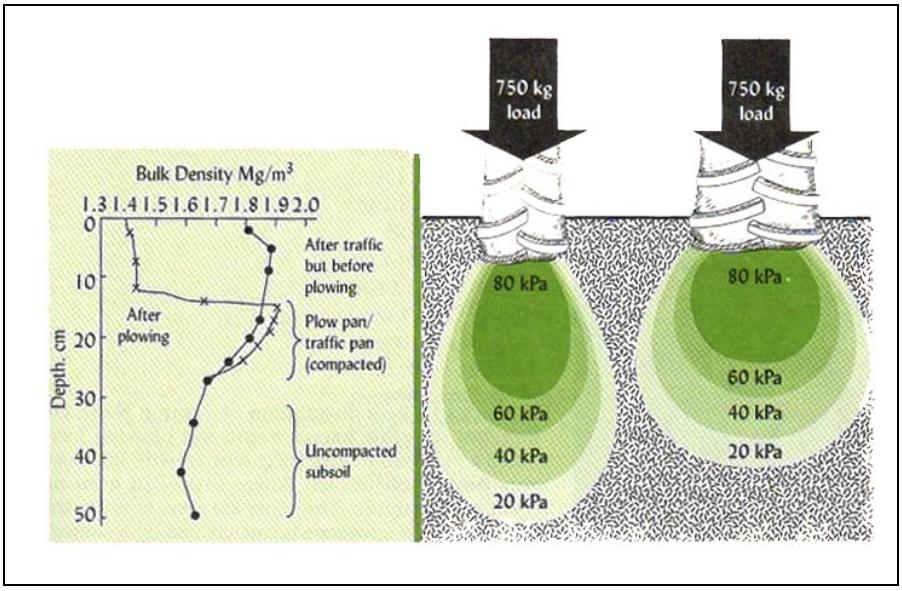


Figure 6.12. Tractors and other heavy vehicles compact the soil to considerable depths and the dense, compacted subsoils are not disrupted by shallow, conventional cultivation in clay soils.
Tractor tyres can compact a sandy loam soil to about 50 cm depth. The narrower the tyre, the deeper it will sink into the soil, and the deeper the soil compaction will extend below it. While ploughing temporarily relieves the compaction in the topsoil, it increases the bulk density of the subsoil below the depth of cultivation. The compacted subsoil (*i.e.* the 'plough pan') greatly inhibits plant root penetration through the upper subsoil. Source: Brady and Weil (2008, p.155).

In the cooler tropical sugarcane-growing areas of Proserpine, Mackay, and Sarina, the autumn planting window is generally confined to the months of May and June when the wet season monsoonal conditions have passed and soil temperatures are still above a critical 17º C level. The warmer spring planting period is traditionally confined to the months of August and September. Rainfall during the winter or early spring can cause significant problems in spring as deeply tilled soils with a full moisture profile can delay access of planting equipment.

6.6.2 Soil compaction: a case study from site H2, Lannercost

6.6.2.1 Deep ripping to relieve soil compaction: the field trial

Study site H2 is located on a 320 ha sugarcane farm at Lannercost, which is regarded as being one of the wetter cane producing areas of the Ingham district where seedbed preparation for the planting of cane and fallow management is critically influenced by the unpredictable weather patterns. The mis-match of harvesting equipment and row spacing (1.6 m), wet harvesting conditions over the ratoon cane cycle, and the absence of permanent crop beds has resulted in significant soil compaction issues at site H2. In the Lannercost area, deep tillage to remove compaction in the fallow phase is not a common practice because growers have number of concerns, mainly:

- bringing large slabs of dense, compacted subsoil to the surface requires a number of subsequent tillage operations to create a satisfactory seedbed;
- a deeply tilled seedbed with a full moisture profile can prevent the entry of machinery for critical farming operations such as planting, fertilising, or weed control.

The owner of site H2, typical of growers in the Lannercost area, utilises a number of shallow cultivations to prepare the seedbed for planting. The yield potential of the subsequent plant cane crop may be compromised by the carryover of compaction from previous ratoon cycles, but the shallow tillage strategy generally enables the entry of cane planting equipment and the establishment of a plant cane crop within the available planting window.

The last ratoon crop at site H2, prior to fallowing at the start of Project BPS001, was harvested on the 21 November 2007 and disced (8-plate offset disc) to a depth of approximately 90 mm post-harvest and followed by another shallow discing (100 mm) after rain. The bare fallow site was soil ECa mapped on 13 May 2008 (206 days after the harvest of the previous ratoon crop) with a Veris 3100 instrument after the site had been disced to an approximate depth of 90 mm. Twenty six georeferenced sites were selected from patterns indicated from the soil ECa survey; another six were added after the plant cane harvest to validate crop yield responses. The soil at each of the soil validation sites was described and characterised with chemical and particle-size analyses undertaken on samples collected from three depths within the soil profile (0 - 25, 40 - 60 and 75 -100 cm respectively). Topsoil bulk density samples to a depth of 10 cm were also taken at each soil profile site.

The effects of shallow cultivation of the clayey soils at site H2, Lannercost, are evident in Figs 6.13a and 6.13b where the discing and light ripping has disturbed and mixed the topsoil to a depth of 80 – 140 mm, but has only scalloped the top of the underlying upper subsoil of light medium clay to heavy clay field texture. Except for some smoothing of the cut surface and sealing of pores, the subsoil was left undisturbed (Fig 6.13b). Billets of cane variety Q200 were planted into the thin, loose, cultivated layer of topsoil on 15 August 2008 using a double disc opener, hand-fed, trash planter and 1.6 m row spacings.

The site was lightly cultivated on 11 - 12 July 2008 to a depth of approximately 140 mm (Fig. 6.13a) with a final discing prior to the planting operation a month later.
Prior to planting, a 32 m wide strip on the northwestern side of the H2 study site was ripped on 11 July 2008 to a depth of 0.5 – 0.7 m using a parabolic ripper in a small trial to determine the influence of residual soil compaction on the yield of the plant crop and subsequent ratoon crops (Figs 6.13c). The site received 96 mm of rain just 4 days after the ripping event and a total of 201 mm in the three weeks after ripping. The concerns of the collaborating grower about the wisdom of deep ripping fallow paddocks were substantiated as this section of the site H2 remained too wet to plant in the 2008 season whilst the balance of the site was successfully planted five weeks after the ripping. However the deep ripping trial did demonstrate that dense, compacted blocks of subsoil could be successfully broken up, and a suitable planting seed bed could be achieved in a heavily compacted soil with a deep ripping (0.5 - 0.7m) and a single pass of a crumble roller (Fig. 6.13d).

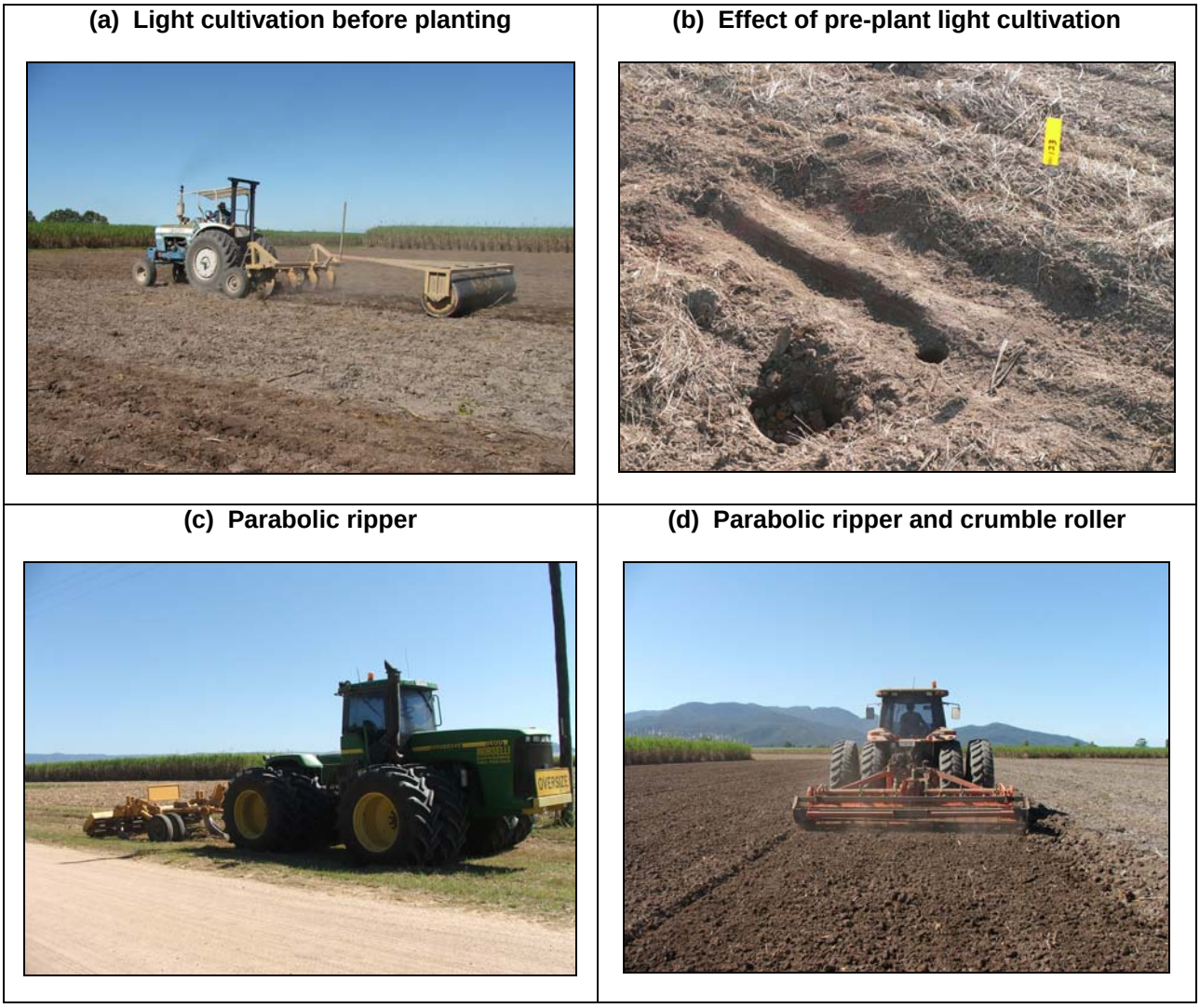


Figure 6.13. Deep ripping by heavy machinery is needed to disrupt subsoil compaction ('plough pans') in heavy clay soils.

(a) Light cultivation by 8-plate offset disc and roller at site H2 in preparing the soil for planting, 11 July 2008.

(b) The pre-planting cultivation disturbed the upper topsoil (removed in part) of sandy clay loam field texture, but the discing has left a scalloped surface on the undisturbed subsoil of light medium clay field texture at soil profile 23 of site H2 on 2 June 2008.

(c) The parabolic ripper that de-compacted the soil over part of site H2 to a depth of 0.5 – 0.7 m.

(d) The acceptable seedbed produced by the ripper and crumble roller combination on 11 July 2008.

A dynamic cone penetrometer, built to the dimensions of Vanags *et al.* (2004; Fig. 6.14a) was used to continuously log soil resistance to penetration to a depth of 480 mm at four replicated locations within 1.5 m of each of the initial 26 soil profile validation locations at site H2 (Fig. 5.10). The penetrometer measurements reflect differences in soil strength, or compaction status of the soil at the selected profile sites. Because soil strength varies with soil moisture status, the penetrometer measurements at site H2 were completed in one day (3 June 2008).

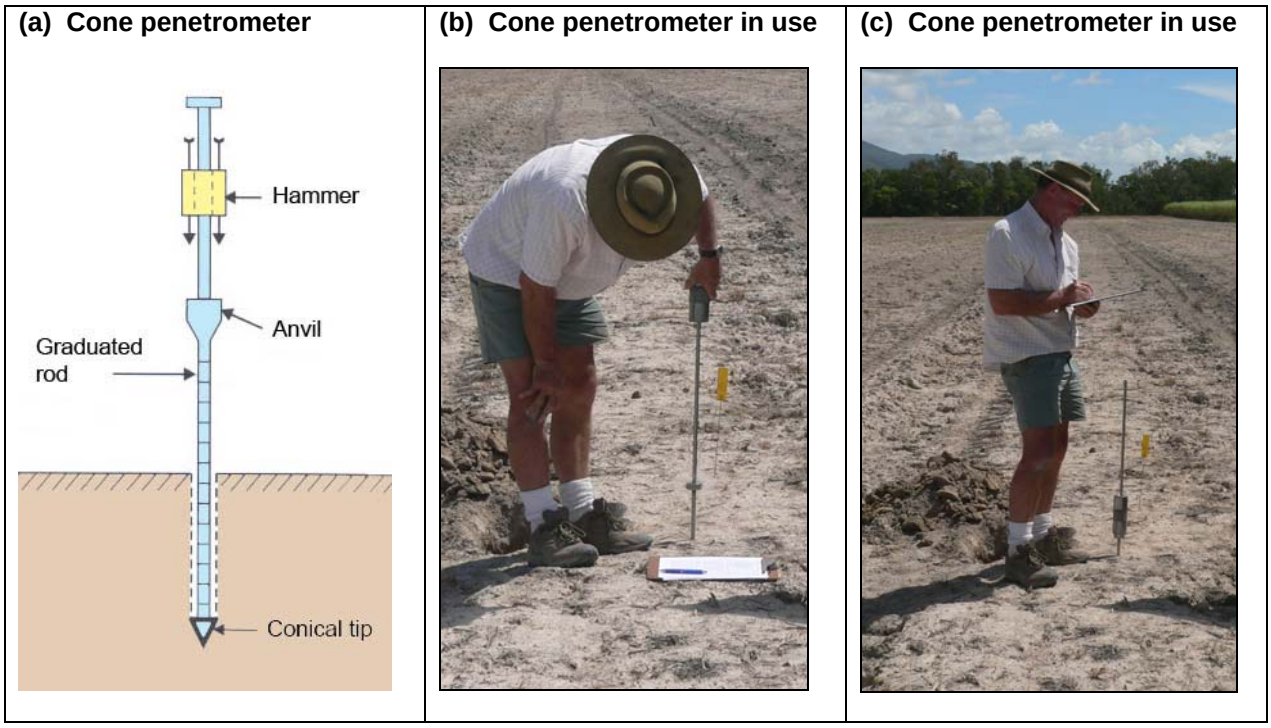


Figure 6.14. The dynamic cone penetrometer and its use in the field.
(a) Dimensions of the cone penetrometer (after Vanags *et al.* 2004): mass of the hammer = 4.115 kg, distance hammer falls to the anvil = 0.523 m, mass of the graduated rod = 1.531 kg, diameter of the conical tip = 12 mm, basal area of the conical tip = 1.13 x 10^{-4} m^2. Source of diagram: Hillel (1998).
(b) Preparing to release the hammer at site H1.
(c) Recording the depth of penetration after each blow of the hammer at site H1.

The four replicated penetrometer measurements were converted to a mean trend in soil penetration resistance with depth by the following method developed by Project BPS001. For each replicate, the mean depth of penetration (D) between successive blows, was calculated from the accumulated depths recorded after each hammer blow. The penetration resistance (R, expressed in MPa) may be calculated from the formula of Vanags *et al.* (2004):

$$R = \{ (m\ g\ H) / A\ \Delta z \} . \{ m / (m + m') \} \qquad \textit{Equation 1}$$

where: R is the resistance to penetration (Pa)
m is the mass of the hammer (kg)
g is the acceleration due to gravity (9.81 m s^{-2})
H is the distance the hammer falls (m)
A is the basal area of the conical tip (m^2)
m' is the mass of the shaft (kg)
Δz is the depth of penetration recorded (m)

Using the dimensions of the actual penetrometer used (Fig. 6.14a), Equation 1 can be simplified to:

$$R = (0.136157 \times 1000) / \Delta z \qquad \textit{Equation 2}$$

where: R is the resistance to penetration (MPa)
Δz is the increase in depth of penetration (mm) from successive blows of the hammer.

The R value was calculated from Equation 2 for each blow of the hammer. The R and Δz values for each of the four replicates, were copied and pasted into a single file of R and corresponding Δz values for each soil profile location, sorted into increasing depth values from which were calculated the mean Δz value within the depth range of 0 - 50 mm, and the corresponding mean R value. The process was repeated down the file, producing mean R and Δz values for each of the 50 mm depth increments; the ten mean R values were then plotted against the mean Δz values. The resultant curve represents the mean penetrometer resistance values in standard depth intervals, and has been derived from all the data contributing to the four replicated determinations at each site in the field.

Bulk density sampling, soil moisture and penetrometer measurements were repeated on 15 October 2008 (61 days after planting and prior to the hill-up operation) at the same profile locations to determine the relative changes in the soil compaction status in an establishing sugarcane crop and in the adjacent, deeply ripped, bare fallow.

6.6.2.2 Root penetration into compacted soils

A search of the literature has revealed little information on the threshold of soil penetration resistance that seriously impedes the growth of sugarcane roots. Cannell (1977) showed that plant roots are generally unable to enter pores narrower than their root caps. Hence, the growth of roots in dense, compacted soils with few large pores means that the roots must overcome the mechanical strength of the soil to push aside soil particles and force their way into the soil. Alternatively, the plant roots have to grow through cracks and fissures in the soil. Ehlers *et al.* (1983) studied soil bulk density, soil wetness, and root growth in both tilled and untilled loam soils and found an inverse relationship between oat root growth and soil penetration resistance; the limiting penetrometer resistance for root growth was found to be 3.6 MPa in the tilled surface soil layer, and 4.6 – 5.1 MPa in the underlying soils.

Root growth of a range of field crops (*e.g.* cereals, cotton, corn, peas, and peanuts) virtually ceases in soils with penetration resistances greater than 3 MPa (Dexter 1987). Hazelton and Murphy (2007) identified a similar threshold for cereal crops, but suggested that it may not always hold because roots can still grow in cracks, fissures, and old biopores in the soil, which may not be detected by the penetrometer. They also indicated that once a penetration resistance of 2.4 MPa is exceeded, root growth is largely restricted to existing pores and planes of weakness in the soil.

In the absence of critical data for sugarcane root penetration into soils, Hughes *et al.* (2009) used a value of 3 MPa as an indicator of soils whose density will inhibit sugarcane root growth.

6.6.2.3 The potential of zonal deep ripping

The dynamic cone penetrometer was used at georeferenced borehole sites across site H2, including the area that had been deeply ripped in July 2008, to quantify the impact of the ripping on soil strength attributes. Unseasonal wet conditions in the ripped trial in July 2008 (Table 3.2) prevented the entry of planting equipment into the paddock and validated the grower's misgivings about adopting a deep ripping practice. A comparative analysis by Hughes *et al.* (2009) of soil penetration resistance curves in lighter- and heavier-textured soils in both the ripped trial area and in the conventional, shallow cultivation (to 100 – 140 cm) confirmed a high degree of residual compaction in both the lighter and heavier textured subsoils.

Figure 6.15 shows soil penetration resistance curves for Profiles P-6 and P-16 that had relatively light textured topsoils (field textures of coarse sandy clay loam - light clay) and were located in the conventional and deep ripped areas, respectively; profiles P-15 (conventional cultivation) and P-21 (deeply ripped) were heavier textured (field textures of light medium clay). The soils under conventional cultivation, regardless of soil texture characteristics, showed little change over the 16 weeks between soil penetrometer surveys with virtually no reduction in their soil penetration resistance below 3 MPa at shallow depths (compare Figs. 6.15a and 6.15b). The soils of the deeply ripped area, however, showed a considerable reduction in soil penetration resistance down to a profile depth of 400 mm (Fig. 6.15c and 6.15d).

