Biosystems Engineering (2006) **94** (1), 19–32
doi:10.1016/j.biosystemseng.2006.01.002
PA—Precision Agriculture

Available online at www.sciencedirect.com
SCIENCE DIRECT
ELSEVIER

Effect of Soil Water on Apparent Soil Electrical Conductivity and Texture Relationships in a Dryland Field

M.C. McCutcheon[1]; H.J. Farahani[2]; J.D. Stednick[3]; G.W. Buchleiter[4]; T.R. Green[5]

[1]Northern Colorado Water Conservancy District (NCWCD), 220 Water Ave., Berthoud, CO 80513, USA; e-mail: mmccutcheon@ncwcd.org
[2]International Center for Agricultural Research in Dry Areas (ICARDA), P.O.Box 5466, Aleppo, Syria; e-mail of corresponding author: h.farahani@cgiar.org
[3]Forestry, Range, and Watershed Stewardship Department, Colorado State University, Fort Collins, CO 80523, USA; e-mail: john.stednick@colostate.edu
[4]USDA-ARS Water Management Research, 2150 Centre Ave., Bldg. D, Fort Collins, CO 80526, USA; e-mail: gerald.buchleiter@ars.usda.gov
[5]USDA-ARS Great Plains Systems Research, 2150 Centre Ave., Bldg. D, Fort Collins, CO 80526, USA; e-mail: tim.green@ars.usda.gov

(Received 28 October 2004; accepted in revised form 6 January 2006; published online 24 March 2006)

Precision agriculture relies on using advanced tools to map and subsequently manage the variability across the field. There is an emerging interest in mapping apparent soil electrical conductivity (ECa) as a surrogate spatial map for soil texture, providing the potential for ECa mapping as a practical tool to delineate soil-based management zones for variable rate application of agricultural inputs. Results from literature are mixed and inconsistent with the practical utility of ECa to map texture (or clay content) remaining elusive because of the complex interactions between ECa and soil transient properties. The objective of this study was to explore ECa relationships with soil properties and evaluate the usefulness of ECa mapping to infer soil texture as soil water content changed from one mapping date to the next. Measurements included multiple field-scale ECa mappings of a 110 ha dryland field of 12 alternating wheat and fallow strips from 2001 to 2003, complemented with extensive soil profile sampling (198 locations) and analysis. Soil ECa values changed across mapping dates and exhibited weak temporal associations. For instance, ECa values increased by three fold from 10 mS/m in September 2001 (after wheat harvest) to 30 mS/m in May 2003 (in the emerged wheat crop). Volumetric soil water content was the dominant factor affecting the spatial and temporal ECa variability, with other measured soil properties having nearly equal, but weak to moderate, correlations with ECa. For the dryland field examined herein and under relatively dry soil water contents, ECa maps represent overall soil variability with limited utility in providing zones of texture similarities for site-specific management.

1. Introduction

Precision farming or site-specific management relies on using advanced tools to map and subsequently manage the variability across the field (Earl *et al.*, 1996; Stombaugh & Shearer 2000). Geospatial measurement of soil electrical conductivity has become one of most useful field agricultural measurement, particularly for spatial characterisation of soil variability such as salinity, texture, and water content (Corwin, 2005). Among the many advanced sensors recently introduced, apparent soil electrical conductivity (ECa) measuring devices provide the simplest and least expensive soil variability measurement (James *et al.*, 2003). The value of ECa mapping in site-specific management has been widely recognised as a surrogate spatial map for soil variability to guide direct soil sampling and identify within-field areas (or zones) of soil similarity (King *et al.*, 2001; Doolittle *et al.*, 2002; Taylor *et al.*, 2003). That provides the potential for ECa mapping as a practical tool to delineate soil-based management zones for variable rate application of agricultural inputs (Lund *et al.*, 2000; Earl *et al.*, 2003; Cockx *et al.*, 2004).

