STABILITY OF SPATIAL PATTERNS DEFINED BY ELECTRICAL CONDUCTIVITY MAPPING OF SOILS WITHIN SUGARCANE PADDOCKS

By

RJ COVENTRY[1], JR HUGHES[2], AE REID[3], P McDONNELL[4]

[1]*Soil Horizons Pty Ltd, Townsville*
[2]*Department of Employment, Economic Development, and Innovation, Mackay*
[3]*Department of Employment, Economic Development, and Innovation, Townsville*
[4]*Burdekin Productivity Services Ltd, Ayr*
ross@soilhorizons.com.au

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Abstract

INFORMATION that describes variations in the soil within paddocks can be used for the application of precision agriculture techniques through site-specific management to improve crop production. This paper outlines some of the possibilities for the enhanced recognition of soil-related patterns using maps of apparent soil electrical conductivity (ECa) responses recorded by a Veris 3100 machine at study sites in the Herbert, Burdekin, and Mackay sugarcane districts. The paper demonstrates the stability of deep (0–90 cm) soil ECa patterns over a six month fallow period and a five year crop cycle. The map patterns, supplemented by strategic soil description and analysis, are shown to be capable of providing a stable GIS layer that may serve as a surrogate for the soil condition, and as a base for assessing soil-related changes within paddocks, especially in paddocks for which detailed soil maps are not available.

Introduction

Recent technological developments have provided tools to support precision agricultural approaches to agronomy and crop production in the sugar industry (Bramley, 2008), including: controlled traffic through GPS-guided steering of machinery; yield monitors on harvesters; 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 geo-referenced sites for soil sampling and testing (Di Bella *et al.*, 2009b), apparent soil electrical conductivity (ECa) mapping (Coventry *et al.*, 2009), and crop yield mapping (Di Bella *et al.*, 2009a) to better understand and manage variability in sugarcane paddocks in North Queensland.

While recognising that a number of spatial mapping layers may be required to interpret paddock-scale variability in soils and crops, this paper aims to demonstrate the potential for soil ECa maps to provide relatively stable, soil-related patterns for use in precision agricultural approaches to rainfed and irrigated sugarcane production systems. Such spatial information also has potential for use at a scale that is relevant to site-specific land and crop management in paddocks where detailed soil maps are not available.

Study sites and methods

Field sites

The data presented in this paper have been derived from three of the five study sites of the SRDC-funded Project BPS001 that represent a range of soil types and farming conditions in the Mackay, Burdekin, and Herbert districts:

- *Mackay site, M1, 11.24 ha:* sodic duplex and acidic-neutral clay soils; T. Bugeja's farm, Rosella; mean annual rainfall approximately 1690 mm; variety Q208 planted on 29 August 2008; plant-cane harvested on 3 August 2009.
- *Burdekin site, B1, 13.32 ha:* light-textured, sandy loam and neutral-alkaline clay soils typical of the Burdekin delta; I. Haigh's farm, Brandon; mean annual rainfall approximately 980 mm; variety Q208 planted on 31 March 2008; plant-cane harvested on 9–11 July 2009.
- *Herbert site, H2, 11.4 ha:* predominantly heavy textured, older alluvial sediments of the Herbert River floodplain; G. and J. Morley's farm, Lannercost; mean annual rainfall approximately 2400 mm; variety Q200 planted over 8.25 ha on 7 July 2008; plant-cane harvested on 25 August 2009; 3.1 ha was deep ripped on 11 July 2008 followed by 120 mm of rain immediately afterwards and was too wet to plant in 2008.

Soil sampling and analyses

Shallow and deep soil ECa mappings over depths of 0–30 cm and 0–90 cm, respectively, were carried out during the fallow phase of farming operations at each site using a Veris 3100 machine (Figure 1).

Commercial operators in the Mackay and Burdekin districts can map 5–20 ha of fallow land per hour depending on paddock conditions. Field descriptions of the soil properties to a depth of 1 m were made from 84 soil profiles that had been located within specific soil ECa spatial patterns across the study sites. Soil chemical and particle-size analyses were carried out by Incitec Pivot Ltd, Werribee, Victoria, on samples from the topsoil (0–25 cm), upper subsoil (45–60 cm), and deep subsoil (75–100 cm) layers of each described soil profile.