This part of Project BPS001 has shown that conventional, shallow (100 – 140 mm) cultivation seedbed preparation strategies improve the bulk density levels of the surface soil (cultivation) layer, but the soils remain highly compacted as little as 100 – 500 mm below the cultivation layer. The deep ripping had a minimal effect on topsoil bulk densities, but dramatically reduced compaction in the subsoil. The effective plant rooting depth (*i.e.* the part of the soil profile with penetrometer resistance values of less than 3 MPa), was increased by the ripping to a depth of 300 – 400 mm, or 2 – 4 times the plant rooting depth available in the conventionally cultivated soils, irrespective of topsoil textures (Figs 6.15c, 6.15d).

The deep ripping trial demonstrated the possibility of utilising GPS-guided zonal tillage techniques to undo residual soil compaction cost-effectively without compromising timely access of planting equipment into fallow paddocks sugarcane producing areas with high rainfall. Zonal tillage under GPS-guidance will facilitate the removal of compaction layers in areas to be planted whilst maintaining compacted wheel tracks for vehicular passage and the drainage of excess rainwater.

Furthermore, deep ripping along the centre of permanent planting beds will open up the soil profile and enhance its ability to store soil water in dry years. The use of higher than normal hill-ups after crop establishment will allow for good drainage of the crop root zone under wet conditions. By combining the two practices under GPS-guidance offers a realistic approach to some fundamental precision agricultural practices of benefit in sugarcane cultivation on clay soils in the wet tropics.

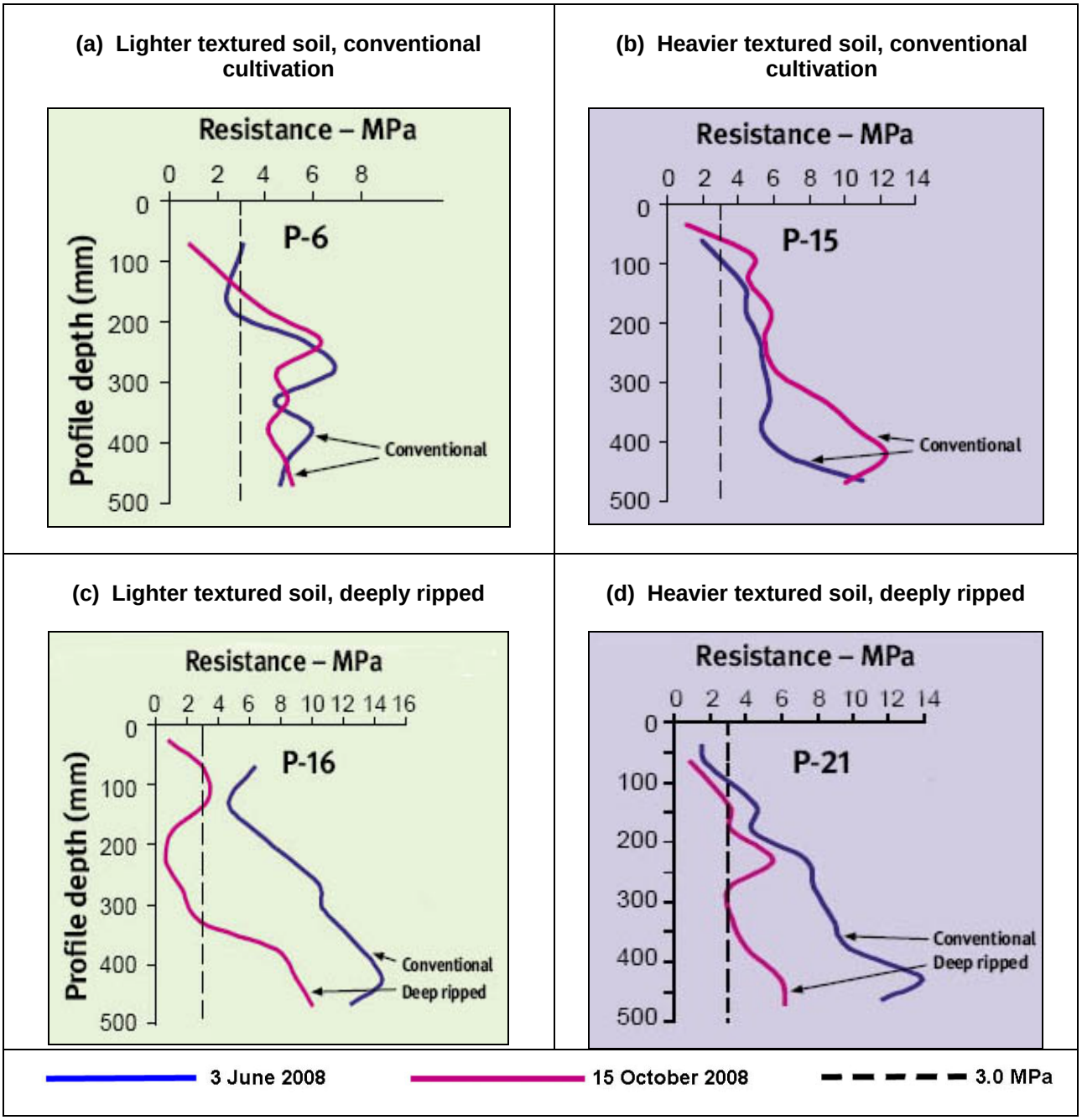


Figure 6.15 Deep ripping reduces penetrometer resistance of subsoils closer to the 3 MPa threshold for root penetration ability of cereals (vertical dashed line) in both light and heavy-textured soils at site H2, Lannercost.

(a) **Profile P-6 Conventional cultivation, light texture:** clay loam (topsoil), sandy loam (subsoil), Surface soil bulk density: 1.60 g / cm^3 reduced to 1.29 g / cm^3 by second cultivation.

(b) **Profile P-15 Conventional cultivation, heavy texture:** silty loam (topsoil), light clay (subsoil), Surface soil bulk density: 1.70 g /cm^3 reduced to 1.19 g / cm^3 by second cultivation.

(c) **Profile P-16 Deeply ripped, light texture:** clay loam (topsoil), sandy loam (subsoil), Surface soil bulk density: 1.35 g /cm^3 reduced to 1.26 g / cm^3 by deep ripping.

(d) **Profile P-21 Deeply ripped, heavy texture:** silty loam (topsoil), light clay (subsoil), Surface soil bulk density: 1.25 g / cm^3 reduced to 1.02 g / cm^3 by deep ripping.

Hughes *et al.* (2009) concluded that the adoption of controlled traffic farming systems and integration of GPS guided zonal tillage below permanent planting beds should facilitate:

- maintenance of compacted wheel tracks enabling timely paddock entry after rain;
- cost-effective removal of sub-surface residual compaction in the crop root zone through zonal deep ripping;
- a transition to a fully integrated, permanent bed, controlled traffic farming system with GPS guidance on all machinery.

6.7 STABILITY OF CROP YIELD OVER TIME

Di Bella *et al.* (2009) identified the stability of yield patterns over time as an important issue that needs to be considered when interpreting a crop yield map. The issues controlling yield stability can be grouped into three categories:

- *Short term yield variability:* controlled by factors that impact on cane yield in a single year. They include flooding, rainfall distribution, nitrogen application, pests, and diseases.

- *Medium term yield variability:* controlled by factors that impact on cane yield during or over one cropping cycle. They include variety selection, plant establishment problems, stool loss, or stool death.

- *Long term or permanent yield variability:* controlled by factors that impact over several cropping cycles. They include soil type, topography, site drainage, climate, and land tenure issues.

The short and medium term factors can be readily manipulated or managed in most cases. The long term or permanent factors generally cannot be easily modified or readily managed. In most cases, the long term or permanent factors will determine the viability of farming operations on a particular parcel of land.

6.8 CONCLUSIONS

The correlations between manually harvested plots and NDVI mapping patterns were strong for sites H2 (Ingham) and M1 (Mackay). But the relationships between the manually harvested plots and spatially-matched NDVI values were poor at both Burdekin sites (B1 and B2). Filtering of data from sample sites with specific growth impediments (*e.g.* early lodging, grass invasion) improved the correlation between the actual sugarcane yields from the small plots and the spatially matched NDVI values at site B1.

In the past, it has generally been considered that managing yield variability in sugarcane crops could be achieved through variable-rate technology in precision agricultural production systems, and that correcting nutrient deficiencies would reduce within-paddock yield fluctuations. However, yield observations and analysis of soil data from the five project study sites in the Mackay, Burdekin, and Herbert Districts have shown that strategies to manage within-paddock variability must consider the multifaceted interactions of variables that are not restricted to nutritional issues in the cultivation zone of the soil profile. Subsoil properties and paddock topography have been found to appreciably influence plant growth and crop yield, particularly in the wetter cane growing regions; they are discussed in the next chapter.

Chapter 7

SIMPLIFYING THE COMPLEXITY OF PADDOCK VARIABILITY

7.1 INTRODUCTION

Variability in plant growth across spatial zones within sugarcane crops arises from the complex interactions of soil nutritional status, soil physical properties (especially soil texture), surface and subsurface drainage, seasonal conditions, soil health, pests and diseases, cane variety adaptability to soil type, and paddock management practices imposed by the grower. Precision agricultural technology is currently available to allow sugarcane growers to provide the inputs required to cope with most of the factors that control paddock variability on a site-specific basis.

Managing crop variability within zones in a sugarcane paddock remains an extremely complex issue, requiring an understanding of all of the variables that influence crop growth within spatially defined zones within the paddock. In this chapter, we have demonstrated some of the interactions among the key data sets (GIS spatial layers) that drive crop variability and have discussed two case studies from the study sites under rain-fed production systems for which reliable soil ECa, paddock topography, and crop yield data are available (site H2 from the 2009 harvest and site M1 from the 2010 harvest).

7.2 THE THREE KEY GIS LAYERS

Project BPS001 has demonstrated that no single GIS spatial layer is sufficient, by itself, to identify and manage the variability inherent in sugarcane paddocks. The application of paddock inputs is likely to be most effective if the yield potential of the management zones within each paddock is defined in terms of three key GIS layers:

- ***a paddock soil layer*** *(stable):*
  based on actual soil data from the field, if detailed soil maps and descriptions are available. In the absence of detailed soil maps, which is the case for most Australian sugarcane farms, deep soil electrical conductivity responses may be used as surrogate soil maps. But the ECa map patterns must be validated against actual soil profile data, especially soil texture and sub-surface drainage characteristics, at strategically located sites. We have shown in Section 5.2 (above) that the deep soil ECa data are related to stable soil properties and may be relied on to produce similar, mappable, spatial patterns from year to year and, in the case of our study, over a 5-year cropping cycle.

- ***a paddock drainage layer*** *(stable within a crop cycle, but influenced by paddock earthworks):*
  based on detailed topographic data that may be readily accessed during soil ECa surveys, or by agricultural machinery equipped with a real-time kinematic global positioning system (RTK-GPS). This layer defines water movement pathways across paddocks and characterises the drainage status of contiguous segments of the crop along each row within the paddock. The surface drainage patterns are closely related to the potential of a site to become waterlogged and the soils to become denitrified under wet conditions, or to dry out rapidly under dry conditions; in either case, these paddock management zones

will have a negative impact on crop yield. The patterns are likely to change if any earthworks are carried out in the paddock. Hence, the patterns are stable within a crop cycle but may change depending on drainage works or other land-shaping activities that may be carried out in the fallow period between successive crops in the paddock.

Project BPS001 has demonstrated the importance of paddock elevation (*i.e.* height above sea level) in predicting crop yield: the higher, better drained parts of the paddock are generally the better yielding areas, particularly in the wetter sugarcane growing regions (Section 6.6, above). The paddock drainage layer may be refined, in the future, by including information on paddock slope angles, slope lengths, within-paddock ponding depths, and ponding elevations that have not been explored in the current project. In addition, the paddock drainage layer could be further enhanced by including estimates of the internal drainage of soil profiles, perhaps through measurements of water infiltration and transmission rates, soil water-holding capacities of specific soil horizons, or the use of field properties of soils indicative of poor profile drainage such as the hierarchy of soil texture data through the profile, and the nature and occurrence of pale grey or bluish grey soils, rusty stains along root holes, red and grey soil mottles, ferromanganiferous gravels, or hardpans in the subsoil.

- ***a crop yield layer*** *(variable responses to seasonal fluctuations in weather regimes, pests and diseases, and paddock management practices and strategies):*
  reflecting differences in soil and site parameters controlling growing conditions within spatially defined areas (*i.e.* management zones) within paddocks. The crop growth patterns may be detected from processed high resolution satellite imagery captured prior to harvest, and from harvester-mounted crop yield monitors (Section 6.2, above). We have found that patterns in crop yield variability are closely related to the distribution of contrasting soil groups in relation to paddock topography. The stability and definition of crop yield zones over time and under varying seasonal conditions have yet to be verified. Nevertheless, the repeatability from year to year of the definition and stability of higher- and lower-yielding crop production zones, under different climatic and management regimes, will be important factors influencing the future direction of precision agriculture in sugarcane.

7.3 INTERACTIONS AMONG KEY GIS LAYERS: TWO CASE STUDIES

7.3.1 Understanding paddock variability at site H2, Lannercost

7.3.1.1 The data sets

At site H2, Lannercost, we have developed a simple template that allows matching of the spatial variations in the 2009 crop yield with patterns in the poorly-drained, clay-rich soils and paddock elevation (as an indicator of drainage) under high rainfall (2340 mm median annual rainfall). The key GIS layers that may be used to simplify the variations in the crop yield patterns at this site (Fig. 7.1a, b) are the soils layer (especially the soil texture; Fig. 7.1c) and the elevation of the site (Fig. 7.1d). The NDVI-based crop yield map (Fig. 7.1a) excludes the 32 m wide area of the deep ripping trial (Section 6.5.2, above) where no crop was planted on the northern side of the paddock. The site elevation map has been used as a preliminary indicator of the variable surface water drainage conditions over the site, but such conditions are controlled also by the connectivity and efficiency of farm drains in the vicinity of, and beyond site H2. Under prolonged, heavy rainfall conditions, the drainage of surface runoff

waters from the site is often impeded in areas of low topographic relief in the northeastern part of the paddock; inadequacies in off-site drainage conditions may cause runoff waters to back-up into the paddock as a result of ineffective drains beyond the flooded paddock (Fig. 7.2).

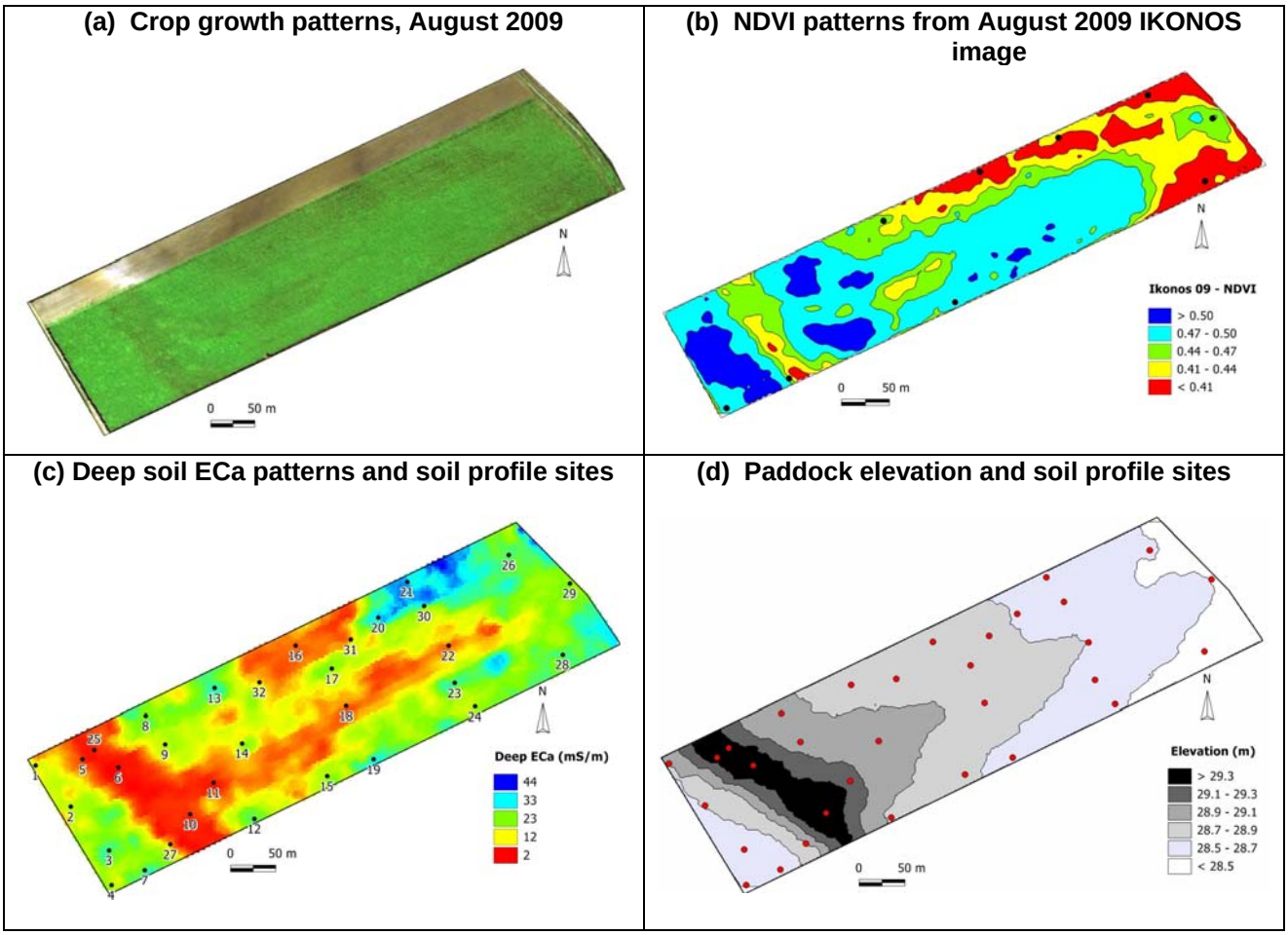


Figure 7.1. The key GIS layers that explain the variability in crop yield at site H2, Lannercost.

(a) Crop growth patterns detected by high resolution IKONOS satellite imagery on 2 August 2009, 22 days before harvesting the plant cane crop. The 32 m wide bare area along the northwestern side of the paddock is where the soil was deeply ripped (Section 6.5.2) and could not be planted after heavy, unseasonal rain in July 2008. Soil profile validation locations are shown.

(b) Normalised difference vegetation index map of the crop, derived from the image in (a). Locations of manually harvested small plots shown as '•'.

(c) Deep soil ECa patterns. The lower values (red) indicate the lighter textured soils and the higher values (blue) indicate the heavier textured soils. Soil profile validation locations are shown.

(d) Site elevation map based on TDK-GPS data provided by T. Parker, Northern Gulf Savanna Natural Resources Management, Mareeba. The total elevation range in the paddock was 1.09 m.