Soil texture is the most important factor affecting crop growth and an understanding of its spatial distribution is essential to precision farming. The practical utility of ECa to map texture (or clay content), however, remains elusive because of the complex interactions between ECa and soil physical and chemical properties. Research clearly shows soil water content and concentration, clay content and mineralogy, temperature, cation exchange capacity (CEC), and organic matter content are among the dominating soil properties affecting ECa (Rhoades *et al.*, 1976; Sheets & Hendrickx, 1995). In fields containing high concentration of salts, ECa measurements effectively portray both the nature and the main cause of ECa variability (*i.e.*, relative salinity). In contrast, ECa in non-saline fields depicts spatial variability without clearly identifying the dominant cause(s) of variability. While literature provides significant insight into causes of ECa variability, results from non-saline fields are mixed and inconsistent. That has resulted in some confusion in the general soils literature (Lesch & Corwin, 2003) and difficulties with the practical utility of ECa mapping in site-specific management.

From theory (*i.e.*, the dual-pathway ECa model as originally formulated by Rhoades *et al.*, 1989 and applied by Corwin & Lesch, 2003 and Farahani *et al.*, 2005), the relationship between ECa and soil stable properties (such as clay content) is shown governed by the status of the soil transient properties of soil water content and concentration and temperature at the time of the ECa mapping. In particular, the transient nature of soil water complicates characterisation of ECa variability by altering its response to a given soil property during a given mapping event. That is most likely the reason why the strength of the literature reported associations between ECa and clay content varies widely with correlation coefficient values ranging from below 0·3 to above 0·8. This may be improved by selecting ECa mapping dates with suitable soil conditions that would increase the likelihood of a useful ECa map (Corwin & Lesch, 2003). For the transient soil water content, some studies suggest that ECa and texture relations are more stable and prevalent at higher water contents (Auerswald *et al.*, 2001; Dalgaard *et al.*, 2001), implying that ECa mapping should be conducted under wet (near field capacity) than dry soil conditions (Taylor *et al.*, 2003). Occurrence of near field capacity conditions is not frequent in most dryland agricultural fields in arid and semi-arid areas such as in the central and northern US Great Plains, especially during recent periods of low precipitation and drought. The utility of ECa mapping in the dry areas may not be recognised in inferring soil texture or delineating soil-management zones suitable for varying agricultural input, but rather providing a general soil variability map useful for guiding soil sampling.

This paper presents a study investigating relationships between ECa and soil properties (with emphasis on soil textural parameters) in a dryland field of alternating winter wheat and fallow cropping strips in the semi-arid eastern Colorado. The objective was to evaluate the usefulness of ECa maps as surrogate maps of soil texture as soil water content changed from one mapping date to the next. The alternating wheat and fallow strips provided a unique opportunity to simultaneously characterise ECa variability in a single field with two differing soil water content regimes while the multiple ECa mappings between 2001 and 2003 and at different phases in the wheat and fallow cycle provided a temporally varying soil profile water contents.

2. Methods and materials

2.1. *Study site*

The study site is located 19 km east of Fort Collins, Colorado and is part of a broader hydrologic study by USDA-ARS Great Plains Systems Research, Fort Collins. The field is 110 ha of a winter wheat and fallow strip cropping system with 12 alternating strips of wheat and fallow [see aerial photo in *Fig. 1*(*a*)]. Winter wheat is planted in only one set of strips each year, allowing the other strips to lie fallow and collect soil water for the next growing season.

Soils consist of Colby, Kim, and Wagonwheel series as shown in *Fig. 1*(*b*). Colby loams are derived from eolian deposits, occur on 5–9% slopes, are well-drained, and have high available water capacity (AWC) of 27·4 cm. Kim sandy loams occur in the north-eastern section of the study site on 2–9% slopes, derived from wind-reworked sediments, and are well-drained with moderate AWC of 16·5 cm. Wagonwheel loams are the dominant soil type at this field and occur on 0–5% slopes, derived from eolian sediments, and are well-drained with high AWC of 27 cm.