Processing of soil electrical conductivity data

The data from the Veris 3100 unit were used to generate maps of spatially defined areas of soil ECa responses at each of the study sites, using the following GIS and data management protocols to ensure the spatial and statistical compatibility of subsequent analyses.

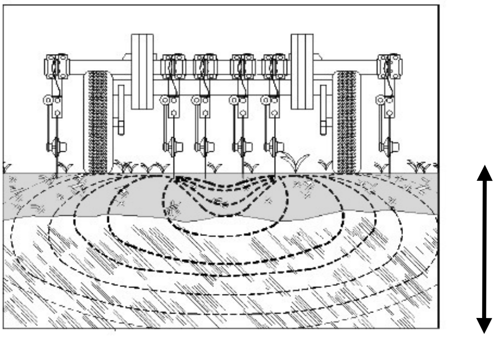


Fig. 1—The Veris 3100 soil electrical conductivity mapping unit extracts geo-referenced data from two soil depths: 0–30 cm (topsoil and shallow cultivation layer) and 0–90 cm (bulk of plant root zone including the undisturbed subsoil). Source: Veris Technologies (2000).

Soil ECa values were interpolated between field observation points (approximately 10 m spacings between Veris runs along sugarcane rows; soil ECa and GPS location data collected at 3 second intervals, or approximately 5 m spacings, along each run) from each site by 10 m block kriging using an exponential variogram (program VESPER; Minasny *et al*., 2005). Soil ECa values were interpolated onto a regular 7 × 7 m grid following the approach of Bramley and Williams (2001). 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 canegrower is likely to adopt for site-specific management inputs. Data were converted by GIS methods (program MANIFOLD; Manifold Net Ltd 2010) to an MGA Zone 55 map projection and displayed as surfaces (program SMS; Ag Leader Technology, 2009). Given the importance in this instance of knowing where any areas of extreme ECa values lay within the field, the data were not de-spiked.

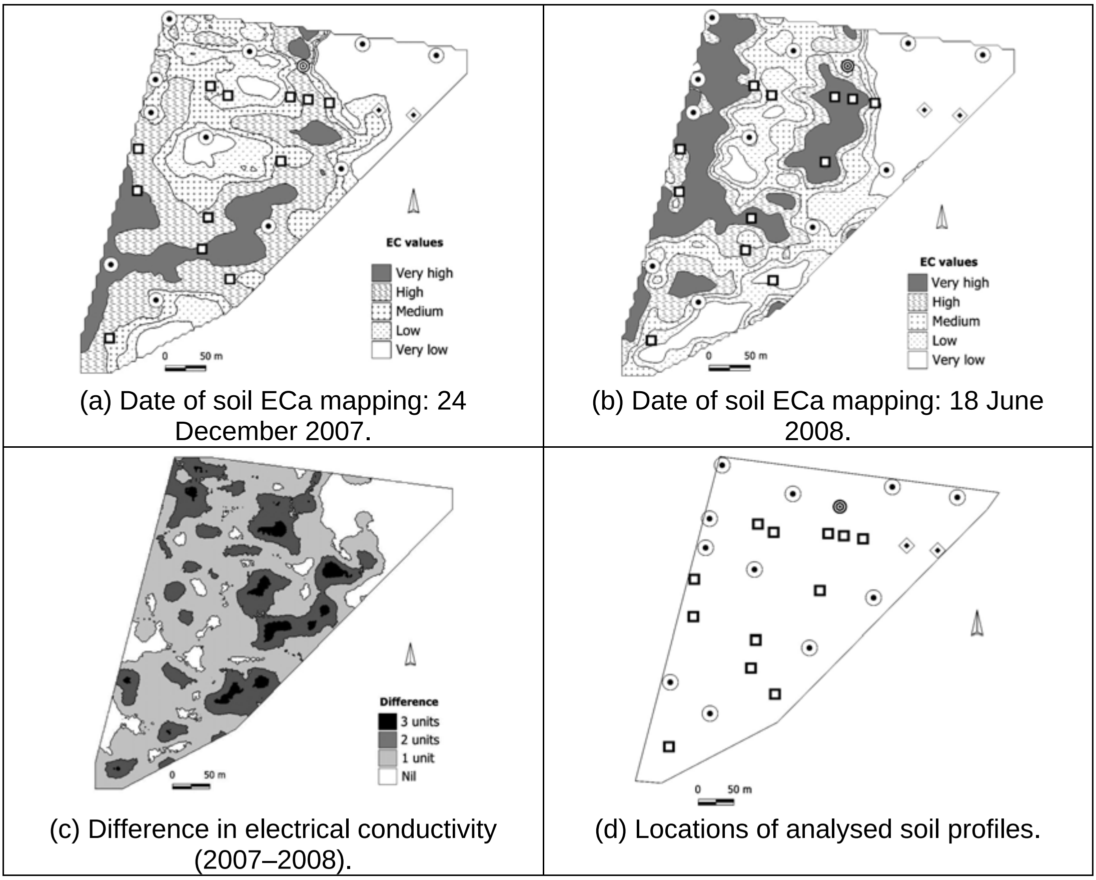
The comparison of soil ECa patterns over time has been facilitated by the preparation of difference maps, using an approach akin to but different from that of Diker *et al.* (2003), where all the grid cell values within a specific contour interval, such as those of Figures 2a and 2b, have been allocated 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 greater (2 or 3 units) change between the soil ECa maps (Figure 2c). 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.