The correlations between the crop yield and the deep soil ECa data, based on mathematical relationships between matching georeferenced 7 x 7 m pixels, was very poor (adjusted R^2 < 20%, n = 1820; Section 6.4.3.2, above). Similarly, the correlations between crop yield and paddock elevation were poor (adjusted R^2 values also mostly less than 20%), except for site M1 with an adjusted R^2 values of 76% and 37% for the regressions of NDVI-estimated crop yield on Lidar elevation data and on RTK elevation data, respectively; Section 6.5, above).

However, if we relied on the statistical relationships between georeferenced pixels as the only indicator of the relationships among the GIS layers, we would gain a relatively poor understanding of the major drivers of the variability within the paddock.

The surface water drainage from site H2 has been considered as two contrasting systems for the removal of excess water in the following discussion of paddock variability. Drainage of the sites lying to the east of the red sandy ridge (Fig. 7.1c) is over long, gentle slopes into farm drains that are prone to flooding; stagnant runoff water may sit in the drains and low-lying parts of adjacent paddocks at and near site H2 for weeks at a time (Fig. 7.2). Surface drainage to the west of the ridge, however, is free and unimpeded over short, relatively steep slopes from the paddock (Fig. 7.1d) into efficient southwest-flowing drains that do not allow accumulated runoff water to back up into the paddock at Site H2.

+ Page 30 Townsville Bulletin Thursday, November 25, 2010

WATERLOGGED . . . Grower Geoff Morley stands knee-deep in his paddock at Lannercost Extension farm

Rain crushes growers' hopes

By MARTIN RASINI

HOPES have been dashed for the harvesting of all remaining cane in northern Queensland with rains this week keeping canefields waterlogged and reducing the crush for the past fortnight across all Queensland mills to just 1.1 million tonnes.

The figure, along with 156,000 tonnes crushed in NSW over the period brings cane crushed in the 2010 season to just over 26 million tonnes, leaving six million tonnes of Australia's estimated 32 million tonne crop still in the paddocks, half of it in the Burdekin.

The Australian Sugar Milling Council said yesterday the best case scenario now was that four million tonnes could be harvested and crushed before Christmas, with the Burdekin to account for most of the additional throughput.

The council said the relentless wet weather forced two northern mills to cease operations this week.

"The Proserpine Cooperative closed its mill on Monday with the best part of 500,000 tonnes of cane left to stand over to the 2011 season," it said

"Further south, Mackay Sugar has closed its Racecourse Mill and a decision is pending as to whether to close the Farleigh Mill.

"This would leave the Marian Mill remaining on standby for further crushing if conditions improve."

The council said there been some positive news, with the Isis Mill at Childers joining the Mossman Mill, north of Cairns, in completing its task, crushing the last of its cane late last Saturday.

"Also, both the Tablelands and Mulgrave Mills in the north are due to finish this week," it said.

"However, chances of harvesting all the crop in the Babinda, Innisfail and Tully regions are diminishing.

"More than 700,000 tonnes of cane remain to be harvested in the area.

"One million tonnes of cane remains to be harvested in the Ingham area and while the area's mills operator, Sucrogen, and growers acknowledge there is likely to be a large quantity of standover cane, there are plans to crush if the weather permits.

The council said at an estimated three million tonnes, the Burdekin had the largest quantity of cane to be cut of any growing district.

The council said about one million tonnes of cane remained in paddocks in the Mackay and Sarina districts, much of which was expected to be lost.

Figure 7.2. Flooded drainage systems close to BPS001 study site H2 at the end of the 2010 harvest season. Source: *Townsville Bulletin*, 25 November 2010.

The values of the three key GIS layers (crop yield, soil texture, site elevation) at the soil profile validation locations at study site H2 are listed in Table 7.1, and have been ranked according to crop yield, as determined from the Techagro^{TM} yield monitor data from the 2009 harvest (Section 6.2, above). The texture of the soil at three sampling depths in each soil profile was determined from particle-size analyses (Section 4.2, above). The site elevations, calculated from RTK-GPS data collected during the EM38 survey (Section 4.1.4, above), indicate heights above the elevation of the lowest soil validation site in the paddock (site 28).

Table 7.1 The association of crop yield (plant cane harvested in August 2009) with soil texture and paddock elevation (drainage) at site H2, Lannercost.

The data are sorted by sugarcane crop yield in tonnes of cane per hectare (TCH) as determined from the 2009 Techagro™ yield monitor data. Soil profiles are located on Figure 7.1. Soil texture cells are coloured from red (lightest = most sand), through yellow, green, and pale blue, to dark blue (heaviest = most clay). Soil field textures are shown in italics for samples lacking particle-size analyses. Site elevations more than 0.4 m higher than location 28 are shaded grey.

Soil profile no.	**Crop yield** (TCH)	**Soil texture** Topsoil (0 – 25 cm)	**Soil texture** Upper subsoil (40 – 60 cm)	**Soil texture** Lower subsoil (75 – 100 cm)	**Elevation** (m)	(m above site 28)
Sites on poorly drained, long, gentle slopes to the east of the red sandy ridge:						
09	131	Sandy loam	Clay loam	Clay	29.06	0.65
14	128	Loam	Clay	Clay loam	28.99	0.58
10	128	Sandy loam	Sandy loam	Sandy loam	29.50	1.09
11	118	Sandy loam	Sandy loam	Sandy loam	29.20	0.87
23	108	Loam	Clay	Sandy loam	28.59	0.18
18	107	Loam	Sandy loam	Sandy loam	28.84	0.43
12	106	Loam	Clay	Clay	28.86	0.45
22	87	Loam	Sand	Sandy loam	28.70	0.29
15	84	Loam	Clay	Clay	28.69	0.28
30	74	*Sandy clay loam*	*Light medium clay*	*Light medium clay*	28.60	0.19
32	66	*Sandy clay loam*	*Sandy clay loam*	*Medium heavy clay*	28.84	0.43
29	59	*Sandy clay loam*	*Light medium clay*	*Light medium clay*	28.46	0.05
20	58	Loam	Clay loam	Clay	28.68	0.27
24	58	Loam	Clay loam	Clay	25.00	0.09
19	57	Loam	Clay loam	Clay	28.62	0.21
17	51	Clay loam	Clay	Clay	28.79	0.38
31	40	*Sandy clay loam*	*Light medium clay*	*Light medium clay*	28.75	0.34
26	33	Clay loam	Clay loam	Clay	28.51	0.10
28	31	*Medium clay*	*Medium clay*	*Light clay*	28.41	0
Sites on well drained, short, steep slopes to the west of the red sandy ridge:						
03	114	Loam	Clay loam	Clay loam	28.60	0.19
07	104	Loam	Clay loam	Clay	28.60	0.19
04	65	Loam	Clay loam	Clay	28.51	0.10
02	53	Loam	Clay	Clay	28.70	0.29
27	53	*Sandy clay loam*	*Medium clay*	*Light clay*	28.86	0.45

7.3.1.2 Paddock variability defined by multiple spatial data sets

- *Drainage to the east of the red sandy ridge*

The data of Table 7.1 show that soil texture and elevation have had a very strong influence on crop yield from the sites to the east of the red sandy ridge at site H2. Six of the eight locations that yielded more than 85 TCH (tonnes of cane per hectare) were at the highest locations in the paddock where it is assumed they were sites with good surface water drainage. The two exceptions (sites 22 and 23), and four of the other high-yielding sites, had the lightest subsoil textures (sand or sandy loam) that is likely to present only minimal impedance to internal soil profile drainage when compared with the clay-rich subsoils of the rest of the soil profiles in this area.
The crop at sites 22 and 23 have benefited from relatively high elevations, which in lands with very low slopes is an indicator of enhanced surface drainage, and light textured subsoils – both of which encourage both internal and external soil drainage and reduce the potential for waterlogging at the site. The sites that produced the poorer crops were generally located at the lower elevations, prone to waterlogging by impeded surface drainage, or had heavier clay-rich subsoils that would have impeded internal soil profile drainage.

The data of Table 7.1 also show that the lower yielding areas at site H2 produced crops of 31 – 84 TCH, had poor surface drainage (as a consequence of elevations of less than 0.4 m above the lowest point in the paddock), or had heavy textured subsoils and slow internal soil profile drainage; either of these factors is detrimental to the growth of sugarcane and will reduce the crop yield, and if prolonged, may kill the crop. Site 32 sits in a higher part of the paddock (elevation 0.43 m higher than the lowest point) and may have been sufficiently elevated for reasonably rapid surface water drainage; its low crop yield is likely to be a consequence of the very heavy field texture of its deep subsoil, which may have resulted in very slow internal profile drainage and waterlogged conditions inhibiting crop production.

- *Drainage to the west of the red sandy ridge*

Site elevation is an irrelevant indicator of surface water drainage in the well drained part of the paddock to the west of the red sandy ridge where runoff water is rapidly lost to efficient southwest-flowing farm drains. Soil texture appears to have been more important than site elevation as a control over crop yield in this part of site H2. Sites 2, 3, 4, and 7 all lie to the west of the low, red, sandy ridge and on short, relatively steep slopes, compared to longer and gentler slopes to the northeast of the sandy ridge. These sites and soils experience relatively rapid runoff of surface water that is able to leave the paddock without being backed up by impeded drainage in adjacent paddocks. The data of Table 7.1 show that site 3 was the highest yielding site (114 TCH) to the west of the red sandy ridge and had the lightest soil textures in both its upper and lower subsoils. Profile 27 was the lowest yielding site (53 TCH) and had the heaviest textures throughout the soil profile.

- *Understanding crop variability across the paddock*

In summary, the variability in crop yield at site H2 has been controlled by waterlogging issues related to slow surface drainage or poor internal drainage of the soil profiles with low hydraulic conductivities in heavy textured subsoil layers. In the part of the paddock with long, gentle slopes and slow movement of surface runoff through farm drains, the elevation of the site (as a surrogate measure of surface drainage from the site) was a significant control over crop yield. Overall, the highest yielding parts of the sugarcane crop were located in the parts of the paddock with the best drainage of surface water and best internal drainage of the soil

profiles. The poorest yielding parts were related to low, potentially waterlogged areas, or to areas where the subsoils were of heavy texture and impeded internal soil profile drainage.

This example shows how the paddock variability can be readily explained in terms of not one, but three GIS layers: a soils layer (the deep ECa map related to soil texture conditions revealed by the ECa map validation process), a paddock drainage layer related to the site topography (a digital elevation layer), and a crop yield layer. All of these data sets are readily obtained and may be used to define areas of relatively uniform crop responses that effectively define the major management zones within the paddock.

7.3.2 Understanding paddock variability at site M1, Homebush

The relationship between soil ECa data from site M1 and actual soil properties, including internal soil profile drainage, has been discussed above (Section 5.3.5, above). In the following section we demonstrate the value of adding topographic data from a paddock elevation model to the data available from a soils GIS layer to provide a better understanding of the causes of variability in crop yield patterns across the paddock.

7.3.2.1 The data sets

The relationships between patterns in stable deep soil ECa measurements (Fig. 7.3a) and actual soil patterns across the paddock at site M1 have been discussed above (Section 5.3.5.4, above). The soils lie on a relatively uniform slope across the paddock towards a drain in the west (Fig. 7.3b), which flows slowly to the north; the off-farm drainage is extremely slow as a consequence of poorly integrated farm drainage in the region. Consequently, parts of site M1 are prone to seasonal waterlogging. The maximum extent of severe waterlogging towards the end of the bare fallow period in July 2008 was mapped by a hand-held GPS unit on a field traverse around the edge of the soil that was too wet to walk over (Fig. 7.3c). The waterlogged conditions persisted for several weeks in 2008 and a similar pattern of waterlogging persisted intermittently from the end of the harvest in November 2010 until May 2011.

The progressive impact of paddock waterlogging is evident in a sequence of false colour infrared, IKONOS satellite images captured before the commercial harvests over the period of the study (Fig. 7.4 a-d). As at site H2 (Section 7.3.1, above), the waterlogging of the crop has been caused in part by low paddock elevations inhibiting surface water runoff, and in part by clay-rich subsoils reducing internal soil profile drainage.

NDVI analysis of IKONOS satellite imagery captured over the first ratoon crop on 19 June 2010 was used to determine patterns in crop yield over the site M1. The imagery was processed using the protocols set out in Section 4.4.2 (above), and the NDVI values (Fig. 7.3d) were calibrated against crop yields from 12 small plots where 5 m rows of sugarcane were manually harvested on 1 November 2010 (during the commercial harvest), and the stalks were counted and weighed. A strong linear correlation (adjusted $R^2 = 0.87$; n= 12) existed between the manually harvested sugarcane yields and the corresponding NDVI values:

$$\text{tonnes of cane / ha} = 729.39\ (\text{NDVI value}) - 278.03$$

The values derived from this equation indicated yields of 100 – 150 TCH across the site. The crop had been subjected to the high winds and heavy rain from Cyclone Ului (March 2010) and other rainfall events that delivered 1691 mm of rain in the 2010 growing season (Table 3.2). The wet conditions persisted and disrupted harvesting across the region. The Te Kowai

weather station, only 8 km from site M1, received more than 5 times the long-term median rainfall during the 2010 harvest season (Table 3.2); the study site was too wet to permit harvesting on 1 November 2010 south of the heavy line shown on Fig. 7.3d. The lower parts of the paddock ponded runoff water through much of the wetter than average 2010 growing season (Table 3.2), and the prolonged presence of surface water in the paddock until April 2011 significantly affected subsequent growth of the second ratoon crop, which is discussed in the next section.

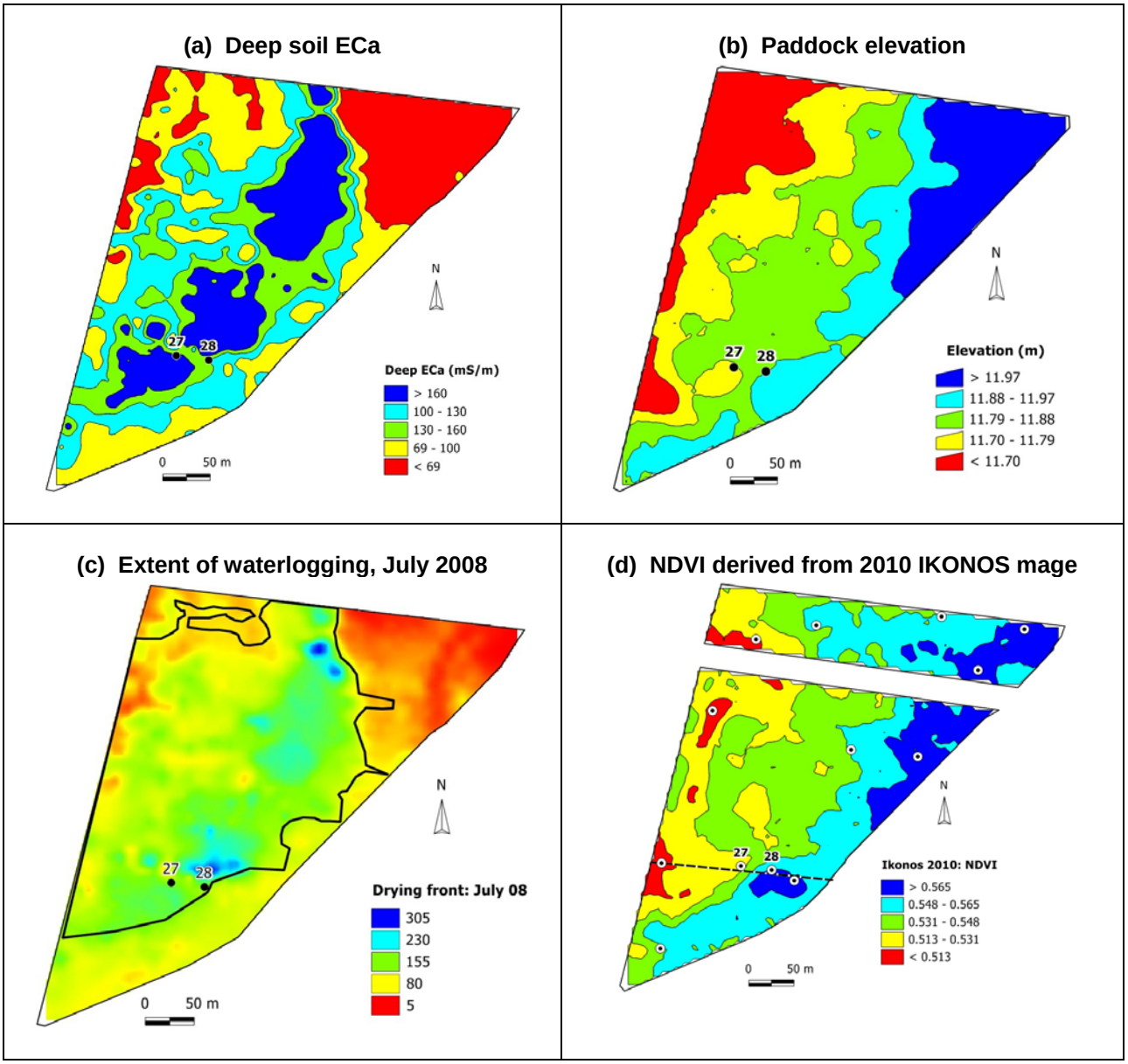


Figure 7.3. Soils, topography, waterlogging, and crop yield patterns at Site M1, Homebush.

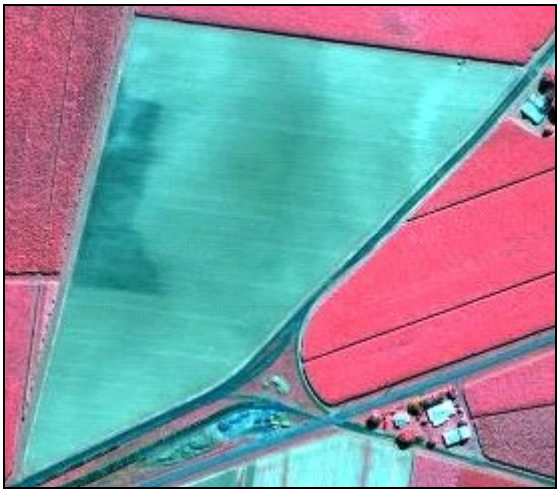
(a) Stable, deep soil ECa patterns detected on 17 June 2008, prior to planting the crop.

(b) Paddock elevation determined through processing of a 1 km² Lidar digital elevation map.

(c) The heavy line indicates the limit of saturated topsoil that was mapped by hand-held GPS on 30 July 2008. The extent of soil waterlogging at that time has been laid over a deep soil ECa map for the site.

(d) Normalised difference vegetation index (NDVI) patterns in first ratoon crop and locations of small, manually harvested plots; IKONOS satellite imagery captured on 21 June 2010. The paddock was too wet to harvest on 1 November 2010 south of the broken line near small plots 27 and 28. The gap towards northern end of part (d) marks the location of an SRDC-funded project (GGP052) aimed at relating soil compaction to crop yield.