2.2. *Apparent soil electrical conductivity measurements*

Soil ECa measurements were collected at four different dates (12 September, 2001; 28 September, 2001; 1 April, 2002; and 22 May, 2003) using the Veris 3100 EC Mapping Unit (Veris Technologies, Salina, KS). The Veris unit [*Fig. 2*(*a*)] has six coulter electrodes mounted on an implement that was pulled by a pickup truck [*Fig. 2*(*b*)]. The unit simultaneously measured ECa for the top 0·3 m (shallow) and 0·9 m (deep) soil (Lund *et al.*, 2000). Manoeuvring speeds through the field averaged 8 km/h with measurements taken every second,

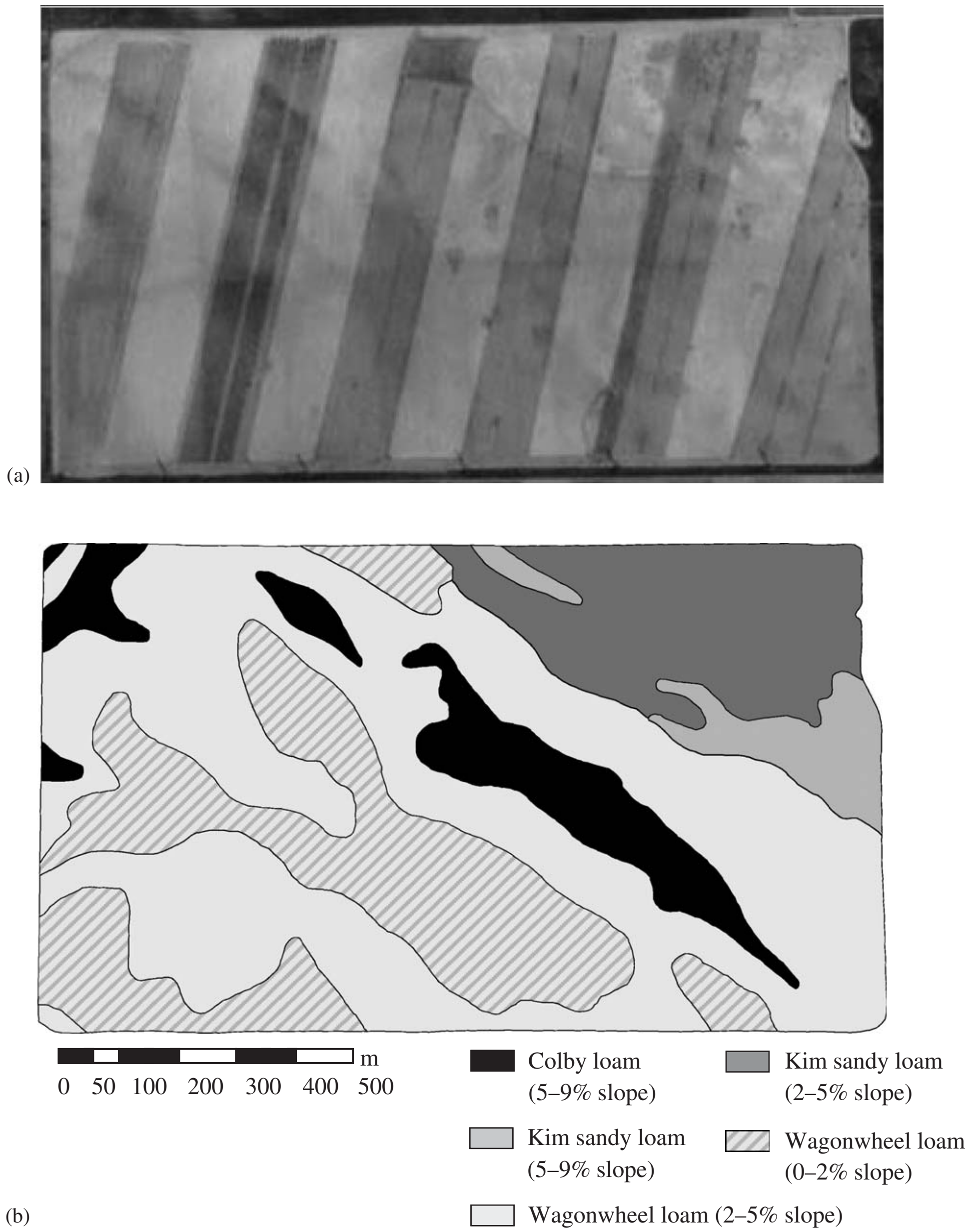
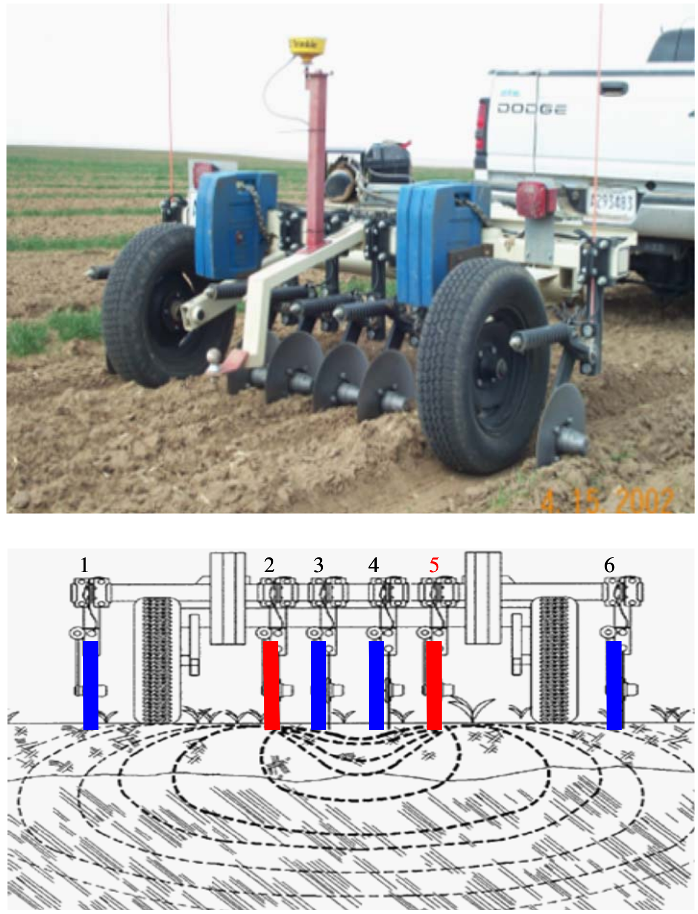