Stability of soil ECa mapping patterns over a fallow period

Soil ECa stability at site M1, Mackay

Site M1, underlain predominantly by poorly drained yellow duplex soils and grey clays, was ECa mapped on 24 December 2007 following deep ripping and offset discing to plough out the previous crop. During the fallow period, 1940 mm of rain fell in 17 significant rainfall sequences including 720 mm in a single event. Multiple discing and spring-tyne cultivations were carried out prior to a second ECa mapping on 18 June 2008.

Both shallow soil ECa mapping events produced 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 Figures 2a and 2b). A linear regression of the shallow ECa values from corresponding georeferenced 7 × 7 m cells of the 2007 and 2008 mapping events was highly significant ($p<0.001$), but the adjusted (adj) R^2 value was only 0.35 (Figure 4a), thus showing that approximately one third of the variability in the observations could be explained by this regression. The ECa difference map (Figure 2c) shows that the shallow soil ECa values over only 32% of the paddock remained unchanged between the two ECa surveys six months apart.



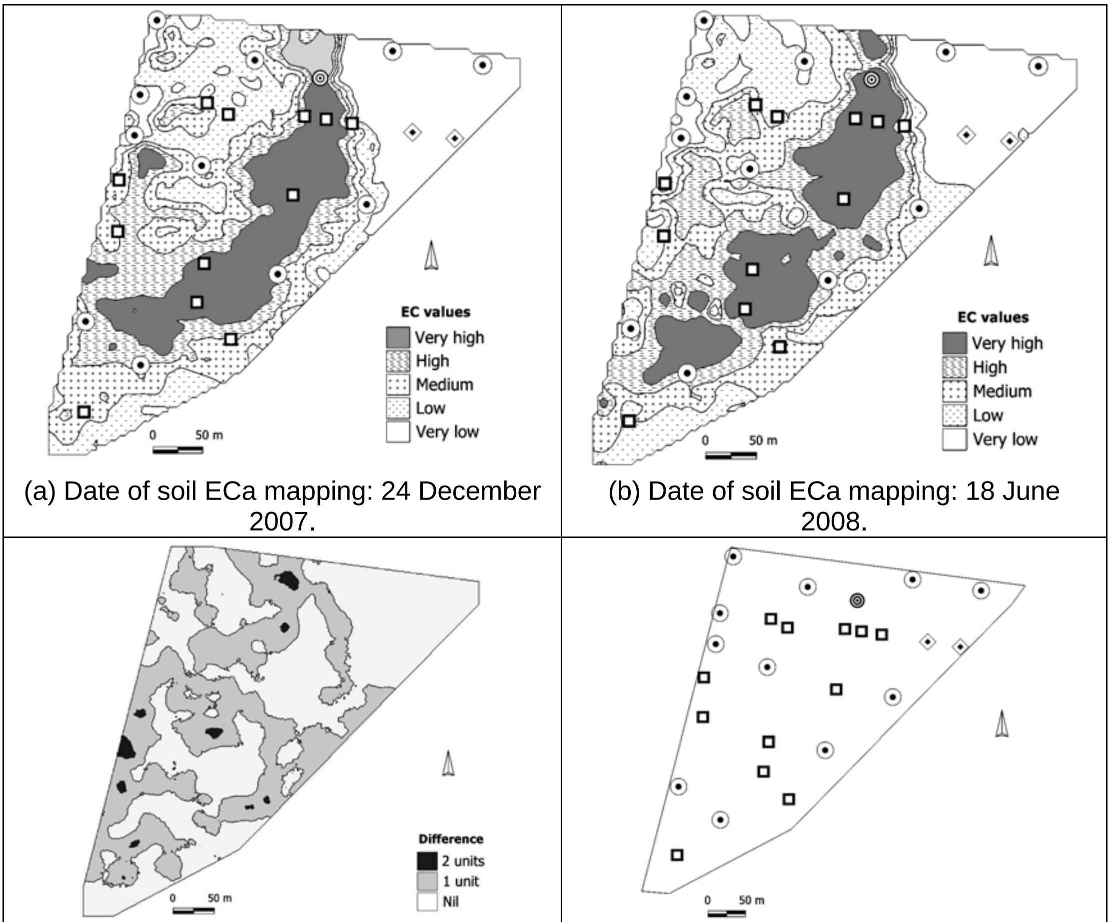
(a) Date of soil ECa mapping: 24 December 2007.