(a) 24 June 2008: bare fallow



(b) 17 July 2009: plant crop (pre-harvest)

(c) 19 June 2010: first ratoon crop (pre-harvest)

(d) 25 May 2011: second ratoon crop (pre-harvest)

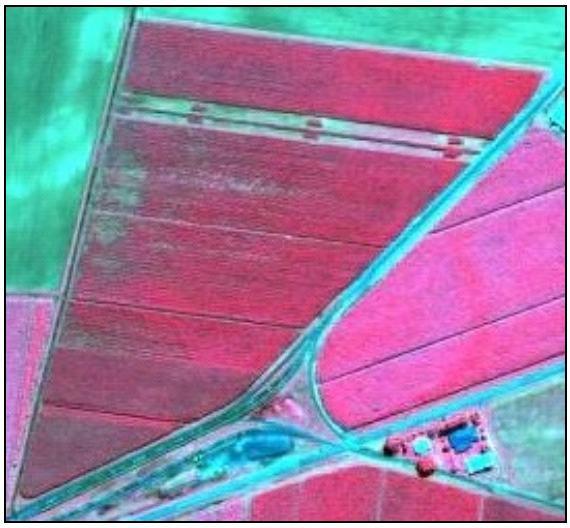


Figure 7.4 Progressive impact of waterlogging on crop yield at site M1, Homebush, as evident in false colour infrared (near infrared, red, green) images derived from IKONOS multispectral satellite images captured annually (May – July) during Project BPS001.

Strong red colours indicate vigorous sugarcane plant growth; bluish grey colours indicate poor crop growth, an open crop canopy, and bare soil. The impact of waterlogging on poor sugarcane growth was weakly apparent on the southwestern corner of the paddock in July 2009 (part b) and on the western side of the paddock by June 2010 (part c). Poor crop growth with an open canopy before harvest, and patches of bare soil, were clearly evident by May 2011 (part d).

Note the area of dark coloured mill ash applied by the grower over the bare fallow in the area of historic poor yield on the western side of the paddock in 2001 during the fallow phase of the previous cropping cycle (part a). The mill ash was applied by the grower in the belief that the weak crop growth in that part of the paddock had been driven by poor plant nutrition rather than by poor paddock drainage and extended periods of seasonal waterlogging.

7.3.2.2 Paddock variability indicated by multiple spatial data sets

Two of the small plots used to calibrate the NDVI-based crop yield estimates were located very close to the southern limit of the 2010 harvest (plots 27 and 28; Fig. 7.3d) and produced manually harvested yields of 114 TCH and 147 TCH, respectively (Fig. 7.5). The soil and topographic characteristics of these two small plots offer insights into the ways in which multiple GIS layers can be used to interpret the reasons for the variability in sugarcane crops at a paddock scale. They also provide awareness of the ways in which the complexity of the drivers of paddock variability may be simplified through the interfacing of different data sets in a GIS context.

Figure 7.5. Growth differences in the first ratoon crop at site M1, Homebush, at the time of harvest on 1 November 2010.
Variability in growth patterns of the first ratoon crop at two of the georeferenced, manually harvested sites used in the calibration of crop yield based on NDVI values from IKONOS satellite imagery. The locations of small plots 27 and 28 producing 114 and 147 tonnes of cane per hectare are shown in Figure 7.3. The photograph, facing south, was taken at harvest on 1 November 2010 and shows the trailer used to weigh the manually harvested cane stalks for the yield calibration exercises at each study site.

The soils at small plots 27 and 28 are remarkably similar, uniform, non-structured clay soils whose topsoils are very dark brown light clays, and the subsoils are dark greyish brown light medium clays at site 28, with a distinct blue/grey colour in the lower subsoil of site 27, indicating poor sub-surface drainage. The subsoil at the slightly lower locality (site 27) became increasingly alkaline with depth and had lime nodules up to 18 mm in diameter below 90 cm depth. The soil at the higher locality (site 28) was strongly acidic in the upper subsoil and neutral at 1 m depth; no lime nodules were evident. In terms of the soil groups mapped at the northern end of site M1 (Fig. 5.14), the soil at locality 27 has strong affinities with Soil Group C, and that at locality 28 is closely allied with Soil Group D.

The close similarity of the soils at localities 27 and 28 is also evident in their chemical and particle-size characteristics (Tables 7.1 and 7.2). The soils differ only in the properties at depth where the soil at site 27 had a more alkaline, slightly more saline, and more sodic deep subsoil (60 – 90 cm depth).

Table 7.2. Acidity, alkalinity, salinity, and fertility properties of the soil samples from small plots 27 and 28, site M1, Homebush.

Sample No.	Sample depth		Acidity, alkalinity, salinity			Macronutrients						Micronutrients	
	Upper limit	Lower limit	pH (water)	Electrical Conductivity	Chloride	Organic Carbon	Nitrate Nitrogen	Available Phosphorus (BSES)	Available Phosphorus (Colwell)	Potassium (Nitric Acid)	Sulphate Sulphur	Available Silicon (BSES)	Available Silicon (CaCl2)
	cm	cm		dS/m	mg/kg	%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg		
M1-27.1	0	25	5.2	0.04	28	1.1	5	16	18	0.79	14	320	51
M1-27.2	40	60	7.6	0.11	66		4						
M1-27.3	60	90	7.9	0.20	190		4						
M1-28.1	0	25	4.8	0.07	27	0.97	28	12	15	0.79	9.8	250	41
M1-28.2	40	60	6.2	0.04	26		4						
M1-28.3	60	90	7.1	0.04	25		7						

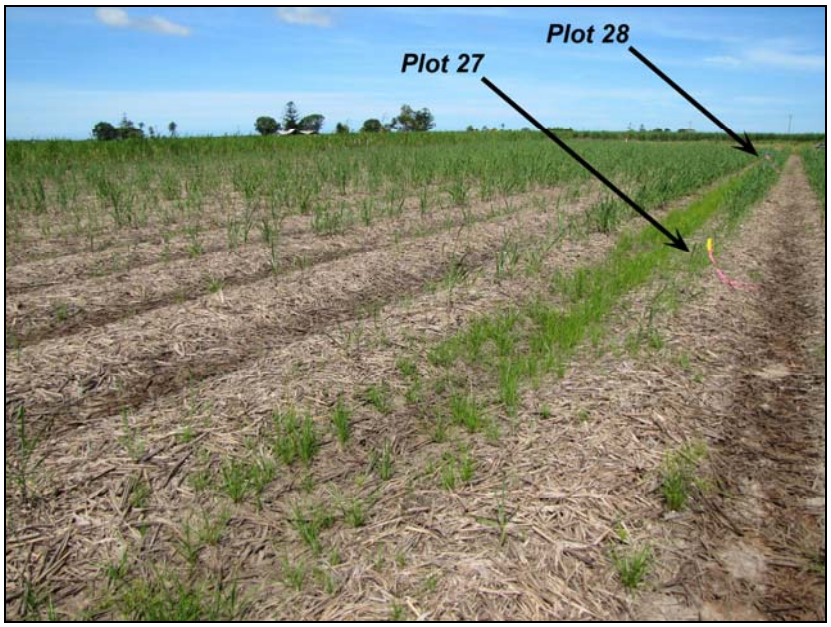
Table 7.3. Exchangeable cation and particle-size properties of the soil samples from small plots 27 and 28, site M1, Homebush.

Sample No.	Sample depth		Exchangeable cations						Exchangeable cations						Particle size				
	Upper limit	Lower limit	Cation Exchange Capacity	Exch. Calcium	Exch. Magnesium	Exch. Potassium	Exch. Sodium	Exch. Aluminium	Exch. Calcium	Exch. Magnesium	Exch. Potassium	Exch. Sodium	Exch. Aluminium	Ca : Mg ratio	Coarse sand *2.0 - 0.2 mm*	Fine sand *0.2 - 0.02 mm*	Silt *0.0-2 - 0.002 mm*	Clay *< 0.002 mm*	Silt + Clay *< 0.020 mm*
	cm	cm	meq/100g						percent					ratio	percent				
M1-27.1	0	25	9.5	4.1	3.0	0.17	0.18	2	43	32	2	2	21	1.4	4	36	28	33	61
M1-27.2	40	60	26.0	14.0	9.9	0.28	1.80		54	38	1	7		1.4	3	23	19	55	74
M1-27.3	60	90	25.8	13.0	9.9	0.25	2.70		50	38	1	10		1.3	2	30	18	50	68
M1-28.1	0	25	7.1	3.0	2.1	0.16	0.08	1.8	42	29	2	1	25	1.4	4	44	30	23	53
M1-28.2	40	60	19.4	12.0	6.6	0.18	0.36	0.29	62	34	1	2	2	1.8	3	27	18	53	71
M1-28.3	60	90	20.2	13.0	6.5	0.21	0.44		64	32	1	2		2.0	1	33	19	48	67

The yield difference of 33 tonnes of cane per hectare between the two plots was significant and relates to a growth difference that is evident even to a casual observer of the crop (Fig. 7.5). As has been shown by Tables 7.1 and 7.2, the yield difference is not driven by soil differences at the small plots. The crop has responded to a small difference in topography that, at this almost flat-lying study site, was related to a significant difference in exposure of the crop to waterlogging (Figs 7.3b, 7.3c). The subtle difference in elevation of some 100 mm between localities 27 and 28 has had a major effect on ponding of storm runoff water from the paddock, the duration of profile saturation, and the intensity of waterlogging at both sites.

The height difference between the sites, although subtle, has had a large impact on the ability of the second ratoon crop to re-establish after the September 2010 harvest. On 17 December 2010, seven weeks after harvest, the development of tillers had been noticeably poorer at the lower locality (Fig. 7.6a). The growth difference in crop at the two sites was even more marked on 5 April 2011 (five months after harvest; Figs 7.6b and 7.6c) and after a prolonged, heavy wet period that had left the paddock waterlogged from November 2010 to May 2011. The paddock was still showing signs of abating waterlogging by this stage where elevated plot 28 had effectively drained, but water was still standing in furrows of the lower locality (Figs 7.6b and 7.6c).

(a) Small plots 27 and 28, facing northeast



(b) Small plot 28, facing east

(c) Small plot 27, facing west

Figure 7.6. Growth of the second ratoon crop in the vicinity of small plots 27 and 28, site M1, Homebush.

(a) Variability in ratooning ability of the crop in response to differences in waterlogging of the soils at the two sites with contrasting yields. Photograph taken, facing east (upslope), on 15 December 2010, 7 weeks after harvest of the first ratoon crop. Note that the evidence of waterlogging in the furrow at the right of the photograph tapers off between plots 27 and 28.

(b) Reasonable growth of the second ratoon crop at, and to the east of the better drained, more elevated locality 147. Photograph taken, facing east (upslope), on 5 April 2011, five months after harvest.

(c) Poor growth of the second ratoon crop at and to the west of the lower, poorer drained locality 114, which retains stagnant surface water in the furrows as a consequence of poorly integrated farm drainage systems in the district. Photograph taken, facing west (downslope), on 5 April 2011, five months after harvest.

This study at site M1 substantiates the value in having access to a number of GIS mapping layers to understand spatial variability in crop growth within a paddock. In addition, an intricate knowledge of the various physical and chemical factors that drive soil ECa signals in the paddock provide an observant operator with additional information from a range of derived spatial layers to support critical management decisions. Where the variability in yield as defined by NDVI or yield maps is not clearly related to soil ECa mapping patterns, then follow up field validation is warranted and necessary. Access to a digital elevation layer may, in many cases, explain the reasons for poor growth not necessarily evident in soil ECa mapping patterns.

From a precision agriculture perspective, the availability of accurate and reliable soil, topography, and yield mapping layers is a fundamental component in identifying and managing within paddock variability and an area where further development and research is required.

7.3.2.3 Implications for farm management

The combined effects of soil differences, topography, and waterlogging have had a large impact on the growth and production of the second ratoon crop at site M1. The soils on the eastern, higher side of the site were well drained, but those on the lower, western side were poorly drained for two reasons. First, the slope of the paddock encourages the drainage of surface water to the west, but a poorly integrated farm drainage network, combined with low slope angles over the region, restrict drainage and cause flooding in the lower parts of the paddocks in most wet seasons. Second, the soils on the western side of the paddock have much deeper, coarse sandy upper soil layers than do the other soils of the transect. They allow reasonable infiltration of rain or irrigation water, but a very clayey layer in the subsoil presents a throttle to water movement through the soil profile. A deep borehole drilled to 2.4 m at soil profile site 6 (Fig. 5.14) on 23 August 2008 passed through relatively dry upper soil layers and into waterlogged soils sitting on the barrier to water movement at 1.6 m depth; deeper drilling on the same day was through much drier, but still moist soil.

Infiltrating water accumulates on top of the dense, clayey subsoil layer and perched water tables develop in most wet seasons, causing waterlogging of the crop root zone and poor growth of the sugarcane crop, but in extended dry periods these soils dry out very quickly resulting in severe crop stress. Because perched water tables and impeded subsoil drainage were not recognised as the reason for poor crop growth on the western side of the paddock, mill ash had been applied to part of the area of poor crop growth (Fig. 3.6b) in an attempt to address what had been interpreted, prior to the start of Project BPS001, as a crop nutrition problem.

The first step in improving paddock drainage is to clean out the existing farm drains and to agitate for communal action to improve the integration and efficiency of the drainage network in the immediate catchment.

A management action that may be undertaken to reduce the impact of waterlogging on crop production is to use the paddock topography GIS layer to delineate the areas involved and to identify the extent to which the planting rows need to be raised in order to stand about 100 - 150 mm higher than the level of ponded water in the paddock. Then, during the planting and hilling-up phases early in the establishment of the crop, ensure that the tops of the rows are raised to the required height. Precision agricultural controls will be required to ensure that the

planting depths and hill-up heights are related to the requirements of specific zones within the paddock. In addition, the sugarcane harvester will require an automatic base cutter height adjuster to allow for variations in hill-up height along the cane row during the harvest.

Another approach to solving this problem is to use a "variable variety planter" that is capable of precision agricultural control over the varieties that are planted along a row according to their tolerance of freely draining or waterlogged conditions.

7.4 PRECISION AGRICULTURE: LINKING THE KEY GIS LAYERS

The major outputs from Project BPS001 are set out in the present document that provides a rigorous understanding of the scientific principles that underpin the use of a set of GIS layers (primarily soil, topography, and crop yield patterns) to understand the complexity of the growth differences within a sugarcane paddock. The cutting-edge technologies developed provide the foundation for a holistic farm management system in sugarcane production that goes beyond current best management practices. The new farming system offers a pathway that can be adopted by growers seeking to change to, and to implement progressively, precision agricultural production of sugarcane.

7.4.1 Adoption of precision agricultural practices in sugarcane production

An understanding of the interactions of variables influencing crop growth in defined zones within paddocks is a prerequisite for developing and adopting best management, precision agricultural practices in sugarcane. The outputs from Project BPS001 allow the specification of precision agricultural methods for managing spatial variability in sugarcane soils and crops. The methods offer a practical approach for the improved economic and environmental management of sugarcane paddocks. Site-specific management of inputs and the variable application of nutrients, soil amendments, and other inputs are based on the crop yield potential of management zones within paddocks. Efficient and effective application of inputs is likely to significantly enhance the quality of waters leaving sugarcane farms while improving the productivity and returns within the production system; the potential benefits to accrue from such an approach to sugarcane production are set out in Section 8.3.2, below.

The following relatively simple model offers a rationale for the progressive implementation, expansion, and refinement over time of precision agricultural practices on any farm where spatial data are available at any level of complexity. The model lists the characteristics of increasingly higher levels of practice that may adopted in precision agricultural operations in sugarcane production. It ranks the farm operations from the PA 4 level (the fundamental entry level into precision agriculture practices) to PA 1 operations at the highest level of implementation.

The sugar industry is in the initial stages of transition to precision agriculture and many of the early adopters are currently operating at levels PA 4 or PA 3 (entry level or partial application of proven technology). Only a few growers in any district are at a stage where they have advanced beyond a PA 3 level and have integrated a few components of level PA 2 (application of proven technology) into their farming practices. No Australian sugarcane grower has yet adopted all the recommendations of level PA 1 (the industry goal).

PA 4 level operations (entry-level practices)

PA 4.1 Control of farm machinery
- *Controlled traffic with GPS guidance for the planting operation.*

PA 4.2 Soil testing protocols
- *Soil testing sites located in major soil units within blocks.*

PA 4.3 Basis of farm input decision-making
- *Whole block nutrient programs which may be applicable to crop classes at a farm scale.*
- *Written records of all farm inputs maintained.*

PA 3 level operations (partial application of proven technology)

PA 3.1 Control of farm machinery
- *GPS guidance for most operations.*

PA 3.2 Soil testing protocols
- *Apparent electrical conductivity (ECa) soil mapping during fallow phase of production cycle.*
- *Georeferenced soil test sites derived from soil ECa mapping patterns.*

PA 3.3 Basis of farm input decision-making
- *Block-based nutrition programs applied to the full crop cycle.*

PA 3.4 Zonal management
- *Site-specific application of ameliorants based on georeferenced soil tests and soil ECa mapping.*

PA 3.5 Spatial data management
- *Spatial data processing and storage methods accord with industry-accepted protocols and standards.*

PA2 level operations (application of proven technology)

PA 2.1 Control of farm machinery
- *GPS guidance for most paddock operations including harves*ters.

PA 2.2 Soil testing protocols
- *Soil testing sites determined by patterns in both soil ECa and crop yield.*

PA 2.3 Basis of farm input decision-making
- *Soil profile texture class hierarchy established using broad sand, loam, and clay texture classes for topsoil and subsoil layers within management zones.*

- *Use of soil maps incorporating soil texture and / or drainage classes at an appropriate PA scale.*
- *Use of crop yield potential zones defined by analysis of site-specific archived satellite imagery or aerial photography collected over a number of sugarcane crop cycles.*
- *Sugarcane varieties selected through analysis of historic spatial yield data on the basis of adaptability to soil properties and position in the landscape.*
- *Crop yield potential zones classified into low-, medium-, and high-yielding categories.*

PA 2.4 Zonal management
- *Zonal management practices derived from access to within-paddock information including spatial data from soil, crop yield, and topography GIS layers.*
- *Site-specific tillage and application of ameliorants expanded to within-paddock variable application of nutrients based on yield potential zones.*
- *Within-paddock nutrient application rates based on a nutrient management protocol that is recognised by the industry.*

PA 2.5 Spatial data management
- *Spatial data processing and storage methods accord with industry-accepted protocols and standards.*

PA 1 level operations (the industry goal)

Some of the components listed as PA 1 practices below are still conjectural and require validation.

PA 1.1 Control of farm machinery
- *GPS guidance for all plant and equipment entering every paddock.*

PA 1.2 Soil testing protocols
- *Soil testing sites determined by ECa, crop yield, topography, and soil texture mapping patterns.*
- *Soil ECa mapping capacity expanded to include mapping in a post-harvest trash blanket environment.*

PA 1.3 Basis of farm input decision-making
- *Utilisation of an expanded hierarchy of soil texture data (e.g. the 15 texture classes of the National Committee on Soil and Terrain, 2009) within defined management zones.*
- *Crop yield potential of management zones adjusted annually in response to weather and harvest data.*
- *Paddock inputs defined by critical properties of crop yield potential zones.*

PA 1.4 Zonal management
- *Fine tuning of inputs based on yield potential zones and seasonal climate forecasting.*
- *Nutrient input rates adjusted to optimise genetic potential of adapted sugarcane varieties in defined management zones.*
- *Nutrient input rates adjusted to reflect the declining yield potential of ratoon crops over a crop cycle.*

PA 1.5 Spatial data management

- *Spatial data processing and storage methods accord with industry-accepted protocols and standards.*
- *Some data management processes may be automated.*

PA 1.6 Going beyond current best management practices

- *Sugarcane varieties selected through analysis of historic spatial yield data on the basis of their adaptability to soil properties and position in the landscape.*
- *Use of variable sugarcane variety planters with the capacity to plant varieties according to the field characteristics of management zones within paddocks.*
- *Use of automated variable depth planters to optimise billet positions in permanent bed farming systems in different soils.*
- *Use of adjustable base cutter height on sugarcane harvesters to allow for harvesting in zones of different hill-up heights in potentially waterlogged sites.*
- *Generation of GIS layers for residual herbicide and pesticide application and soil erosion control, based on cane variety attributes and patterns in soil, topography, drainage, and crop yield.*
- *Use of a GIS topography layer of high definition covering paddock and inter-paddock areas, farm drains, storm water drains, and roads.*
- *Use of sensor data to determine spatial patterns in soil and crop properties and to assist in defining management zones in paddocks.*

7.4.2 Variable rate application issues

Variable rate application technology has often been seen as the ultimate goal of precision agriculture. To date, such technology is commonly based on supplying the macronutrient (particularly nitrogen) deficiencies identified through soil chemical analysis results from georeferenced sampling sites in paddock zones, which possibly have been identified by a soil ECa mapping program. However, patterns in sugarcane crop yield maps determined by NDVI-processing of satellite images or by harvester-mounted yield monitors (Section 4.4, above), often display large within-paddock variability in crop growth. Variable rate of nutrient application programs based on soil chemical analysis alone is regarded as being flawed if the yield potential of the sampled spatial zone is not considered. Further research is required to determine the stability of yield potential zones as defined by current yield mapping systems. This research would ideally incorporate the analysis of yield mapping patterns over a number of crop cycles and different seasonal conditions (Section 8.5, below).