Fig. 1. (a) Aerial photo (USGS, 1999) of the dryland field showing the alternating winter wheat and fallow cropping strips and (b) soil map (Mike Peterson, USDA-NRCS, pers. Comm.., June, 2003)

corresponding to an average 2·2 m spacing between measurements in the direction of travel. The coulters were always set to penetrate the soil to a depth of about of 10 cm. A parallel swather (AgGPS Parallel Swathing Option, Trimble Navigation Limited, Sunnyvale, CA) mounted inside the truck guided parallel passes through the field. A global positioning system (GPS) unit (AgGPS 132, Trimble Navigation Limited) with sub-meter accuracy provided spatial coordinates for each ECa measurement. Elevation data were measured using a Trimble 4700 Dual Frequency RTK (real-time kinematic) GPS and were mapped on transects spaced 5 m apart with an accuracy of ± 2 cm vertically and horizontally [Fig. 3(a)]. The maximum relief in the field was 29 m and followed a swale oriented west-east and slightly northwest-southeast.

The first measurements of ECa and soil samples (detailed later) were taken on 12 September, 2001. At the time of the first ECa mapping, winter wheat was already harvested from one set of the alternating strips in July 2001, referred to as post-harvest stubble strips in this study [light green strips in Fig. 3(b)]. The remaining

(a)



(b)

Fig. 2. (a) The Veris 3100 Mapping System mounted behind truck and equipped with Trimble geographical information system and (b) schematic of coulter electrode configuration with coulters 2 and 5 inducing current while coulters 3 and 4 measuring shallow (0–0·3 m depth) and coulters 1 and 6 measuring deep (0–0·9 m depth) apparent soil electrical conductivity ECa

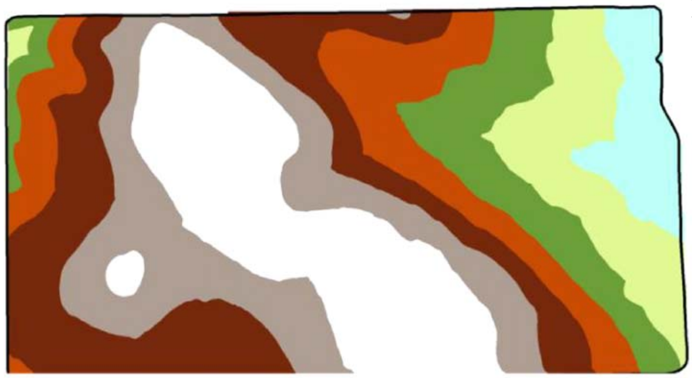
strips were prepared for autumn planting and are referred to as fallow [dark green strips in *Fig. 3(b)*]. The first ECa mapping covered the entire field (fallow and stubble strips), but only provided reliable shallow ECa data as deep data were found to be in error due to sensor malfunction. To obtain simultaneous shallow and deep ECa data, the field was remapped on 28 September 2001, but only in stubble strips since winter wheat was planted in fallow strips just prior to 28 September. The third ECa mapping occurred on 1 April 2002 and only in stubble strips due to the presence of the winter wheat in previous fallow strips. In September 2002, the stubble strips [identified in *Fig. 3(b)*] were planted to winter wheat. The fourth ECa mapping occurred on 22 May 2003 and covered these stubble strips having emerged winter wheat. All ECa mappings occurred in approximately the south–north direction (N15°E) with parallel paths spaced 13·3 m apart [*Fig. 3(b)*], yielding nearly 36 000 data points per mapping of the entire field (roughly 327 data points per ha). References to fallow and stubble strips throughout this paper reflect field conditions in September 2001 [as depicted in *Fig. 3(b)*].

2.3. *Soil sampling and analysis*

Soil samples were taken at 198 locations across the entire field (95 locations in fallow and 103 locations in stubble strips), on two transects per strip spaced 40 m apart as previously shown in *Fig. 3(b)*, to a depth of 0·9 m in 0·3 m increments, for a total of 594 samples. Soil samples were collected immediately following the ECa mapping on 12 September 2001, 1 April 2002, and 22 May 2003. As shown in *Fig. 3(b)*, the two transects overlaid the Veris pathways to match as close as possible ECa and soil sample locations.

For all soil samples collected in September 2001, soil laboratory analysis included gravimetric soil water content θ_w, texture [per cent sand and clay contents

(a)



(b)

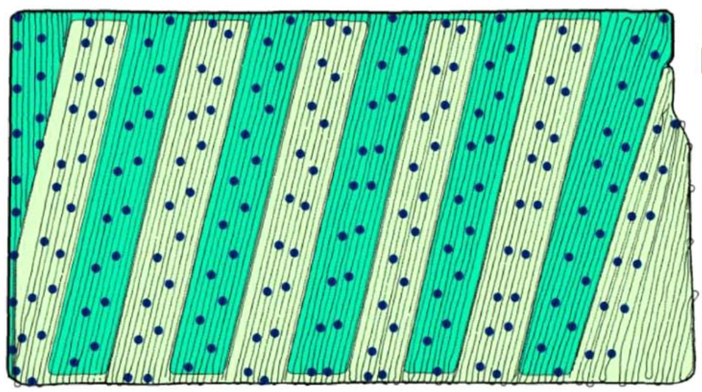


Fig. 3. (a) Elevation map for the study field and (b) map of apparent soil electrical conductivity measurement pathways and location of soil profile samples across fallow and stubble strips