(b) Date of soil ECa mapping: 18 June 2008.

(c) Difference in electrical conductivity (2007–2008).

(d) Locations of analysed soil profiles.

Fig. 2—Shallow (0–300 mm) soil ECa patterns and soil profile types at Site 1, Mackay: (a) patterns produced by ECa mapping after harvest on 24 December 2007; (b) patterns produced 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).



(a) Date of soil ECa mapping: 24 December 2007.

(b) Date of soil ECa mapping: 18 June 2008.

(c) Difference in electrical conductivity: 2007–2008.

(d) Locations of analysed soil profiles.

Fig. 3—Deep (0–900 mm) soil ECa patterns and soil profile types at Site M1, Mackay: (a) patterns produced by ECa mapping after harvest on 24 December 2007; (b) patterns produced 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).

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. Both deep ECa maps have delineated the yellow earth and yellow duplex soils of the northern parts of the paddock, and highlight the distribution of the grey clay soils defined by the pattern of high soil ECa readings through the middle of the paddock (Figures 3a, b).

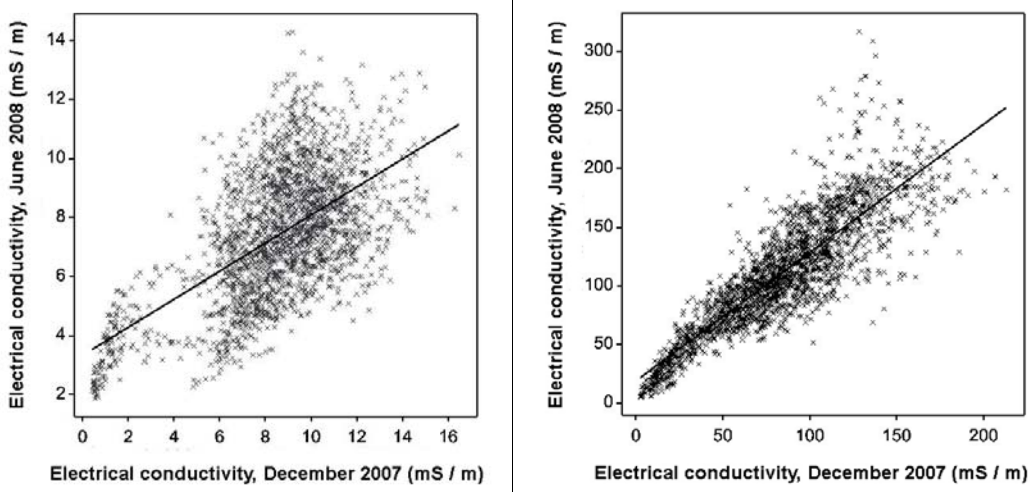
The deep soil ECa difference map (Figure 3c) indicates that 59% of the area of the paddock showed no change between ECa mapping events, and that 94% of the area changed by 1 unit or less.

The general similarity of the deep soil ECa readings is also reflected in successive soil ECa surveys, reinforcing the stability of the map patterns with time.