7.4.2.1 Variable rate application of nitrogen

Field observations and validation of crop yield patterns in Project BPS001 established that poorly drained soils located in low, waterlogged parts of Sites H2 and M1 are the main drivers of low yields from zones within paddocks (see Section 7.3, above). However, it is unclear if the low yields in the poorly drained soils can be attributed to:

- a nitrogen deficiency due to denitrification in waterlogged soils;
- leaching losses of other plant nutrients from soils under prolonged wet conditions;
- the sugarcane root system being so compromised by extended waterlogged conditions that the plant is unable to extract nutrients when the soil dries out.

From a variable rate application of nutrients perspective, the foregoing issues raise two critical paddock management questions whose answers are fundamental in determining the effectiveness of nitrogen applications after the paddock dries out:

- Should more nitrogen be applied to the previously waterlogged zone to offset the nitrogen losses through denitrification?
- Should less nitrogen be applied to the formerly waterlogged zone because the compromised root system of the crop is no longer able to extract any added nitrogen from the soil?

Further research is required to determine the most effective nitrogen management strategy in paddock zones subject to waterlogging and extended anaerobic conditions.

7.4.2.2 Variable rate applications in older ratoon crops

It is evident that crop yield declines with the ageing of the ratoon within a cropping cycle. It is unclear if the best strategy to manage nutrient inputs to older ratoon crops should be increased in an attempt to maintain yield, or reduced because of a diminishing yield potential associated with the ageing of the ratoons. Again, further research is required to determine a cost-effective nutrient input strategy.

7.4.2.3 Variable variety planting along paddock rows

Analysis of strategic spatial mill yield data over time may provide an indication of the adaptability of various sugarcane varieties to specific soil texture groups and growth performance in low-lying areas of paddocks that are subject to seasonal waterlogging. This analysis would need to incorporate digital elevation data and soil texture information derived from deep soil ECa map patterns.

Historic satellite yield data is available for most of the area supplying the Mackay Sugar mills and extensive parts of the area have been soil ECa mapped since 2001. RTK-GPS elevation data is increasingly accessible since the adoption of GPS automatic guidance systems on machinery in the Central District. An analysis of this comprehensive spatial data set over a range of seasonal conditions may provide significant productivity gains where specific cane varieties are allocated to defined spatial zones in a precision agriculture context.

7.5 CONCLUSIONS

The information gained from the field verification of soil ECa mapping patterns and crop yield or plant biomass GIS layers has underpinned our understanding of the complexity of managing spatial variability in sugarcane lands. Access to deep soil ECa maps, accurate yield maps from harvester yield monitors or processed satellite imagery, detailed topographic data, and soils information from strategically located field validation sites will reduce the cost and effort required to gain knowledge of soil properties in management zones within paddocks. Pivotal to the development of a precision agricultural management program is knowledge of both topsoil and subsoil properties in spatially defined areas within paddocks, and an understanding of how those properties relate to yield from the same area, both over time and under the influence of changing seasonal conditions.

The relationship between contrasting soil texture properties and their relative spatial positions in the landscape has provided an important insight into understanding the reasons for within-paddock yield variability. This information coupled with an enhanced appreciation of the

interaction of variables that drive crop growth has facilitated the development of a number of possible management strategies to manage within-paddock variability, namely:

- site-specific mechanical tillage strategies based on soil ECa mapping and a knowledge of associated soil properties, especially the soil texture of subsoil layers;
- conservation of organic matter through the adoption of zonal tillage strategies with intensity of tillage operations modified by knowledge of soil properties;
- site-specific application of ameliorants defined by soil ECa mapping zones and site-specific soil analysis;
- sugarcane variety selection based on adaptation to defined soil properties and tolerance of waterlogged conditions;
- within-paddock variation in bed height defined by topography and soil type to minimise the effects of waterlogging in low-lying areas of paddocks;
- fitting of automated base cutter height controllers on harvesters to accommodate changes in bed height.

Project BPS001 has identified some of the problems in adopting “on the go” variable rate application of nutrients as the stability of yield zones defined by processed satellite imagery is not well understood. The specific nutrient inputs required by the spatially defined yield zones must be determined by the yield potential of the zones themselves. It is anticipated that the yield potential of soils with contrasting soil texture properties and lying in the lower topographic locations within the paddock may be significantly influenced by seasonal conditions. A soil with poor subsurface drainage characteristics may have a relatively high yield potential in drier than normal seasons and a poor yield potential in average or wetter than normal seasons. Access to accurate seasonal forecasting is therefore a highly desirable attribute to include in protocols for determining nutrient inputs for defined spatial zones, and also in extracting optimum results from variable rate application technology in a precision agriculture system. Further research is required to determine the stability of spatially defined crop management zones over a number of crop cycles and weather patterns and this, ideally, should be integrated with ongoing research into enhanced methods of predicting seasonal conditions

Chapter 8

PROJECT BPS001: DRIVING PRECISION SUGARCANE AGRICULTURE FORWARD

8.1 PROJECT BPS001: CRITERIA FOR SUCCESS

Project BPS001 began in July 2007, a decade after the first precision agriculture conference for the Australian sugar industry was held in Townsville with the theme of *'Precision agriculture: what can it offer the Australian sugar industry?'* (Bramley *et al.* 1997). The potential of precision agriculture to bring about increases in the productivity and environmental integrity of Australian rural industries, especially in the production of grains, grapes, and cotton, was well-publicised over the next decade, during which much of the enabling technology became readily available (*e.g.* hand-held GPS, equipment-mounted GPS and computers, GPS base stations, GPS-guided steering and controlled traffic, crop imagery, soil ECa or soil EM maps, harvester yield monitors, variable rate application equipment, etc).

Apart from the pioneering efforts of Independent Agricultural Resources to establish a consultancy at Mackay to service the modest precision agriculture needs of the Central and Burdekin Districts (see Section 2.4, above), very few practical outcomes were delivered to the sugar industry. This may well have been because of the complexity of the drivers of variability of the yield of a tall, perennial, grass crop grown under tropical conditions and influenced by the interactions of soil nutritional status, soil physical properties (especially soil texture), surface and subsurface drainage, seasonal conditions, soil health, pests and diseases, sugarcane variety adaptability to soil type, and paddock management practices. However, the results of the SRDC-funded *'Sugar Yield Decline Joint Venture'* (Garside and Bell 2006) had begun to set sugarcane growers thinking about sound agronomic practices, their integration, and their adoption into new farming systems.

Interest in precision agriculture and a background of innovative farming in the sugar industry were strong at the time that Project BPS001 started in 2007 and the overall aims of the project were two-fold:

- to provide stepping stones to a better understanding of the principles that underpin precision agriculture methods for sugarcane production,
- to develop a foundation for delivering some of the benefits of precision agriculture to the sugar industry.

The objectives of the BPS001 project proposal accepted for funding by SRDC were:

> *The project will develop and promote techniques for establishing zones for targeted application of best management practices within cane paddocks. The zones will be identified by mapping features in satellite imagery, soil electromagnetic induction (EM) responses,* [known as *'apparent soil electrical conductivity (ECa) responses'* when collected by the Veris 3100 soil ECa mapping unit] *actual soil properties, and sugarcane yields. They will be georeferenced (assigned latitudes and longitudes) and viewed, queried, and analysed at various scales in a geographic information system, a process that will integrate data collected from different sites and at different times.*

The resulting map units will allow the subsequent development and promotion of variable rate, site-specific, best management practices for sugarcane production and improved environmental stewardship over and above the management of the crop or paddock as a single, homogenous entity.

The research will address two main questions:

- *How do satellite imagery and EM* [ECa] *map patterns relate to variations in space and time in soils, and in sugarcane yield?*
- *Are there general relationships between image analysis, EM* [ECa] *signals, crop yield, and soil properties that are widely applicable within and between regions?*

Over the last four years, Project BPS001 has attempted to link understandings of sugarcane crop agronomy and farming practices with spatial analysis in a geographic information system context to answer the two main research questions. In this chapter we have evaluated the capability of the project to meeting that challenge, and have assessed its success in terms of four additional questions:

- To what extent has the project met its objectives and answered the research questions?
- How has the project contributed to the way that precision agriculture is regarded by the sugar industry?
- How has the project empowered service providers to progress precision agriculture in the sugar industry?
- What issues have been identified as requiring further research to take precision agriculture to a higher level in the Australian sugar industry?

8.2 PROJECT BPS001: MEETING THE RESEARCH OBJECTIVES

Project BPS001 has fulfilled its original objectives, and has gone further. Critical field observations and the analysis of data collected from the field validation of GIS mapping layers confirmed that alleviating plant nutritional disorders in isolation would not necessarily reduce crop growth variability within a paddock. The project identified that managing variability in sugarcane paddocks requires a comprehensive understanding of the agronomic drivers of crop growth in conjunction with the capacity to utilise and integrate the data from a number key GIS mapping layers.

The major achievement of BPS001 has been to work out how to use three key GIS layers over a paddock (soil ECa patterns as a surrogate for detailed soil information, paddock elevation as a surrogate for site drainage, and crop yield derived from processed multispectral satellite imagery or harvester-mounted yield monitors) to understand the patterns of crop production and their management in spatial zones in paddocks.

The main relationships among the spatial data layers that have emerged from Project BPS001 are set out below; their significance to precision agricultural management is given in italics.

- Shallow soil ECa mapping patterns are unstable over short periods of a few months, such as within a fallow period (Section 5.2.1, above). The major drivers of shallow soil ECa patterns are likely to be strongly related to transient soil properties such as soil moisture or bulk density, as was found to be the case (Section 5.4, above).
    - *The shallow soil ECa patterns are highly variable over time and their relationships to soil or site characteristics have not been demonstrated conclusively.*

- Deep soil ECa maps are stable over short periods such as within a fallow period of 6 months and over longer periods such as a cropping cycle of 5 + years (Section 5.2.2, above). Patterns of deep soil ECa values were related to soil profile patterns in the field at each study site (Section 5.3, above). Deep soil ECa values are driven by subsoil characteristics that are related primarily to soil texture (Sections 5.4 and 7.3, above).
    - *Deep soil ECa mapping patterns assist in determining the sub-surface drainage status of spatially defined zones within a paddock but borehole validation may be required.*
    - *The stability of deep soil ECa mapping patterns has installed a degree of confidence for growers entering a precision agriculture program as the mapping cost is a one-off cost and RTK elevation data is also available through the soil mapping survey process.*
    - *Deep soil mapping patterns are useful in determining the spatial positioning of trial sites to remove variability of contrasting soil textures in replication plots.*

- High exchangeable sodium contents influence soil ECa values (Section 5.3.3, above). This is a significant driver of soil ECa patterns in sodic or saline soils.
    - *Access to yield mapping patterns will assist in defining zones of elevated sodicity and contribute to the cost-effective selection of field validation sites for determining soil sodicity levels for site-specific gypsum application.*

- It is possible to have profiles with different morphological properties producing similar deep soil ECa values and residing within the same deep soil ECa mapping unit (Section 5.3.4.3, above).
    - *Selection of sites for field validation of soil ECa map patterns will be enhanced where soil ECa maps are used in conjunction with crop growth and digital elevation mapping layers.*

- Soil moisture and soil texture appear to have been significant drivers of soil ECa values in non-sodic soils (Sections 5.3.4 and 5.3.5, above)

  These mapping patterns can be used to:
    - *define priority irrigation areas within a paddock and assist with the location and positioning of tensiometers or similar instruments for measuring soil moisture status;*
    - *provide useful insights into the spatial location of zones with poor subsurface drainage issues and areas with a propensity for soil compaction;*
    - *select zones within paddocks that are still suitable for harvesting under wet conditions.*

- Despite the capacity of site mapping by Veris 3100 unit and soil EM38 to detect patterns of light textured sandy ridges in heavy clay terrains, the two systems produce relatively poorly correlated soil maps (Section 4.1.1, above)
    - *This result suggests that detailed field validation of EM 38 mapping patterns may be required in order to determine the role and value of EM 38 technology in a sugarcane precision agriculture farming system.*

- Crop yield maps may be produced from data collected from harvester-mounted yield monitors (Section 4.4, above) or from Normalised Difference Vegetation Index (NDVI) maps produced from multispectral satellite images captured close to the date of harvest (Section 6.2, above).
    - *Both of these approaches may be used to produce a crop yield map, but neither was entirely satisfactory. From both a precision agriculture context and a sugar industry perspective, the role of these technologies need to be assessed in greater detail for the reasons discussed in some detail below (Section 8.5.1, above).*

- Crop yield maps based on processed satellite imagery were well correlated with manually harvested small plot data in three out of four sites analysed, but the correlations were poor in a high-yielding plant cane crop in the Burdekin that was flowering at the time of satellite image capture (Section 6.2, above).
    - *This issue is part of the flawed methods that are currently available for crop yield mapping and are discussed in greater detail below (Section 8.5.1).*

- Deep soil ECa maps were poorly correlated with crop yield maps (Section 6.4.2, above).
    - *The reasons for this are now well understood and the contributions derived from access to a digital elevation layer are recognized.*
    - *Selection of georeferenced sites for the field validation of soil ECa map patterns should take into account the patterns evident in associated yield maps, particularly where cost issues constrain the number of soil samples to be collected for laboratory analysis.*

- Paddock elevation maps based on detailed RTK-GPS data may be used as surrogates for maps of paddock surface water drainage and appear to be well correlated with crop yield maps at some sites (Section 7.3, above).
    - *A number of topographic features of paddocks in addition to site elevation (i.e. height above a datum level and derived directly from a digital elevation model) may strongly influence crop yield. They include: slope angle, slope length, depression depth, depression elevation, and depression closure, and can be developed from digital elevation data sets, but have not been investigated in this project.*
    - *Soil morphological data derived from descriptions of the soils at field validation site (e.g. soil colour and mottle patterns, ferromanganiferous gravels, drainage-impeding soil layers; see Section 8.4.1.2, above) may help improve estimations of internal soil drainage status.*

- A combination of spatial data sets is needed to simplify the complexity of the interaction of drivers of crop growth variability: soils, topography (paddock drainage), crop yield (Section 7.3, above).
    - *A commercial case study incorporating these three spatial data sets to define soil analysis sites and develop a variable rate nutrient program has been included in this chapter; this case study clearly demonstrates the success of the project in integrating GIS spatial layers with basic agronomic expertise (see Section 8.3.1, below).*

8.3 PROJECT BPS001: CHANGING FARMING PRACTICES

8.3.1 The role of the precision agriculture consultant

A recurrent theme throughout this report has been the emphasis on the complexity and variability of the factors controlling sugarcane crop yields. The development of precision agricultural strategies to manage the spatial and temporal variability in crop growth within a sugarcane paddock requires a combination of specialised skills, including:

- high level data management and computer skills to set up numerical and spatial data files for interrogation, analysis, display, and storage in GIS and web-based environments;
- spatial analysis skills to allow the overlaying of data layers as diverse as soil profile descriptions, soil test results, soil ECa maps, processed satellite imagery, soil ameliorant and nutrient application rates, and digital terrain data;
- high level agronomic skills to be able to recognise and devise strategies to manage crop growth differences that may be attributed to issues related to:
    - short term influences such as the impact of irregular watering, temporary flooding, weather patterns, uneven nutrient applications, pests and diseases;
    - longer-lived influences such as crop nutrient imbalances, waterlogging, plant establishment problems, cane stool losses through poor harvesting practices, or inappropriate selection and application of herbicides;
    - long-term influences that may operate across whole cropping cycles such as unsuitable soil type, unfavourable paddock topography, irregular paddock drainage, and long term climatic effects.
- astute observational skills to detect subtle changes in any of the foregoing agronomic issues and an ability to devise a management strategy before the emerging problem becomes a major issue that impacts on crop yield;
- sugarcane farming skills and equipment to be able to implement management recommendations for specific management zones within the cane paddock.

It is clear that the skill package needed to drive successful precision sugarcane agriculture lies in the combination of skills delivered in a good working relationship between a farmer and a paid consultant. The consultant will also need to have well developed interpersonal skills to allow ready interactions with the grower on the one hand, and on the other with even more specialised problem-solvers such as computer programmers, plant physiologists, soil chemists, GPS specialists, etc, who will inevitably be called on from time to time.

Project BPS001 has identified the need for sugarcane growers to work closely with precision agricultural consultants to identify and manage spatial zones with a paddock. The sugar industry has to learn that precision agriculture is a specialised business and, like any specialised business, requires an investment in the best advice that is available. The days of

providing a grower intending to adopt precision agricultural principles and practices with a pocket manual to leave in the glovebox of the ute and a double-sided fact sheet are long since gone!

Changes in precision agriculture practices in sugarcane production must flow from the realisation that a range of high level skills is needed to support the grower. Some of the tools needed to empower precision agricultural consultants have been developed in Project BPS001 and they are outlined in Section 8.4 of this report (below).

8.3.2 Benefits of precision agriculture in sugarcane production

We have asserted at various places in this report that adopting site-specific nutrient applications will save the sugarcane grower money by allowing the emplacement of the nutrients needed by specific parts of a paddock and avoiding unnecessary over-applications in some parts of paddocks through blanket dressings across the whole paddock. In this section we have presented the results of a small desk-top study, using real-world data from site M1, Homebush, to validate the economics of this assertion.

8.3.2.1 Precision agriculture: an economic case study at site M1, Homebush

The study was based on applying Project BPS001 results to the decision-making processes involved in choosing nutrient management strategies for the second ratoon crop at site M1 following the harvest of the first ratoon crop late last year. We have set the scene for the study in a summary of the main paddock management activities carried out between planting the crop in August 2008 and harvesting the first ratoon crop in November 2010 (Section 8.3.2.1, below).

Two options for fertilising the second ratoon crop are considered: the paddock has been treated as a set of three yield zones (low, medium, and high) each with its own site-specific nutrient requirements that would be spread separately over each zone, and it has been regarded as a single entity over which a blanket dressing of nutrients that would be applied at a single rate across the whole paddock. The nutrient requirements for each of the three crop yield zones, and for the whole paddock, were determined using the *Six Easy Steps* guidelines and site-specific soil data.