using the hydrometer method (Gee & Bauder, 1986)], per cent calcium carbonate [% $CaCO_3$ using the modified pressure-calcimeter method (Sherrod *et al.*, 2002)], and $EC_{1:1}$ and $pH_{1:1}$ (the 1:1 soil:water electrical conductivity and pH methods). The second round of soil sampling (1 April 2002) was conducted in the 103 previously sampled locations in the stubble strips for bulk density (ρ_b, using intact soil cores 7·6 cm in length and 7·14 cm in diameter) and θ_w determination. It should be noted that drought conditions were experienced in 2001 and 2002 as a result of abnormally low rainfall and winter precipitation combined with warmer temperatures and higher evaporative demands. These conditions resulted in difficulties in April 2002 in obtaining reliable samples for bulk density and gravimetric soil water determination below 0·3 m soil depth due to very dry subsurface soil conditions. An inverse distance weighted map of ρ_b from stubble strips was generated (using ArcGIS 8·2) to estimate ρ_b values for the fallow strips. Volumetric soil water content θ_v values were calculated using ρ_b and θ_w values. The third round of field sampling occurred on 22 May 2003 and included soil water content measurements at the 103 sample locations in the stubble strips. Volumetric soil water content (top 30 cm) was measured using time domain reflectometry (TDR) with 30 cm rods. The mobile TDR arrangement allowed for rapid spatial measurements with two parallel rods inserted vertically into the soil using a hydraulic device (Giddings Machine Co., Fort Collins, CO) mounted on an all-terrain vehicle. A TraseBE TDR instrument (Soil Moisture Equipment Corp., Santa Barbara, CA) was used which computes θ_v from a universal calibration curve. Soil water content data was integrated with position data using a global positioning system (Pathfinder Pro XRS by Trimble Navigation Ltd., Sunnyvale, CA). On 22 May 2003, a total of 332 TDR measurements were taken at 103 locations (3 to 4 repetitions per location) with mean soil water content computed for each location.

2.4. *Data analysis*

All ECa readings within a 5 m radius of each soil sample location [shown in *Fig. 3(b)*] were averaged (using ArcGIS 8·2, ESRI, Redlands, CA) to obtain a representative ECa value for each sample location for quantitative analysis with soil properties. In a few sample locations, the averaging radius was increased to 7 m to obtain a minimum of three ECa measurements.

Summary statistics of field-scale ECa and sample location ECa and soil properties were calculated using SAS (SAS Institute Inc., Cary, NC). The means and standard deviations of sample-location-averaged ECa and of field-scale raw data were only slightly different, indicating that the total of 95 sample locations in fallow strips and 103 sample locations in stubble strips were adequate to represent ECa variability across the field.

Paired *t*-tests were used to determine significant differences at a 95% confidence level between measurement days, cropping strips, and depth intervals. In order to compare data using *t*-tests, the differences between two values measured at different times or at different depth intervals at the same sample location for all sample locations were calculated. If the calculated differences fell within a distribution with mean equal to zero (*i.e.* no difference between parameter values) at a 95% confidence interval, the values were assumed to have come from the same distributions.