The relationship between the 2007 and 2008 deep ECa data was much stronger than that of the shallow ECa data (Figures 4a, 4b).

A linear regression for deep ECa values was highly significant (adj R^2 0.75, $p < 0.001$; Figure 4b).

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 (Figure 4b), or when a curvilinear relationship was fitted.



(a) Shallow soil ECa values. (b) Deep soil ECa values.

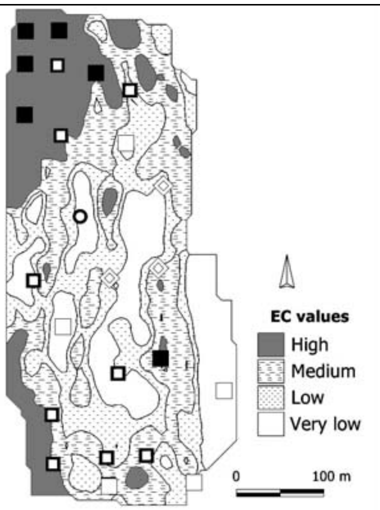
Fig. 4—Relationships of shallow and deep soil ECa signals from corresponding georeferenced 7 x 7 m cells from two Veris 3100 mapping events (24 December 2007, 18 June 2008) within a fallow period at the Mackay study site (n = 2312).

Soil ECa stability at site B1, Burdekin

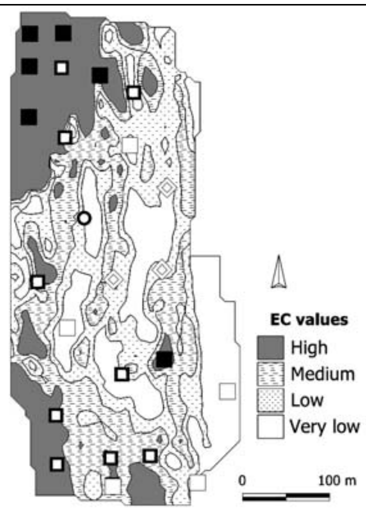
Site B1, underlain predominantly by well drained red sandy soils and poorly drained dark clays, was ECa mapped on three separate occasions: 15 December 2007 immediately after harvest of the last ratoon crop before plough out; 24 March 2008 during the fallow period after double discing, bed forming, and herbicide applications; and 19 July 2009 after harvest of the plant cane crop (Figure 5).

The stability of the soil ECa map patterns at site B1 was similar to that at site M1.

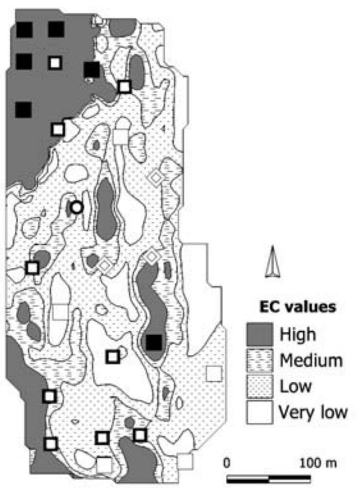
The shallow ECa patterns varied between mapping events, but the deep soil ECa patterns (Figures 5a, 5b, and 5c) were more stable and produced much stronger relationships between mapping events (adj R^2: 0.82, 0.92, 0.72 for 2008 vs 2007, 2009 vs 2007, and 2009 vs 2008, respectively).



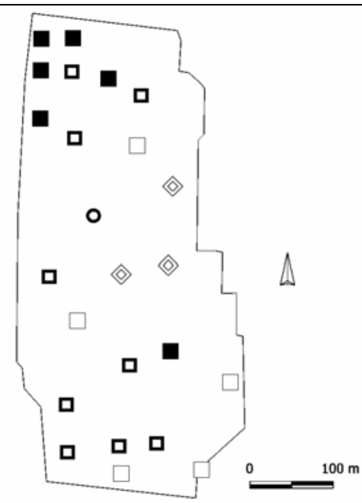
(a) Deep soil ECa mapping: 12 December 2007.



(b) Deep soil ECa mapping: 25 March 2008.



(c) Deep soil ECa mapping: 19 July 2009.



(d) Locations of analysed soil profiles.