The case study provided an economic analysis of the advantage of utilising variable rate nutrient applications and the moderation of inputs by the crop yield history in specific parts of the sugarcane paddock. We have identified the issues that must be addressed by a grower working with a precision agriculture consultant; we have offered (in italics in Section 8.3.2.3, below) explanations for the proposed recommendations for paddock management that are aligned with Project BPS001 outcomes.

Although the site data are real, the management decisions are hypothetical. Nevertheless, they illustrate the kinds of issues that a sugarcane grower and precision agricultural consultant must face, and indicate the potential cost savings and environmental benefits that can flow from adopting a precision agricultural approach to sugarcane production.

8.3.2.2 Setting the scene

- *The plant cane crop*

The pre-existing fifth ratoon crop at site M1 was ploughed out in December 2007 and the paddock of 9.3 ha was maintained as bare fallow with soil ECa mapping and an RTK-GPS topographic survey, recommended by a consultant, carried out towards the end of the fallow phase in June 2008 (Fig. 8.1a). Bulk samples of topsoil (0-25 cm depth) were collected from the three main zones evident on the deep soil ECa map, and three subsamples were submitted to a NATA-registered and ASPAC-affiliated soil testing laboratory for chemical and particle-size analysis.

The crop was planted in August 2008 using a generic, block nutrient program. An aerial photograph captured over the crop during active growth confirmed that the plant cane crop had grown well and relatively uniformly (Fig. 8.1b). The NDVI patterns derived from a high resolution, multispectral, IKONOS image captured just before the plant cane harvest indicated stronger growth along the higher, eastern side of the paddock with a lower yielding section along the lower, western side of the site (Fig. 8.2a).

The plant cane was harvested on 31 July 2009 and a standard industry fertiliser dressing of 170 kg/ha of nitrogen, 20 kg/ha of phosphorus, 90 kg/ha of potassium, and 10 kg/ha of sulphur was then applied.

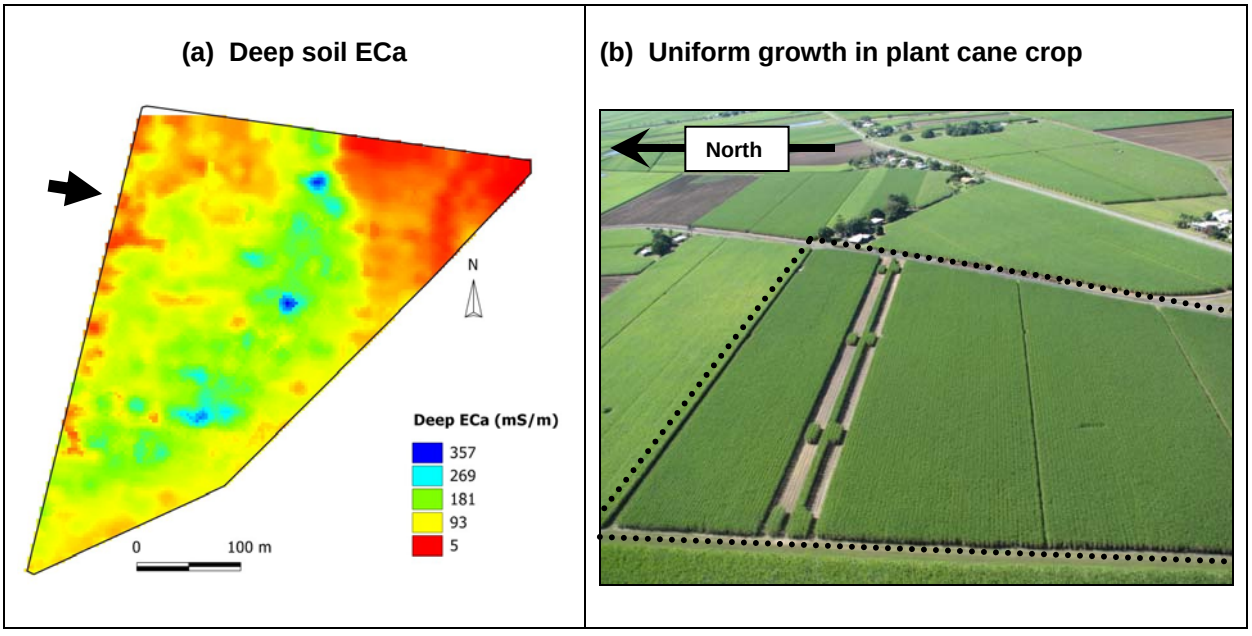


Figure 8.1. Deep soil ECa and growth patterns in the plant cane crop, Site M1, Homebush.
(a) Deep soil ECa patterns detected towards the end of the bare fallow, pre-plant period in June 2008. The broad arrow indicates the orientation of the photograph shown in part (b).
(b) Uniformity of sugarcane growth evident in the aerial photograph of the plant cane crop taken on 22 May 2009. The heavy dotted line encloses the northern end of site M1. The gaps along the most northerly of the three irrigator tow-paths evident are part of the compaction trial of SRDC Project GGP052.

- *The first ratoon crop*

Variable growth patterns in the first ratoon crop were evident in the NDVI map of the crop that was derived from a high resolution IKONOS satellite image captured in July 2010, well before the rain-delayed harvest of the first ratoon crop on 1 November 2010. Using the regression algorithm generated from the calibration of the 2010 yield mapping layer (Section 6.2.3, above), NDVI values (Fig. 8.2a) were transformed into actual yield values and displayed in a 3-zone map (Fig. 8.2b).

The crop yield map enabled an average yield to be assigned to the spatially defined yield zones evident in the mapping layer (Fig. 8.2b). This map also indicated significant variability in crop yield across the paddock, and the eastern side of the site still had better yield relative to the western side of the paddock, with average yields of 70 tonnes of cane / ha (TCH) for the low yielding western side of site M1, 90 TCH for the medium zone, and 120 TCH for the high yielding zone along the eastern side of site M1. The block displayed within-paddock yield variability of 50 TCH.

The information from the crop yield map was combined with the paddock elevation and soil ECa data to select sites for soil sampling and analysis. The rationale behind this important decision-making step is set out in the next section. The results from the soil tests were then used to determine a nutrient application program over the second ratoon crop; the advantages of using a 3-zone site-specific strategy and a blanket application over the whole crop were compared and contrasted below.

8.3.2.3 Decision-making: nutrient inputs for the second ratoon crop

The variability in yield of the first ratoon crop, evident in the 3-zone yield map (Fig. 8.2b), was sufficient for the grower to consider varying the nutrient applications for the second ratoon crop to better match the variable yield patterns. The variability in yield was of concern to the grower as he had applied a standard industry fertiliser dressing to the previous ratoon crop. The grower was contemplating the purchase of a variable rate applicator provided this could be justified by the consultant.

Empowered by the BPS001 decision support package to address these issues, the consultant would be wise to follow a sequence of steps, namely:

1. Determine the agronomic reasons for the variability in crop growth, particularly in the low yielding areas.

2. Define what cost-effective management options are available to address the crop variability issues, including the option of reducing nutritional inputs where remedial management options may be limited.

3. Communicate with the grower to determine previous nutrient application rates, management strategies, and issues peculiar to the specific paddock.

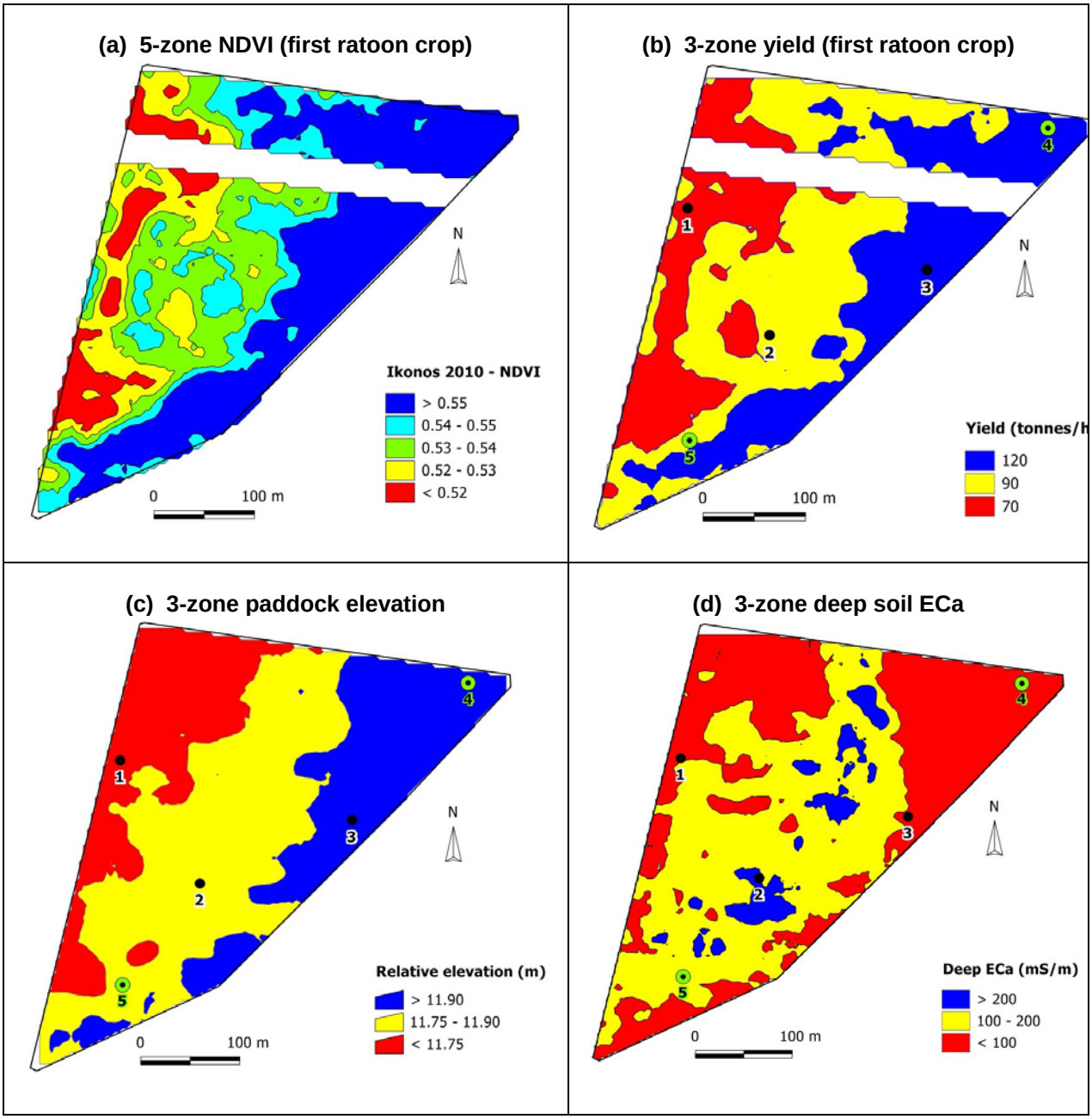


Figure 8.2. Site conditions and growth patterns in the first ratoon crop at site M1, Homebush.

(a) 5-zone NDVI map of the first ratoon crop derived from IKONOS satellite image captured on 21 June 2010, 4 months before harvest.

(b) 3-zone yield map based on growth patterns in the first ratoon crop determined from NDVI processing of an IKONOS satellite image captured on 21 June 2010, 4 months before harvest.

(c) Paddock topography from a 1 km^2 Lidar digital elevation map supplied by the Queensland Department of Environment and Natural Resources and used with permission.

(d) Deep soil ECa patterns detected in the bare fallow, pre-plant period in June 2008, showing the three sites selected for the calculation of nutrient applications (sites 1 – 3) and two additional sites to be analysed in the next fallow phase of the crop cycle (site 4 and 5).

- *Determining the agronomic reasons for the variability in crop growth*

The first step in determining the reasons for variable crop growth is to account for the effects of soil variability within and between the yield zones was to determine the locations of georeferenced, soil testing sites and collecting soil samples for chemical and particle-size analysis from the topsoil layer (0 – 25 cm depth), the upper subsoil (40 – 60 cm depth), and

the lower subsoil (75 – 100 cm depth). The site selection process could be supported through access to the stable deep ECa map from 2008 (Fig. 8.2d) in conjunction with the crop yield map from the 2010 harvest of the first ratoon crop (Fig. 8.2b), sequential satellite imagery captures in conjunction with false colour images (Fig. 7.4), and the elevation mapping layer (Fig. 8.2c).

The first step in determining the reasons for variable crop growth is to account for the effects of soil variability within and between the yield zones was to determine the locations of georeferenced, soil testing sites and collecting soil samples for chemical and particle-size analysis from the topsoil layer (0 – 25 cm depth), the upper subsoil (40 – 60 cm depth), and the lower subsoil (75 – 100 cm depth). The site selection process could be supported through access to the stable deep ECa map from 2008 (Fig. 8.2d) in conjunction with the crop yield map from the 2010 harvest of the first ratoon crop (Fig. 8.2b), and the elevation mapping layer (Fig. 8.2c).

This accords with the Project BPS001 findings that:

- *no GIS layer in isolation is sufficient to identify and manage paddock variability,*
- *access to three GIS layers (a deep soil ECa layer, paddock topography layer, and yield mapping layer) will significantly contribute to a consultant's ability to provide reliable, balanced management recommendations.*

Soil analysis site 1 (Fig. 8.2) was selected to determine the reason for the poor yield (60 TCH) in the area of low values of the deep soil ECa pattern in the low-lying part of the paddock, and was contrasted with the high yield (120 TCH) in the area of low values of the deep soil ECa pattern at site 3. Soil analysis site 3 was selected to determine if nutrients were limiting the yield potential of the relatively well elevated, high yielding zone. Soil analysis site 2 was selected on the basis of the high values of the deep soil ECa mapping pattern and the moderate yield rating (90 TCH).

The high cost of soil analysis generally restricted a consultant to three topsoil sample analysis sites per paddock. However, the adviser always has the opportunity to supplement the laboratory-based data by selecting additional strategically-located borehole sites for describing the soil profile and making field assessments of soil texture properties as well as observing soil colour, mottle patterns, ferromanganiferous gravels, perched water tables, and other soil characteristics that assist in determining the field pH, soil salinity, soil sodicity, and sub-surface drainage conditions influencing the nature of any constraints to plant growth that may be present in the soil.

Two such sites are shown in Fig. 8.2. Site 4 was chosen in an area of high yielding duplex soils with very sandy topsoils and strongly acidic subsoils; soil chemical analysis of the topsoil and subsoil during the next fallow phase will provide very useful information for liming and possibly other treatments to optimise production in this productive zone. Site 5 is in an area of moderately yielding clay soils that is slightly elevated above the part of the paddock whose yield was compromised by seasonal waterlogging. Soil chemical analysis of both topsoil and subsoil may reveal the need for gypsum or other treatments to lift the production of the soils in the zone of intermediate crop performance.

These recommendations follow the Project BPS001 findings that:

- *the high cost of chemical analysis generally constrains the number of samples that can be taken in a paddock so the site selection process is critical step in providing an accurate nutrient input recommendation,*

- *georeferenced site selection should be based on deep soil ECa mapping patterns, digital elevation, and historic crop yield pattern data, where available.*

The soil test results did not indicate any nutrient deficiencies that may have accounted for the variability in crop yield across the site (Table 8.1). The soil texture data in the low yielding zone along the western side of the paddock (soil analysis site 1) indicated light textured soils and potentially good subsurface drainage, which corresponded with the low values of the deep soil ECa map pattern.

Project BPS001 has shown that:

- *particle-size analyses is a cost-effective, reliable, and repeatable means of determining soil texture,*
- *deep soil ECa mapping patterns and the associated hierarchy of soil texture classes through the soil profile at field validation locations provide a useful insight into the subsurface drainage characteristics of spatially defined areas in a paddock,*
- *Veris 3100 soil mapping patterns do not necessarily correlate well with yield mapping patterns and this can be due topographic issues evident in elevation mapping layers.*
- *It is possible to have profiles with different morphological properties producing similar deep soil ECa values and residing within the same soil ECa mapping pattern.*

Table 8.1. Topsoil (0 – 25 cm depth) characteristics of three field validation locations at site M1, Homebush.

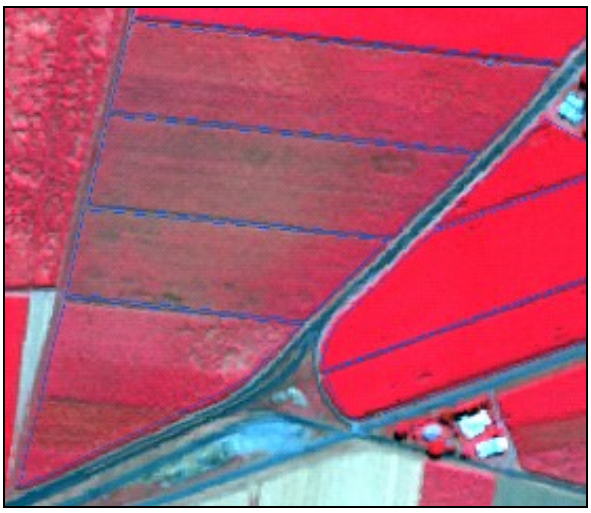
Soil properties	70 TCH yield zone	90 TCH yield zone	120 TCH yield zone
Soil analysis locations (Fig. 8.2)	1	2	3
Deep soil ECa value (mS/m)	39	191	84
Chemical properties (0 – 25 cm)			
pH (1:5 soil:water)	6.0	5.4	4.7
Organic carbon (%)	0.70	0.93	1.1
Phosphorus – BSES (mg/kg)	71	36	38
Cation exchange capacity (meq / 100 g)	3.5	11.2	4.97
Calcium (meq / 100 g)	1.9	6.0	1.9
Magnesium (meq / 100g)	1.2	4.0	1.2
Potassium (meq / 100 g)	0.21	0.31	0.21
Sodium (% of exchangeable cations)	1.3	1.5	0.6
Particle-size properties (0 – 25 cm)			
Fine sand % + coarse sand %	71.8	41.2	63.4
Silt % + clay %	28.2	58.8	36.6
Particle-size properties (40 – 60 cm)			
Fine sand % + coarse sand %	62.5	26.2	35.6
Silt % + clay %	37.5	73.8	64.4
Particle-size properties (75 – 90 cm)			
Fine sand % + coarse sand%	66.2	26.2	41.5
Silt % + clay %	33.8	73.8	58.5

The elevation mapping layer (Fig. 8.2c) emphasised the low-lying nature of the western side of the paddock where the farm drain did not have sufficient slope to remove ponded, surface runoff water from the paddock during the wet season, as was confirmed by the land owner. A deep borehole augered at soil analysis site 1 revealed a throttle to water infiltration at 1.6 m depth which lay below the detection limit of the Veris 3100 soil ECa mapper. Examination of the soil profile at analysis site 2 confirmed the heavy clay field texture and the blue grey colour of the deep subsoil (75 – 100 cm depth); the soil properties indicate the regular occurrence of seasonal water logging, which was a contributing factor to the relatively low yield of this paddock zone. Similarly, the redder colours of the clay-textured deep subsoil in the 75 – 100 cm zone of the profile at soil analysis site 3 indicated the more freely draining subsurface characteristics of the well elevated area along the eastern side of site M1.

