Prediction of soil moisture retention properties using proximal sensor tools

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Abstract
Site specific crop management is largely dependent upon the provision of adequate data and information including climate, disease and soil to support decision making. Readily available and rapidly sensed soil properties including proximally sensed and terrain derivatives were explored for this purpose. Proximal datasets including EM38, EM31, γ-ray spectra and terrain derivatives were collected in 2006/2007 from five paddocks across North West Victoria. These paddocks were selected to represent major soil/landscape relationships observed in this region. Statistical analysis, including spatial autocorrelation, was undertaken to examine predictive capabilities of these datasets. The significant explanatory variables for field capacity (FC) and permanent wilting point (PWP) were not consistent across the paddocks. Gamma ray (γ-ray) spectrometry and elevation were proven to be significant variables in the spatial modelling of soil moisture retention properties.

Key Words
Proximal, ECa, EMI, soil moisture retention.

Introduction
Knowledge of the variability in key soil properties, such as plant available water capacity, will enable more precise targeting of inputs to match anticipated crop yield, and be useful in crop modelling applications such as APSIM (Keating *et al.* 2003). Mapping these soil properties has value to advance management decisions while optimising water use efficiency in the Australian grains industry. Proximal sensing technologies, including electromagnetic induction (EMI) and γ-ray spectrometry are efficient tools and methods to collect data that may be used to predict soil properties for modelling and monitoring applications.

Proximal soil sensing approaches used for site specific management purposes (e.g. fertiliser application) in north west Victoria has generally comprised EMI surveys to map soils and to target sensitive crops to particular paddocks (Jones *et al.* 2008). Across the region, dryland crop yields have been strongly influenced by the factors of climate, soils and topography (Rowan and Downes 1963). The determination of soil moisture retention properties including plant available water (PAW) and plant available water capacity (PAWC) by EMI techniques have only recently been explored (Robinson *et al.* 2009). Gamma ray (γ-ray) spectrometry for soil measurement can be undertaken either as airborne or vehicle-mounted systems that capture the γ-radiations (scintillations) from soil materials that contain radioactive minerals and isotopes. Potassium, thorium, uranium and total count (records the overall radioactivity levels within the 256 channels of γ-ray spectrometers) are the primary derived datasets from γ-ray sensing systems. Ground-based γ-ray spectra investigations of soils have established relationships with soil parameters including clay content and mineralogy (Taylor *et al.* 2002).

The relationships between grain yield and proximal sensors have been quantified for soils and landscapes of the southern Mallee (north west Victoria) by Robinson *et al.* (2009). This paper investigates the relationship between proximal sensed, terrain-derived datasets and soil hydraulic properties of permanent wilting point (PWP) and field capacity (FC). This study is complementary to Rab *et al.* (2010) and Fisher *et al.* (2010) who quantified soil-water retention properties of dryland cropping soils using traditional laboratory and inverse modelling of multi-steps outflow methods.

Methods
The study area is located approximately 450 km north-west of Melbourne, in the southern Mallee and northern Wimmera regions of Victoria, south eastern Australia. Five paddocks were selected to represent the major soil and landform features of the Mallee and northern Wimmera identified in existing soil and land resource descriptions contained in Rowan and Downes (1963) and Robinson *et al.* (2006). Landscapes

include a series of NNW/SSE trending ridges, known as stranded beach ridges, with self-mulching Vertosols (Isbell 2002) derived from late-Pleistocene to Holocene redistribution of inter-ridge lacustrine sediments. These clay plains and ridges comprise gilgaied plains of gentle relief, with ridge slopes and crests (<5%) and depressions common. Plains on which low hummocks occur (Rowan and Downes 1963) as clusters up to 3 km across contain Hypercalcic Calcarosols (Hypercalcic Calcisol) and Grey Vertosols (Haplic Vertosol), with Red Sodosols (Haplic Solonetz, Abruptic) located on the eastern slopes of hummocks.

Proximally sensed geophysical and terrain data were acquired in December 2006 using a mobile survey system (MSS). Positional data was logged on a 1 s interval using a NavCom Starfire™ DGPS sensor (SF-2050G™) with a real-time horizontal accuracy of <20 cm and a vertical accuracy <50 cm. Bulk soil ECa was measured using a Geonics™ EM38DD sensor and an EM31-MK2 sensor. An Exploranium™ GR320 spectrometer (GPX256) with a 4.2 litre thallium-activated sodium iodide detector crystal was used to collect γ-ray spectra. A DEM was generated for each of the five paddocks using elevation data (mASL) from the DGPS. Topographic variables including profile curvature, planimetric curvature, slope gradient (%), slope aspect (0–360^o), and relative elevation (height of cell relative to a defined radius of surrounding terrain cells) using 15, 30 and 50 m radii were derived for these DEMs.

Soil samples from 100 locations per paddock, to a depth of 110 cm, were collected using a systematic sampling approach on a grid that aligned with proximally sensed and topographic derivatives. Soil samples were cut into five depth increments of 0–20, 20–40, 40–60, 60–80 and 80–110 cm. Soil-water content at –1500 kPa (PWP) and −33 kPa (FC) matric water potentials were determined for 0-20 cm and 40-60 cm depths using disturbed samples (2 mm sieved sample) on a 1-bar and 15-bar ceramic plate in a pressure plate apparatus.

The significance of spatial correlation for FC and PWP was determined using the Moran's I statistic (Moran 1948). The significance of spatial autocorrelation (a measure of correlation between adjacent observations by characterizing their weighted covariance in two-dimensional space, and comparing this against the population variance) in the measured parameters was determined using this analysis technique. Where there is significant spatial correlation, statistical modelling must include this in the error structure. A Conditional Auto Regressive (CAR) error model was used in our spatial regression analyses (S+SpatialStats (S-PLUS : Copyright (c) 1988, 2002 Insightful Corp.)). Coefficients of determination (R^2) for these models were determined by the method of Nagelkerke (1991).