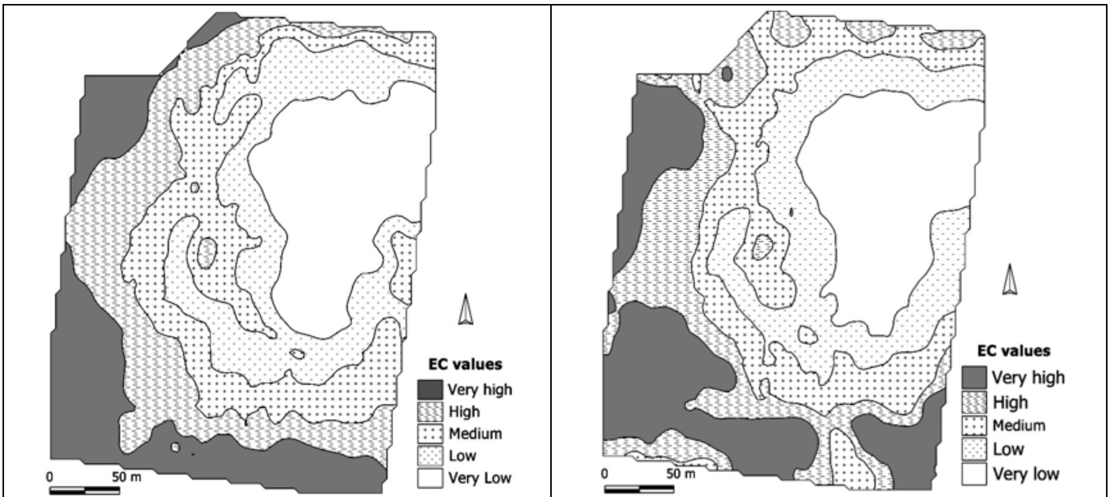
Fig. 5—Deep soil ECa patterns (0–900 mm) from three mapping events at Site B1, Burdekin (13.33 ha), and locations of analysed soil profiles. (a) soil ECa mapping on 12 December 2007 after harvest of fifth ratoon crop before plough out; (b) soil ECa mapping on 25 March 2008 towards the end of the fallow stage; (c) soil ECa mapping on 19 July 2009 after harvest of plant crop (d) locations of analysed soil profiles: generalised soil profile characteristics (after Northcote, 1979) are shown as: ☐ well drained red sand (Uc 5), ◘ non-structured clay (Uf 6), ■ cracking clay (Ug 5), ◈ dark coloured massive earth (Gn 2.0), **O** red duplex soil (Dr 4).

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 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.

Stability of soil ECa mapping patterns over a crop 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 have been attempted (A Crowley, pers. comm.). Therefore, we specifically re-mapped a sugarcane block at Mackay that had been soil ECa mapped 5 years previously during the fallow phase of the preceding crop cycle.

The shallow soil ECa map patterns were found to have varied considerably between the 2003 and 2008 mapping events. Linear regressions for log transformed data explained only a small proportion of the variability (adj R^2 0.25, $p < 0.001$); the log transformation was required for the data to meet normality assumptions. However, the deep soil ECa patterns were found to be remarkably stable between the two separate surveys five years apart (compare Figures 6a, 6b). There was a strong linear relationship between the log transformed values from corresponding georeferenced 7 × 7 m cells of the 2003 and 2008 mapping events (adj 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.



(a) Deep soil ECa patterns, March 2003. (b) Deep soil ECa patterns, May 2008.

Fig. 6—Deep soil ECa patterns collected from the same sugarcane paddock is located 5.4 km southwest of site M1, Mackay: (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).

Soils and ECa mapping patterns

Non-saline, heavy textured duplex and clay soils with fairly similar soil ECa responses occurred over much of site H2 (Herbert). A low ridge towards the south-western margin of the site represents a remnant of channel sand deposited by a past stream which traversed the heavier soils of the Herbert River floodplain (Coventry *et al.*, 2009). The low relief of the site has been significantly modified by levelling 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 (Figure 7).