Yield patterns evident in annual false-colour infrared satellite imagery throughout Project BPS001 established that the eastern portion of the study site consistently had a higher yield relative to the low lying western side of the paddock (Fig. 7.4). The poor growth areas evident in the false colour images of the last ratoon crop in 2007 (fifth and last ratoon crop prior to the fallow phase of the current cropping cycle; Fig 8.3a) are closely allied with poor growth in the second ratoon crop in 2011 (Fig 8.3b). The co-operating grower confirmed that, under average to above average rainfall seasonal conditions, the eastern zone always out-yielded the western side of the paddock. He had made an attempt during the fallow phase in 2001 to improve the productivity of the poor yielding western section of the paddock by trialling an application of 200 tonnes/ha of mill ash to a small section of the block (Figs 3.6c, 7.4a); it made little difference to the performance of the crop and was still evident on the satellite imagery and in the soil profiles seven years later in 2008.

Allocating a yield potential to a defined zone will be significantly enhanced where a consultant has access to historic yield data (processed satellite imagery or yield monitor data) over a number of seasonal conditions, as was the case in this study. In addition, access to accurate seasonal weather forecasting would enable further refinement of site specific input programs and zonal management strategies.

(a) 27 July 2007: fifth ratoon of pre-BPS001 cropping cycle (prior to harvest and plough-out in December 2007)



(b) 25 May 2011: second ratoon crop of the BPS001 cropping cycle (pre-harvest)

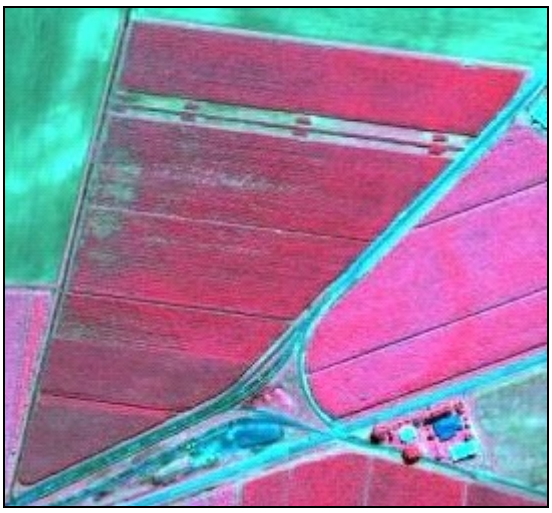


Figure 8.3 The impact of waterlogging on crop yield in the previous and current cropping cycles at site M1, Homebush, evident in false colour infrared images have been derived from IKONOS multispectral satellite imagery captured before harvests in 2007 and 2011.
Similar images throughout the current cropping cycle (2008 – 2011) are presented in Fig. 7.4.
(a) Poor crop growth as a consequence of waterlogging on the western side of the paddock towards the end of the previous cropping cycle. Image captured on 27 July 2007.
(b) Devastated crop as a consequence of waterlogging from November 2010 to April 2011. Image captured on 25 May 2011.

- *Defining cost-effective management options*

Through interrogation of key GIS layers, the ability to identify subsurface constraints to crop growth, supported by agronomic field observations, has now placed the consultant in a strong position to alter nutrient input recommendations according to predicted yield from spatial zones within the paddock.

This enacts the project BPS001 suggestion that paddock inputs can be adjusted relatively easily on an annual basis where the key GIS layers are available.

There were only very limited management options available at the start of the second ratoon of the present crop cycle to adequately address subsurface soil drainage issues or to improve surface drainage external to the site. Based on an average to above average rainfall prediction for the next growing season, the consultant therefore recommended reducing nitrogen inputs to the low yielding potentially waterlogged zone to the average yield achieved in the first ratoon crop yield map (70 TCH). The appropriate nitrogen input was calculated, using the *Six Easy Steps* guidelines, as 95 kg of nitrogen / ha (Table 8.2).

This is consistent with the recommendations from Project BPS001 that:

- *Access to accurate seasonal weather forecasts will contribute significantly to the integrity of nutrient input recommendations.*
- *Paddock inputs can be adjusted relatively easily on an annual basis where the key GIS layers are available.*

- *Access to and analysis of archived satellite imagery will assist in determining the yield potential of defined management zones.*

The nitrogen rate in the high yielding zone was maintained (120 TCH), and that for the medium yield zone was allocated by averaging the low and the high rates (Table 8.2). The actual nitrogen rate for each yield zone was determined by the *Six Easy Steps* protocol for establishing district average nitrogen application rates. For site M1, the district average is 1.4 kg of nitrogen / tonne of cane up to a 100 TCH, and 1.0 kilogram of nitrogen / per tonne of cane thereafter. The elemental nutrient costs of Table 8.2 were based on the Mackay 1 tonne bag prices with a $15 / tonne freight component and included GST.

A comparison was made of the costs involved in carrying out the variable rate nutrient program which incorporated the 3-zone yield prediction for the paddock (Fig. 8.2), and a block application nutrient program derived from soil test results collected using the industry-recommended transect / zigzag sampling procedure across the whole paddock. The latter was achieved by averaging the key nutrient values from the 28 borehole locations of Project BPS001 that had been chosen as field validation sites for the soil ECa mapping exercise (Fig. 5.3d). In order to use the *Six Easy Steps* guidelines, the averaged soil test data were transformed into a whole of block nutrient program for the site (Table 8.2)

Table 8.2. Nutrients required by the second ratoon crop at site M1, Homebush, and the associated input costs.

The inputs were calculated using a 3-zone, site-specific model and as a blanket dressing over the whole paddock. Nutrient requirements for each zone were estimated using the BSES *Six Easy Steps* guidelines for Mackay.

Soil test		Low yield zone (70 TCH)		Medium yield zone (90 TCH)		High yield zone (120 TCH)		Three yield zones combined	Whole paddock treated as a single unit	
Area (ha)		2.2		4.3		2.8		9.3	9.3	
No. of soil tests		1		1		1		3	26	
Phosphorus, BSES (mg/kg)		71		36		38			38	
Potassium (meq/100 g)		0.21		0.31		0.21			0.22	
Potassium, nitric acid (meq/100 g)		0.78		0.97		0.92			0.78	
Sulphate sulphur (mg/kg)		17		9		7			11	
Variable rate inputs from Six Easy Steps										
Nutrient	**Nutrient cost * ($/kg)**	**Low yield zone (70 TCH)**		**Medium yield zone (90 TCH)**		**High yield zone (120 TCH)**		**Three yield zones combined**	**Whole paddock treated as a single unit**	
		Rate/ha	**$/ha**	**Rate/ha**	**$/ha**	**Rate/ha**	**$/ha**	**$/ha**	**Rate/ha**	**$/ha**
Nitrogen	1.71	95	162	130	222	160	274		160	274
Phosphorus	3.11	10	31	10	31	0	0		10	31
Potassium	1.5	80	120	100	150	100	150		100	150
Sulphur	1.3	15	20	15	20	15	20		10	13
Nutrient input cost / ha			$333		$423		$444	**$408 ****		**$468**
Nutrient input cost / zone		2.2 ha @ $733		4.3 ha @ $1,819		2.8 ha @ $1,243		**9.3 ha @ $3,795**	**9.3 ha @ $4,352**	

* Nutrient costs are based on 1 tonne bag prices at Mackay with a freight rate of $15 / tonne and derived from elemental nutrient components of urea (N), diammonium phosphate (P), potassium chloride (K) and ammonium sulphate (S) as at 20 June 2011.

** Calculated from the sum of the nutrient input costs per yield zone across the 9.3 ha paddock.

8.3.2.4 Benefits derived from a precision agricultural approach

- *Economic benefits*

Table 8.2 shows that the total nutrient input cost over the 9.3 ha of the second ratoon crop at site M1 amounted to $3,795, or $408 / ha when applied to the three site-specific zones within the paddock that were defined in terms of deep soil ECa, paddock topography, and the first ratoon crop yield maps.

A similar calculation, also based on *Six Easy Steps* guidelines, showed a higher nutrient cost ($4,352, or $468 / ha) if the nutrients were applied as a uniform dressing over the whole of the paddock. A saving of $60 / hectare was achieved in the 3-zone, site-specific, variable rate application of nutrients which equated to a saving of $557 (13%) on the cost of a whole of paddock blanket dressing of the same nutrients.

An analysis of 26,000 sugarcane paddocks (average 2.8 ha/paddock) within the Mackay sugarcane growing area indicated that 30% of paddocks displayed within-paddock yield variability in excess of 40 tonne/ha in the 2008 season (mill records from Mackay Sugar Ltd, 2011). This equates to approximately 22,500 hectares (8,000 paddocks) which potentially could be allocated high, medium and low yield potentials within defined management zones.

Based on the results from the study case at site M1 set out in the previous section, this represents a potential regional saving of $1,350,000 in nutrient inputs or a potential reduction of 720 tonnes of elemental nitrogen (1,560 tonnes of urea). However, further research is required to determine the implications of reducing nitrogen inputs with a reducing yield potential associated with the aging of ratoons in a crop cycle.

- *Environmental benefits*

It is reasonable to assume that the quality of water leaving the paddock would be significantly enhanced by the 3-zone, variable rate application of nutrients, as the low yielding zone in close proximity to the external drain would have received the least nitrogen applied to the paddock. Despite applying higher nitrogen rates in the high yielding zone, as suggested by the 3-zone variable application model, the quality of drainage water from the site is unlikely to be compromised: the amount of nitrogen applied has been calculated on the basis of the requirements of the actively growing crop in the high yielding area and the applied nutrient should be fully utilised by the crop.

- *Other precision agriculture issues*

A number of additional precision agriculture management recommendations follow from the case study of an early ratoon crop, namely:

- It appears that sugarcane production has been affected by waterlogging in the western part of the paddock at site M1, with better growth on the eastern side, for at least two cropping cycles (more than 8 years). This suggests that there is some stability in crop growth patterns across cropping cycles. It also shows that the decision in the preceding case study to reduce fertiliser inputs over this area was taken in the light of a long-term constraint to crop production over a specific part of the paddock, and was not in response to single, potentially abnormal and unseasonal event.

- During the next fallow phase of the crop cycle, lime should be site-specifically applied over the high yielding zone to raise the soil pH, increase the availability of phosphorus (see data for soil analysis site 3; Table 8.1), and further enhance the productivity of the zone.

- The hill height of the plant cane could be raised in the poorer yielding, topographically lower parts of the paddock that are prone to waterlogging.
    - This would reduce the effects of waterlogging and improve the productivity of the low yielding zone.
    - Nitrogen rates could then be amended to reflect the improved productivity of the zone.
    - An automated height adjuster for the base cutter would then need to be fitted to the sugarcane harvester to allow for the changing bed height in the low-lying zones of the paddock. We recognise that further development is required to improve the efficiency of automated base cutter height controllers.

- A variable variety planter could be engineered and used to plant varieties according to their adaptability to soil type and topography based on soil ECa, yield maps, and the elevation layers.

- Site-specific application of cane 'ripeners' via high clearance tractors or aerial spraying on zones would be advantageous where cane maturity and CCS levels have been influenced by water logged conditions.
    - False colour satellite imagery captured at critical times of crop growth may assist in defining spatial boundaries for subsequent 'ripener' applications.

8.3.2.5 Conclusions from the case study

This case study has successfully used a decision support-package based on the Project BPS001 research results to pinpoint key locations at site M1 for soil analysis, and to develop a variable rate nutrient program for the second ratoon crop based on zonal yield predictions and seasonal weather forecasts. The case study has illustrated a sound, science-based methodology for developing variable rate nutrient programs and other precision agricultural management strategies. However, it is recognised that there are crucial areas where further research is necessary to underpin the methodology and these are tabulated in Section 8.5.3 below.

Site-specific application of nutrients (e.g. '*Six Easy Steps*'), pesticides, and herbicides should be based on spatially defined management zones within paddocks including, but not limited to, the yield potential and key soil properties of the zones. To fully capture this benefit, the definition of the management zones will require a spatial analysis of the impact of seasonal growing conditions on the patterns of crop yield over long sequences of wet, dry, and 'average' years. Hence, in August 2010, the BPS001 Project Team submitted to the Sugar Research and Development Corporation an *Expression of Interest* for project funding to explore the implications of the stability of crop management zones in sugarcane paddocks under changing climatic conditions. But the bid was unsuccessful.

Although Project BPS001 has simplified, to a certain extent, the complexity of managing crop yield variability within a paddock, this case study has clearly demonstrated that an effective precision agriculture program can only be delivered by an adviser or consultant with the ability to integrate a thorough working knowledge of both GIS systems and agronomic

principles and practices. In addition, a basic grasp of soil science and good communication and extension skills are a pre-requisite for a career as a precision agriculture consultant. Continued government research support for consultants and advisers in this field will ensure the achievement of the significant economic, environmental, and social outcomes that precision agriculture can bring to the sugar industry.

8.4 PROJECT BPS001: EMPOWERING PRECISION AGRICULTURE PRACTITIONERS

The major outputs from the project are set out in the present document that provides a rigorous understanding of the scientific principles that underpin the use of a set of GIS layers (primarily soil, topography, and crop yield patterns) to understand the complexity of the growth differences within a sugarcane paddock. Such knowledge became the foundation for developing a new approach to holistic farm management that can be implemented within a precision agricultural system for sugarcane production.

The outcomes from Project BPS001 have provided ways to use currently available precision agricultural technology to apply the inputs necessary to manage most of the site-specific factors that give rise to paddock-scale variability in crop yield. The project outcomes, discussed in this chapter, are cutting-edge technologies for sugarcane production that go beyond current best management practices. New tools for identifying and managing paddock variability are presented in Section 8.4.1, below. Benefits for farm productivity, the sugar industry, and the environment that are expected to flow from the application of the BPS001 outcomes have been discussed above. Awareness of the benefits of adoption of the project outcomes is being delivered to all levels of the sugar industry from farmers to political leaders, and to the wider community using established and respected local networks in Queensland's sugarcane lands (Section 8.4.2, below).

8.4.1 New tools for paddock management

8.4.1.1 Soil sampling protocols

Project BPS001 has very clearly demonstrated that subsoil textures and site topography are both closely linked to sugarcane crop growth patterns (see Section 7.3, above). The project developed a protocol for collecting georeferenced soil samples, including both topsoils (0 – 25 cm depth) and subsoils (40 – 60 cm and 75 – 100 cm depths), and was used in the field validation of the soils occurring in soil ECa patterns (Section 4.2, above).

Conventional sugarcane nutrient management decisions are made on the basis of soil tests collected using the 'standard procedure' outlined by Schroeder *et al.* (2010) in which soil samples are collected from a depth of 0 – 20 cm that embraces the cultivated layer of topsoil. The procedure recommends that samples should be collected from areas smaller than 2 – 3 ha and of relatively uniform soil type; multiple samples should be collected from large blocks and from distinctly different soil types within a block. The soil samples should be collected using a soil auger or soil coring tube at 10 – 12 locations, usually sited in a zigzag or grid pattern within the soil sampling zone (Schroeder *et al.* 2010).

Subsoil conditions were not regarded as important controls over crop growth, hence the 'standard procedure' for sugarcane soil sampling does not specify a strategy for collecting subsoil samples.

Project BPS001 results showed that restricting field observations and soil sampling and analysis to the cultivation layer of a paddock omitted a lot of valuable information that may point the field operator towards a better understanding of the factors driving crop variability and their possible management. A focus in the field on the topsoils alone may lead to inefficient or limited agronomic interpretations, or even wrong farm management decisions, where a relatively uniform cultivation layer overlies subsoils with strongly contrasting characteristics, where there are impediments to surface drainage, or where poor subsoil drainage conditions prevail (as discussed at sites M1 and H2; Section 7.3, above). In our experience, these soil conditions are the norm where laser leveling and other land-forming processes have been employed in preparing the land for sugarcane production.

Such situations can be readily and unambiguously addressed using actual topsoil and subsoil information from a few hand-augered boreholes that are located at the strategically-chosen locations used to validate soil ECa map patterns, and supplemented by field observations of crop growth responses to changes in weather and site drainage conditions over time.

The new soil sampling protocol involving the observation and georeferenced sampling of both topsoils and subsoils has already been adopted by productivity services groups and a number of agricultural consultants in the Central, Burdekin, and Herbert Districts.

8.4.1.2 Tools for managing poorly drained areas

Ineffective paddock drainage and impeded farm drainage systems are constant problems at times of heavy rainfall in the almost flat-lying alluvial plains of the sugarcane lands of Central and Northern Queensland. A major output from Project BPS001 was defining the relationship between the elevation of a site within a paddock, the nature of its soil substrate, and variations in its yield of sugarcane, as was borne out in the cases studies reported in Section 7.3 (above).

In wet years like those prevailing throughout Project BPS001, lower topographic areas of poorly drained sugarcane paddocks with medium – heavy clay subsoils are likely to become waterlogged and produce poor crop yields; paddock zones in slightly higher, better drained areas and with lighter textured subsoils are likely to produce heavier crop yields. In drier years, however, this yield pattern is likely to be reversed with better growth on the heavier soil that can hold more soil moisture for longer periods to sustain the crop for longer than the crop growing on the elevated, well-drained, droughty soils of lighter texture.

Project BPS001 has used a simple paddock elevation model from digital terrain data collected from RTK-GPS systems, and has assumed that higher parts of any paddock were better drained than the lower parts where runoff water tends to back up as a result of inefficient off-farm drainage systems. The digital terrain models are capable of much refinement to include key surface water drainage parameters such as paddock slope angle and slope length, which contribute to the depth and velocity of the runoff waters. Further refinement of the terrain models may be derived from including estimates of the efficacy of internal soil profile drainage by the inclusion of hydromorphic soil properties such as very dark coloured topsoils, rusty iron-stains along root holes, bleached subsurface soil horizons (A2 horizons), grey (‘gley’) subsoil colours, and the occurrence throughout the soil profile of predominantly grey soil mottles, iron segregations in the soil matrix, ferruginous (red) or manganiferous (black) nodules, drainage-impeding soil layers, and shallow water tables.

GIS modelling of digital terrain data from adjacent farms, and farther afield, offers an opportunity to plan and manage better drainage systems between paddocks, within farms, and within sub-catchments. More efficient off-farm drainage systems have the potential to provide the ultimate tool for the management of poorly drained parts of farms by eliminating the backing-up of drains, the ponding of run-off waters on farms, and the frequent waterlogging of low-lying paddock zones.

Until such efficiencies are introduced on a catchment-wide basis, the tools suggested by BPS001 (Section 7.3.2, above) will help to provide solutions to crop production problems in poorly drained spatial zones within a paddock. They include:

- techniques for identifying cane varieties adapted to both soil variability and spatial positions in the landscape. Hence, the development of a 'variable variety planter' to allow on-the-go changes along the row in sugarcane varieties during planting, and according to the potential for waterlogging at any particular location, would greatly assist in matching cane varieties to specific soil conditions.

- adoption of variable height hill-up operations after crop establishment to raise the height of the top of the planted row in potentially waterlogged areas in a paddock. To capitalise on this approach will require an automated base cutter height adjuster fitted to the sugarcane harvester to allow for variability in the height of the soil at the crest of the planted row (as has already been adopted by A. and J. Bugeja, owners of study site M1).

8.4.1.3 Tools for managing nutrient applications

More efficient use of crop inputs (*e.g.* fertiliser, soil amendments, water, pesticides) will result from site-specific applications based on Project BPS001 outcomes and the principle of applying the input needed to support crop growth on spatially defined zones within the paddock, and applying only the level of input needed by each specific zone within the paddock, thereby minimising environmental risk from off-farm losses of excessive inputs.