A normal distribution is required for paired *t*-tests and linear regressions so Kolmogorov–Smirnov tests (Neter *et al.*, 1996) were performed for each ECa distribution to test for normality. All ECa data sets were found to be normally distributed (no test was performed on the bimodal distribution of the combined fallow and stubble ECa data from 12 September 2001). Linear regressions were performed on each ECa data set (separated by date and depth) using SPlus (Insightful Corporation, Seattle, WA) with ECa as the dependent variable and soil properties as independent variables. Most statistical tests, including linear regressions, assume random distribution of values and ignore spatial autocorrelation of data. For spatially correlated data, spatial regression techniques that correct for spatial correlation of the regression parameters are needed (Kachanoski *et al.*, 1988). The first regression on each data set was performed using all independent variables and the residuals of the regression were subjected to a Moran's I test to determine if spatial autocorrelation existed. The Moran's I compares the variance of a variable with the sum of cross-products of a particular parameter value at two different locations, weighted by the inverse of the distance between the locations. The Moran's I varies between $-1{\cdot}0$ and $+1{\cdot}0$ (Levine & Associates, 2002), in which high values are indicative of high spatial autocorrelation. An expected Moran's I value is compared to the actual value calculated whereby the distribution of Moran's I values is assumed to follow a normal distribution. A *z*-statistic was used to analyse the statistical significance of calculated Moran's I values. If the *z*-statistic is greater than 1·96, the data set is spatially correlated with a 95% level of confidence. When residuals were shown to be spatially correlated, a spatial regression was performed on the data set, again including soil parameters as independent variables. In all regressions, a stepwise selection procedure was used, beginning with all variables in the regression and eliminating the least significant terms until only terms significant at a 95% confidence interval remained.

3. Results and discussion

3.1. *Soil electrical conductivity and water content in fallow and stubble strips*

Summary statistics of measurements across cropping strips and time are given in Table 1 for ECa and in Table 2 for soil properties. Spatial variability is exhibited for the 12 September 2001 ECa mapping of the entire field (shown in *Fig. 4*) in which mean shallow ECa was more than twice as large in the fallow strips (22·5 mS/m) than in the stubble strips (10·3 mS/m). For the 12 September 2001, volumetric soil water content θ_v values in fallow strips were greater than in stubble strips at all depth intervals, with respective means of 0·18 and 0·11 m^3/m^3 for the top 0·3 m soil (Table 2). As shown in *Fig. 5*, these higher θ_v values in fallow strips are consistent with the higher shallow ECa data in fallow.

Statistical differences existed between ECa in fallow and stubble strips and between θ_v in fallow and stubble and at all depth intervals. For the 12 September 2001

Table 1
Summary statistics of shallow (0–0·3 m depth) and deep (0–0·9 m depth) apparent soil electrical conductivity (ECa) measurements across cropping strips for all mapping dates

Measurement date	*Cropping strip*	*Soil surface condition*	*Shallow ECa, mS/m*			*Deep ECa, mS/m*		
			Mean	*SD*	*Range*	*Mean*	*SD*	*Range*
12 September 2001	Fallow	Bare	22·5	6·7	6·4–46·6	—	—	—
12 September 2001	Stubble	Standing stubble	10·3	4·1	2·0–45·6	—	—	—
28 September 2001	Stubble	Standing stubble	10·0	3·5	1·0–26·8	14·9	4·0	1·1–34·5
1 April 2002	Stubble	Standing stubble	14·4	4·4	4·0–31·8	11·9	3·1	2·0–25·9
22 May 2003	Stubble	Emerged wheat	30·1	5·9	8·3–51·9	30·9	5·2	1·2–54·7

Mean, mean of all measurements across the cropping strip; SD, standard deviation; range, minimum and maximum values.

Table 2
Correlation coefficients *r* between apparent soil electrical conductivity (ECa) measurements in stubble strips at different mapping dates

Measurement date	*Correlation coefficient (r)*					
	Shallow ECa			*Deep ECa*		
	12 Sept 2001	*28 Sept 2001*	*1 Apr 2002*	*12 Sept 2001*	*28 Sept 2001*	*1 Apr 2002*
28 Sept 2001	0·74	—	—	—	—	—
1 Apr 2002	0·28	0·34	—	—	0·76	—
22 May 2003	0·39	0·34	0·10	—	0·48	0·32

All values statistically significant at 95% confidence level.