Results

The explanatory variables that had a significant effect on FC and PWP at the two depths (0–20 and 40–60 cm) for the five sites and the combined analysis is presented in Table 1.

Table 1. Variables that had a significant effect (p<0.05) on FC and PWP in each of the five paddocks (1, 2, 3, 4 and 5) and the combined analysis (C). Note, negative associations are shown in red italics, positive associations in green.

Variable[1]	FC (0–20 cm)	FC (40–60 cm)	PWP (0–20 cm)	PWP (40–60 cm)
Elevation	*1, 2,* **C**	*4, 1, 2,* **C**	*4, 1, 2,* **C**	*4, 2,* **C**
RAD_TC	5, 4, 3, 2, **C**	5, 3, **C**	3, **C**	3, **C**
RAD_K	1			1
RAD_U	*3*	2, ***C***	5, *3*	
RAD_TH		*5, 3,* ***C***	5	***C***
EM38condv[2]	4	4, *1*	4	*1*
EM38condh[2,3]		*5*		1
EM31cond	*4,* ***C***	*4*	*5, 4,* ***C***	
Aspect	5, 1	5, 1	5, 3	5
Slope	*1*	*3*		
Plancurv[4]	5, 4, **C**		4, **C**	
Relev30	*1*	4, 1	1	*2*
Relev60		*1*	*1*	*1,* ***C***
Relev100	*1*, 2	2	4, 2	*5*, 4, 2

1 Aspect, Slope, Curv and Procurv were modelled as 3 level (a < b <c) factors
2 This variable was not recorded for Paddock MM
3 This variable was not recorded for Paddock DJ
4 This variable had only 5 non zero values at RD and was omitted from that analysis.

Results from this analysis (Table 1) show that no explanatory variable was significant ($p<0.15$) at all five paddocks, for either FC or PWP or depth range (0–20 or 40–60 cm). The radiometrics total count (RAD_TC) was significant at four of the five paddocks for FC0–20 but was only significant at two paddocks for FC40–60 and a single paddock for PWP0–20 or PWP40–60. The simple measure of elevation was significant at three paddocks for FC40–60 and PWP0–20 and two paddocks for FC0–20 and PWP40–60. The EMI measurements (EM38condv, EM38condh, EM31cond), which are currently quite widely used for predicting spatial variability for precision agriculture, were only significant explanatory variables for the soil water parameters at two paddocks or less. Using the spatial linear models with the significant ($p<0.15$) explanatory variables the percentage variation accounted for at each of the five paddocks varied between 11 and 43% (data not shown).

The relationship between routinely measured soil properties and FC and PWP are presented in Table 2. For the combined data set, the explanatory variables including radiometrics total count and elevation were significant for all of the soil water parameters and R^2 values were between 59 and 61% for the spatial linear models (Table 2).

Table 2. Significant explanatory variables used in spatial linear modelling of FC and PWP at two soil depths using combined data for five paddocks (n = 500).

Parameters[A]	Depth (cm)	Intercept	Regression coefficients of explanatory variables[B]							R^2 (%)	RSE[C]
			Elev	RAD_TC	RAD_U	RAD_TH	EM31cond	Plancurv	Relev60		
FC	0-20	-3.40	0.18	0.12				3.11		59	6.13
	40-60	7.55	0.25	0.09	-0.23	-0.11				58	5.94
PWP	0-20	-5.83	0.13	0.07			-0.04	2.04		61	3.61
	40-60	1.68	0.15	0.04		-0.07			-2.31	59	3.33

[A] FC (% wt) and PWP (% wt) are water content at -33 and -1500 kPa matric potentials
[B] Regression coefficients are significant at the P value of <0.01
[C] df (0-20 = 486, 40-60 = 487)

Discussion

Differences in soil moisture retention properties across paddocks have been found to contribute to resultant crop yields, including PWP, in the southern Mallee (Rab *et al.* 2009). There appear to be very few accounts that relate proximal measurements to temporally stable soil parameters such as PWP and FC. EMI surveys have demonstrated potential in prediction of stable soil properties for site specific management in the region (Jones *et al.* 2008). RAD_TC and aspect were significant explanatory variables with a significant positive association for FC and PWP while elevation and EM31cond demonstrated a negative association with FC and PWP for all sites. Spatial linear models for FC and PWP at 0–20 cm generally had higher R^2 than those for 40–60 cm ($p=0.05$). Increasing PWP and FC, correlating with ECa, was observed for texture contrast and gradational soils with shallow topsoils. This positive relationship with radiometric total count measurements related to FC and PWP correspond to high topsoil clay content observed by Taylor *et al.* (2008). The sandy surface soils with relatively lower PWP and FC values generally emit fewer γ-rays, which is consistent with findings by Taylor *et al.* (2002) for radiometric total count.

Conclusion

Proximal sensing systems have demonstrated a rapid approach to measure soil moisture retention properties including FC and PWP. While EMI and γ-ray spectrometry provide a measure of soil response, not only is information captured about soils and soil variability within paddocks, but when combined with other data (such as yield or climate) may offer valuable data to inform spatial crop yield prediction models. γ-ray spectrometry and elevation have proven significant variables in the spatial modelling of soil moisture retention properties. As γ-ray spectrometry has largely only been acquired by airborne systems, there appear to be useful relationships between ground-based γ-ray and soil properties that are worthy of further investigation. Terrain elevation has proven useful in understanding spatial distributions of soil properties and the ability to map these. The developed equations can be used to predict FC and PWP for similar soils elsewhere. However, further research is needed to validate/improve the predictive models for a wider range of soils and landscape conditions.

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