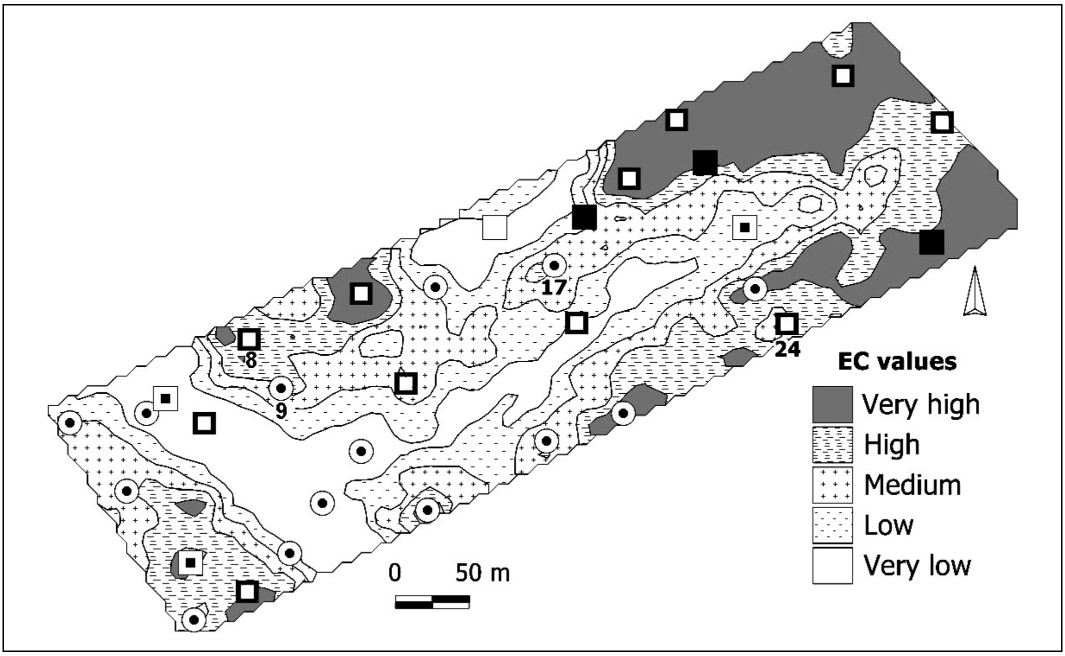


Fig. 7—Deep soil ECa patterns at site H2, Lannercost, showing locations of analysed soil profiles. Generalised soil profile characteristics (after Northcote, 1979) are shown as: ☐ uniform sand (Uc 5), ⊡ uniform loam (Um 5), ◘ non-structured clay (Uf 6), ■ cracking clay (Ug 5), ⦿ yellow duplex soil (Dy 3 or Dy 5). Data for profiles 8, 9, 17, and 24 are given in Tables 1 and 2.

The main morphological and chemical characteristics of the topsoils and subsoils of four soils (two duplex soils and two non-structured clays) from the same soil ECa mapping unit are summarised in Tables 1 and 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 2).

The uniformity of the heavy subsoils is reflected in the similarity of their deep soil ECa signals (Table 2).

Discussion

Soil electromagnetic mapping methods have been used to identify patterns of soils in a variety of Australian primary production systems (grapes, Bramley and Williams, 2001; grains, O'Leary and Peters, 2005; cotton, Stewart *et al.*, 2005) where the influences of soil depth, salinity, clay mineralogy, clay content, and soil water properties have been demonstrated. Similarly, the ECa signals of the present study were found to have been moderated by elevated soil moisture contents and cation exchange capacity, both of which are tied to soil texture.

Table 1– Properties of selected topsoils (0–25 cm depth) from site H2, Lannercost. The profiles are located on Figure 7.

Profile number (Figure 7)	Profile type (Northcote, 1979)	Veris Deep ECa (mS / m)	Thickness of fill over undisturbed soil (cm)	Field texture *	pH (1:5 water)	CEC (cmol(+)/kg)	Organic carbon (%)	P (BSES) (mg/kg)	Exch Ca (cmol(+)/kg)	Exch Mg (cmol(+)/kg)	Exch K (cmol(+)/kg)	Exch Na (% CEC)	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 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 Figure 7.

Profile number (Figure 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 (cmol(+)/kg)	Exch Na (%CEC)	Clay (%)	Field texture *	pH (1:5 water)	CEC (cmol(+)/kg)	Exch Na (%CEC)	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.

At each of the study sites, none of which had high contents of soluble salts in any of the soils, the lighter textured, sandier soils produced low ECa signals and were readily delineated by the deep soil responses recorded by the Veris 3100 machine (Figures 3 and 5).