Adoption of these principles is the basis for more efficient and cost-effective use of farm inputs, especially fertiliser and soil conditioners such as lime and gypsum, by specific applications to management zones within paddocks. The economic advantages of this approach, saving the grower potentially $60 / ha over the alternative, uniform blanket application of nutrients across a paddock, have been explored in Section 8.3.2, above.

An assessment of the commercial drivers for a grower to adopt the precision agriculture principles developed in Project BPS001 is currently in progress. Technological change through the adoption of BPS001 outcomes is being supported by *Project Catalyst* with 30 leading sugarcane growers in the Central District and 10 (eventually expanding to 20) in each of the Burdekin and Herbert Districts. The pilot group of 50 - 70 growers is being supplied with tools to move towards adopting the BPS001 protocols for soil ECa mapping, georeferenced soil testing, paddock elevation mapping, crop yield monitoring, and variable rate nutrient applications.

The Queensland Department of Employment, Economic Development, and Innovation (DEEDI) is assessing the farm economics of *Project Catalyst* operations with 25% of the farmers undertaking a profit probe and the rest doing economic assessments. Results of the economic analysis will not be available until 2012 because of the requirement to use a

minimum of 2 - 3 years of data to provide an accurate assessment of the actual economics involved in adopting the BPS001 precision agriculture outcomes.

It is expected that, as more specific and targeted inputs are applied to spatially defined zones in paddocks, economic gains and environmental benefits will inevitably follow. This will have a direct positive impact on the adopters of the new technology. In addition to more efficient management of inputs at a sub-paddock scale following the Project BPS001 outcomes, the precision agricultural approach will assist growers to decide whether inputs should be boosted or reduced in certain parcels of land, or if land in marginal areas should, in fact, remain in sugarcane production.

8.4.1.4 Tools for managing water quality

The quality of the stormwater runoff from a farm reflects the variety of soils, site characteristics, and management strategies applied at the farm. Similarly, the water quality of the runoff from an individual paddock on the farm reflects the variety of the soils, environmental niches, and management practices that have been applied to the paddock. Clearly, some spatial zones within a paddock will be more prone to soil erosion or leaching of agrichemicals than another. The outcomes from Project BPS001 suggest that it may well be possible to develop some tools for tracking water quality issues back to a particular zone within the paddock where a specific treatment may be applied to improve the quality of the runoff originating in that zone.

Significant water quality improvements, as well as the economic benefits discussed in the previous section, may be generated by paddock inputs based on site-specific management of spatially-defined zones of crop yield potential. Developments in this area will provide information that could be used in a future re-assessment of farm management regulations such as those of the *Environmental Risk Management Planning* (ERMP) guidelines of the Queensland Government.

Given the increasing importance of water quality issues and land management strategies, future agricultural production will demand a higher level of economic and environmental rationalisation to match management and inputs to cropping variability. The environmental imperative is such that the need for site-specific inputs within paddocks is even stronger now than four years ago when Project BPS001 started.

Improved tools for zonal paddock management and more efficient and effective crop production delivered by Project BPS001 will also prove to be very useful tools for water quality managers. To be able to track water quality problems back to specific zones within a paddock, and to apply and monitor site-specific amelioration of the problem zone, would be a key achievement in helping to fulfill the Queensland Government's *Reef Plan* for profitable and sustainable land management practices in sensitive coastal catchments.

8.4.1.5 Tool for getting started in precision agriculture for sugarcane production

An *'Operations manual for soil electrical conductivity mapping: a guide to collecting, analysing, and interpreting soil ECa data in precision sugarcane agriculture'* has been prepared (Coventry *et al.* 2011) in order to fulfill a requirement written into an early draft of the project funding contract when an understanding of the enabling role for precision

agriculture consultants still lay beyond the limits of our perceptions (see Section 8.3.2, above). Nevertheless, it provides basic information for growers who may be thinking about undertaking soil ECa mapping and sets out information relevant to:

- how to go about soil ECa mapping,
- field operational issues,
- data processing protocols,
- stability of shallow and deep soil ECa patterns over time,
- field validation of soil ECa data,
- how to interpret and use soil ECa data in combination with other key data sets (*e.g.* topography, crop yield) to simplify and explain the complexity of paddock variability in sugarcane crops,
- why a precision agricultural consultant should be engaged.

8.4.1.6 Tools for the progressive adoption of precision agriculture methods

Entry into precision agriculture practices has been simplified by the outcomes of BPS001 where basic farming practices have been outlined for adoption by entry-level operators (Section 7.4, above). Improving knowledge of relationships among GIS layers will provide pathways for continual on-farm improvements and will eventually embrace precision agricultural activities as diverse as soil preparation strategies, zonal ripping, zonal application of plant nutrients, breeding cane varieties adapted to both soil variability and spatial positions in the landscape (such as potentially waterlogged areas), managing irrigation water, controlling weeds, and refining spatially-defined management techniques based on crop yield potential.

A step-wise progression into higher operational levels of precision agriculture practices has been well defined by Project BPS001 (Section 7.4.1, above). It will instill confidence in growers to use new tools in progressively adopting the new farming system, and should encourage them to progress towards adopting higher level precision agriculture methods that have the potential to equal or exceed current best management practices.

8.4.2 Adoption of the BPS001 research outcomes

Adoption strategies are currently in place to help ensure achievement of the BPS001 outcomes. But it will take time for the new technology to filter through the industry; most of the strategies will continue beyond the completion of Project BPS001 on 1 August 2011. The three main approaches discussed below are:

- communication of project outcomes to date,
- on-going extension through Project Catalyst,
- precision agriculture training courses.

8.4.2.1 Communication of project outcomes to date

On-going, daily, informal communications between project investigators, growers, and industry extension officers have set in place an increasing ground-swell of support for the project through the progressive delivery of project findings over the last four years. BPS001 investigators have participated in many meetings, made presentations of project plans and outcomes, fostered inter-regional visits by Productivity Services staff, and have discussed implications of the project with sugarcane growers, industry extension officers, cane

productivity groups, and other land managers in North Queensland. The project's outcomes have been delivered to all levels of the sugar industry, from individual sugarcane growers to Mr Tony Burke, the Federal Minister for Agriculture, Fisheries, and Forestry in October 2009.

In addition, BPS001 investigators have offered scientific support to two SRDC-funded Grower Group Innovation Projects that offered excellent avenues for communication of BPS001 achievements directly to leading, innovative growers in the Central, Burdekin, and Herbert Districts:

Project GGP052: The next step for precision agriculture aimed to understand the interaction of the variables contributing to spatial variability within sugarcane paddocks and, in particular, the impact of traffic (soil compaction) and plant disease on crop yield.

Project GGP057: SECMAPPER (Soil Electrical Conductivity Mapper) developed a new, heavy duty machine for mapping apparent soil electrical conductivity patterns below green cane trash blankets and crop stubble.

8.4.2.2 On-going extension through Project Catalyst

Project BPS001 investigators occupy significant positions in the planning and operation of *Project Catalyst* that is supported by the Coca-Cola Foundation ($5 million), the World Wildlife Fund, and the Federal Government's *Reef Rescue Project*. It is administered by Reef Catchments, a Mackay-based natural resource management group, and operates in the Central, Burdekin, and Herbert-Tully Districts. The focus of *Project Catalyst* is on innovative management of sugarcane lands. It encourages the adoption of improved coastal land use practices by providing practical knowledge and sugarcane grower support for technological change in ways that are being increasingly supported by government and utilised by farmers.

The project aims to:

- improve sugarcane farming practices in the Mackay-Whitsunday region by reducing the losses of nutrients, agrichemicals, and fine sediments from farms to off-site, non-target areas,
- monitor the subsequently enhanced quality of waters entering the Great Barrier Reef lagoon in the region,
- boost and assess the economic viability of a pilot group of growers in the region whose farm management skills will be upgraded to the level of Reef Catchments Class A practices that will exceed the current best farm management practices in the region.

The precision agriculture component of *Project Catalyst* is underpinned by, and promotes the adoption of Project BPS001 outcomes, such as soil ECa mapping, multispectral satellite image analysis, crop yield monitoring, georeferenced sampling of soil profiles, and site-specific of paddock inputs in spatially defined zones within sugarcane paddocks. The BPS001 results are being used in the further development of precision agricultural approaches to improved management techniques for increased productivity and enhanced environmental integrity of sugarcane production systems.

Three BPS001 investigators have been directly responsible for delivering *Project Catalyst's* strategies for improved plant nutrient, herbicide, and soil management practices on sugarcane farms across the region (A. Crowley in the Central District, P. McDonnell in the Burdekin, and L. Di Bella in the Herbert until his appointment as Manager, Herbert Cane Productivity Services Ltd, Ingham, in June 2011). The strong link between Project BPS001 and *Project*

Catalyst provides a unique and exciting opportunity to connect agricultural management practices, increased farm productivity, and environmental icons such as the Great Barrier Reef, with the scientific understandings from Project BPS001.

8.4.2.3 Precision agriculture training courses

As the outcomes from Project BPS001 have become more widely communicated, there has been an emerging recognition in the sugar industry and by environmental managers in northern and central Queensland that there is more to precision agriculture than GPS-guided steering systems on tractors. Some natural resource management groups have supported the past purchases of specialised equipment (*e.g.* variable rate fertiliser boxes) for use in proposed precision agricultural practices. It is becoming evident that a number of the farmers who have purchased such equipment lack awareness of the wider possibilities that precision agriculture offers their enterprises, and that specialised training in new farming practices is needed to allow them to capitalise more fully on their investments.

Since May 2011, BPS001 investigators have been involved in fruitful discussions with BSES staff, natural resource management groups, and others seeking project linkages to develop a training course in precision agriculture, with financial support from SRDC and regional industry and environmental groups.

Through the initiatives of *Project Catalyst* and BSES Ltd, mechanisms will exist beyond the completion of Project BPS001 to put the outcomes from the project into the hands and the minds of industry service providers and sugarcane farmers.

8.5 PROJECT BPS001: FUTURE RESEARCH OPPORTUNITIES

8.5.1 Crop yield mapping

Crop yield maps occupy an important role in modern sugarcane production. Processed satellite imagery has been used by mills for regional yield estimation for the forward selling of sugar on the global markets. Satellite image-based yield estimation is also used by milling organisations to determine harvest start dates and harvesting scheduling. Yield predictions at a paddock level have also been used by milling organisations to calculate farm and regional crop estimates with moderate success. The process is reasonably complicated as specific algorithms are required to accommodate differences in the reflectance of the different sugarcane varieties. The cost of satellite imagery has reduced over time and relatively high resolution imagery such as Spot 5 (10 m resolution) is now affordable and is being considered by mills for yield estimation purposes.

Access to accurate and reliable crop yield maps is fundamental in progressing precision agriculture practices in sugarcane. High resolution processed IKONOS satellite imagery was used during the course of Project BPS001 to produce yield maps of study sites. Satisfactory results were achieved at the Mackay and Ingham sites (M1 and H2) where NDVI values matched reasonably well with small plot, manually harvested yield data (adjusted R^2 for the correlations of 0.76 and 0.66 respectively). However at the Burdekin sites (B1 and B2) unfiltered correlations between NDVI values and manually sampled small plots were poor (adjusted $R^2 = 0.03$ and 0.44 respectively). The poor results at the Burdekin sites are attributed to a number of factors including lodged cane (common in high yielding irrigated crops), weed invasion issues, sugarcane flowering, and possibly pixel saturation from the heavy yielding

plant cane crop at the B2 site. The improved results at the Mackay and Ingham sites can be attributed to the erect growth status of the crops although flowering issues remained a concern

It is possible that Burdekin satellite image captures prior to the onset of lodging and flowering (possibly in February or March, or as early as January in favourable growing seasons) may improve the accuracy of NDVI-based yield maps. However, a number of issues need to be addressed if processed satellite imagery is to be relied upon for reliable and accurate crop yield maps for precision agricultures, these issues include:

- Earlier image capture may address lodging and flowering issues, but wet season cloud cover will often prevent on successful satellite image captures.
- Partially irrigated paddocks will influence vegetation reflectance and the integrity of crop yield maps (Burdekin blocks are commonly irrigated on a weekly basis).
- In some instances there may be at least a 6 month interval between a March satellite image capture and harvesting the paddock.

The value of satellite imagery for regional yield estimation is recognised when there is not a requirement for a high level of accuracy in every paddock. At this stage, Project BPS001 investigators have some concerns with the ability of satellite imagery to produce consistent and reliable crop yield maps for precision agriculture purposes using single date image captures. However, there is a belief that multi-temporal image captures during the growth phase of sugar cane (October to March) may significantly improve crop yield maps. But it is also recognised that cloud cover concerns during this period is likely to restrict the success of preparing accurate yield maps suitable for precision agriculture.

All the project sites were harvested with machines fitted with Techagro™ yield monitors. Equipment failure at the Mackay site compromised the value of those data. Yield monitor technology is regarded as being the preferred mechanism for delivering yield maps in precision agriculture because the data is generated at the appropriate stage of the harvest period, and the integrity of the data is not compromised by the variables which affect satellite NDVI yield maps (*e.g.* crop lodging, weed issues, stool tipping, and flowering). Separate linear algorithms were used to convert cane harvester monitor sensor signals into actual tonnes of cane per hectare. Research undertaken by Jensen *et al.* (2010) has indicated that Techagro™ yield monitors are able to produce reasonably accurate yield maps, but further work is required to provide the accuracy suitable for precision agriculture.

Both the processed imagery and harvester monitor systems for crop yield mapping require further research and refinement. In the future it is anticipated that precision agriculture will utilise both systems with the yield monitors generating the critical paddock-based yield map and satellite imagery captures during the growing season for defining agronomic and management issues such as impact of crop pests and disease, poor irrigation practices, weed infestations, etc. The two approaches will enable a precision agriculture consultant to adjust nutrient inputs annually based on current and historical yield data (where available) and to predict the spatial locations of pest and disease incursions for site-specific application of pesticides and other inputs in subsequent crops. High resolution false- and true-colour satellite imagery as an additional spatial layer to fine tune crop yield interpretations, and resultant management decisions, has been successfully used at site B1 (Section 6.2.4, above) and its role in sugarcane farming will increase as the cost of imagery reduces over time.

The role of accurate long term weather forecasting (12 month seasonal outlook) will contribute significantly to the rapid progression of precision agriculture in sugarcane particularly in relation to nutritional inputs and variable rate application. The project has identified the likelihood of a soil with poor subsoil drainage characteristics positioned in a

low-lying area of a paddock having a poor yield potential in a wet year. However, in a drier year the yield potential of the zone would be significantly enhanced. A precision agriculture consultant with access to the three key GIS mapping (soil ECa, paddock elevation, and archived yield maps) and an accurate seasonal outlook is in a strong position to deliver variable rate nutrient programs for paddocks with inherent variability problems on an annual basis.

8.5.2 Definition of paddock management zones in terms of crop yield potential

Australian sugarcane crop production is highly variable spatially within paddocks and across districts, and temporally from season to season. This variability is predominantly attributed to fluctuations in seasonal climatic conditions, soil interactions, crop age (ratoon number), and to a lesser extent, farm management practices. A poor understanding of the interactions among the variables controlling crop yield gives growers similarly poor insights into which farming practices might be best used to maximise crop production. They also reduce the ability of sugar mills to form accurate regional yield forecasts prior to harvest. Both of these issues cost the industry millions of dollars in lost revenue.

The problems could be overcome if we knew how stable crop yield zones are over time and under changing seasonal conditions. Such knowledge could be gained by relating historical regional climate records over the last three crop cycles (15+ years), to seasonal crop productivity and biomass variability mapped by archived satellite imagery over the same time period, and are available from Mackay Sugar Ltd. The new project would be underlain by soil and landscape data, and integrated with yield data derived from three sources: mill and grower paddock records (including variety and crop age), harvester-mounted yield monitors, and manually harvested plots. Analysis of the spatial and temporal interactions among these parameters would produce much more accurate crop yield estimates from spatially defined paddock zones that take into account climatic and site variability.

Should the boundaries of such zones prove to be stable over time (and under defined weather conditions), then it will be possible to determine the yield potential of the crop management zones within a paddock. In wetter than normal years, like those prevailing throughout Project BPS001 (Table 3.2), lower topographic areas of sugarcane paddocks with medium – heavy clay subsoils are likely to produce poor crop yields; paddock zones in slightly higher, better drained areas and with lighter textured subsoils are likely to produce heavier crop yields. In drier years, however, this yield pattern is likely to be reversed with better growth on the heavier soils that can better hold the soil moisture supplies to sustain crop growth for longer periods than in the elevated, well-drained, droughty soils of lighter texture.

The definition of the yield potential of stable paddock management zones that take into account soils, topography, and different seasonal conditions over a number of cropping cycles will provide a robust and reliable starting point for the variable rate application of crop inputs.

8.5.3 Tools to manage sugarcane crops to their zonal yield potential

Several research targets follow from the definition of zonal yield potentials as discussed in the previous section. They include research to:

- define management zones within paddocks based on a spatial analysis of the impact of seasonal growing conditions on the patterns of crop yield over long sequences of wet, dry, and 'average' years;

- demonstrate the repeatability and stability of defined crop yield potential zones over time;

- determine the optimal number of crop yield potential management zones within a paddock;

- identify the influence of topography and soil properties (especially soil texture) on the stability of crop yield patterns under varying seasonal conditions;

- explore the impact of paddock irrigation on deep soil ECa signals and the potential for deep soil ECa mapping of subsoil moisture status;

- following the protocols available for nitrogen applications, develop new protocols for variable rates of application of other paddock inputs (particularly phosphorus and potassium) based on crop yield potential;

- match sugarcane varieties to specific spatial conditions (soil and topographic niches) within paddocks through the use of a 'variable variety planter' to allow on-the-go changes along the row during planting;

- ascertain the most effective inputs required to match crop nutrient needs to the ageing of ratoons in a cropping cycle;

- adjust crop nutrient inputs to potentially compromised sugarcane root system needs under waterlogged conditions;

- determine differences in nutrient losses through denitrification (and variations in nutrient inputs needed) in waterlogged soils of different soil texture.

8.6 CLOSING WORDS

Project BPS001 has achieved its goals and has provided an integrated pathway for carrying out future research and development into profitable, practical, and more sustainable ways to grow sugarcane crops. Along the way, the project has spawned some innovative concepts which have been well accepted by early-adopter growers and forward-thinking, precision agricultural practitioners.

We are pleased by, and proud of, the view that the project has advanced of the over-arching role of precision agriculture in sugarcane production. We have presented a rigorous understanding of the scientific principles that underpin the use of a set of GIS layers (primarily soil, topography, and crop yield patterns) to understand and manage the complexity of sugarcane crop variability.

We have provided a new approach to holistic farm management that can be implemented progressively within a precision agricultural farming system by all sugarcane growers. We have generated some cutting-edge technologies for the sugar industry that go beyond current best management practices, and a strategy for their practical and sequential adoption by sugarcane growers.

We have made some interesting discoveries in addressing the basic questions set out in the original research proposal. More importantly, we have raised many new questions to challenge another generation of researchers. May they be inspired, as we have been, by the insights of two great scientists:

"The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them." – Sir William Henry Bragg (1862–1942), British X-ray crystallographer, Nobel Prize in Physics, 1915.

"Discovery consists of seeing what everybody has seen and thinking what nobody has thought." – Albert von Szent-Györgyi de Nagyrápolt (1893–1986), Hungarian physiologist, Nobel Prize in Physiology or Medicine 1937.

Chapter 9

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Chapter 10

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