On the other hand, the heavier clay soils were easily identified from the high values of their deep ECa signals, especially where those clays were found to have relatively high cation exchange capacities or high exchangeable sodium percentages.

While soils with similar deep ECa readings generally had similar soil profile morphologies and properties (as within the sandy or clayey soils at sites M1 and B1), it is possible for soils with different profile morphologies to produce similar deep soil ECa signals, as at site H2 (Figure 7).

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. Project BPS001 is currently investigating the role of spatial patterns derived from 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.

The soil verification field work may be carried out at relatively few sites and the choice of their locations will be 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.

Conclusions

Repeated soil ECa mapping of study sites within a single fallow period, and over a 5-year cropping cycle, have shown that the patterns of deep soil ECa values are relatively stable and repeatable, provided that earthworks have not modified the landscape significantly between ECa mapping events.

Soil ECa mapping is 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 soil verification field work may be carried out at relatively few sites and the choice of their locations will be aided by the patterns derived from a soil ECa survey; site selection is likely to be improved with access to additional spatial layers such as those related to crop growth and other site variables.

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 are not available.

Deep soil ECa mapping offers a rapidly-acquired, low cost source of soil-related data whose full significance is not yet recognised. The technique has potential to guide grower decisions on land management strategies by defining basic changes in soil-related zones within sugarcane paddocks at a scale appropriate to the management of site-specific inputs. The relative stability of deep soil ECa patterns and their strong relationships with actual soil types provide a base mapping layer for use in geographic information systems supporting the development of precision agricultural practices in sugarcane production systems.

Acknowledgements

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REFERENCES

Ag Leader Technology (2009) SMS. http://www.agleader.com/products/sms-advanced/

Bramley RGV (2008) Precision agriculture–an avenue for profitable innovation in the Australian sugar industry or technology we can do without? SRDC Technical Report, 3/2007, pp. 5–59. Sugar Research and Development Corporation, Brisbane.

Bramley RGV, Williams SK (2001) A protocol for the construction of yield maps from data collected using commercially available grape yield monitors. www.crcv.com.au/ CRCVProtocolBkfinal.pdf Cooperative Research Centre for Viticulture, Adelaide.

Coventry RJ, Pollock DC, Hughes JR, Di Bella LP (2009) A role for soil EM mapping in precision agricultural practices for sugarcane production. *Proceedings of the Australian Society of Sugar Cane Technologists* **31,** 265-273.

Di Bella LP, Sefton M, Marrero S, Ponce E, Fernandez F, Esquivel M, Coventry R (2009a) Sugarcane yield monitoring in the Herbert District. *Proceedings of the Australian Society of Sugar Cane Technologists* **31**, 274–281.

Di Bella LP, Coventry RJ, Sefton M, Moody PW, Hanks M, Stringer JK, Kerkwyk RE (2009b) The use of geo-referenced soil test data in the Herbert District. *Proceedings of the Australian Society of Sugar Cane Technologists* **31,** 296-306.

Diker K, Buchleiter GW, Farahani HJ, Heerman DE, Brodahl MK (2003) Frequency analysis of yield for delineating management zones. Proceedings of the 6th International Conference on Precision Agriculture and Other Precision Resources Management, 14–17 July 2002, Minneapolis, USA. American Society of Agronomy–Crop Science Society of America–Soil Science Society of America, Madison, Wisconsin, USA.

Manifold Net Ltd (2010) Manifold Systems. http://www. manifold.net

Minasny B, McBratney AB, Whelan BM (2005) VESPER version 1.62. Australian Centre for Precision Agriculture, The University of Sydney, NSW. http://www.usyd.edu.au/su/agric/acpa

Northcote KH (1979) 'A factual key for the recognition of Australian soils'. (Rellim Technical Publications: Glenside, South Australia).

O'Leary G, Peters J (2005) Standards for electromagnetic induction mapping in the grains industry. Grains Research and Development Corporation. http://www.spaa.com.au/downloads/emprotocol.pdf

Stewart C, Boydell B, McBratney A (2005) Precision decisions for quality cotton: a guide to site-specific cotton crop management. The University of Sydney and Cotton Research and Development Corporation.

Veris Technologies (2000) Veris 3100 soil EC mapping systems, operating manual. Geoprobe Systems, Salina, Kansas.