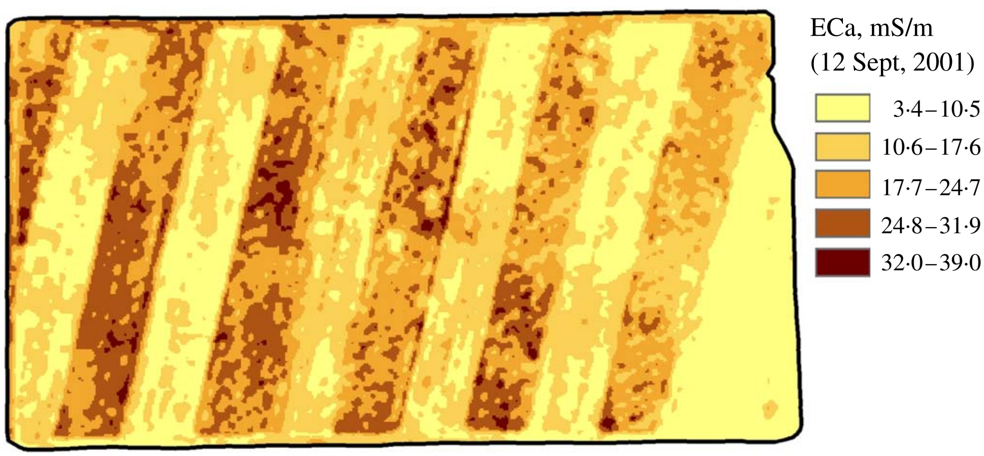


Fig. 4. A continuous map of shallow apparent soil electrical conductivity ECa using measurements taken 12 September 2001 across fallow and stubble cropping strips (ECa delineations represent five classes of equal intervals)

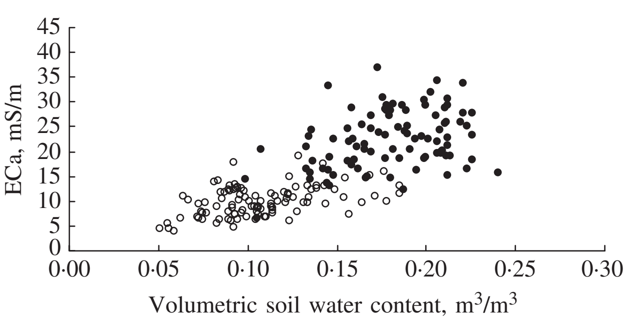


Fig. 5. Shallow apparent soil electrical conductivity (ECa) versus volumetric soil water content at 103 sample locations across stubble strips and 95 sample locations across fallow strips on 12 September 2001: ●, fallow strips; ○, stubble strips

mapping (*Fig. 4*), boundaries between fallow (darker) and stubble (lighter) strips as well as the northern and southern boundaries of the field (kept in fallow and stubble, respectively) were well identified by ECa, with the map of ECa (*Fig. 4*) resembling the map of the cropping strips [*Fig. 3(b)*]. As discussed above, this ECa contrast between the strips was caused by variations in water content between the drier stubble strips and the wetter fallow strips.

3.2. *Soil electrical conductivity variability*

Measurements show substantial spatial (discussed above for 12 September 2001 mapping) and temporal variability in ECa values (Table 1). As expected, mean ECa values measured in the stubble strips on 12 September (10·3 mS/m) and 28 September (10 mS/m) were similar. This was mainly because there were no rainfall or field operations on the stubble strips between these two mapping dates. Temporal variability is demonstrated in *Fig. 6*, showing mean ECa values at each of the 103 sample locations across the stubble strips and time. *Figure 6* also shows time variability of ECa for soil profile layers, for instance the flip-flop between shallow and deep ECa measured in September and April. From September 2001 to April 2002, shallow EC_a values in stubble strips increased from a mean of 10–14·4 mS/m while deep ECa decreased from 14·9 to 11·9 mS/m, respectively. The largest temporal change

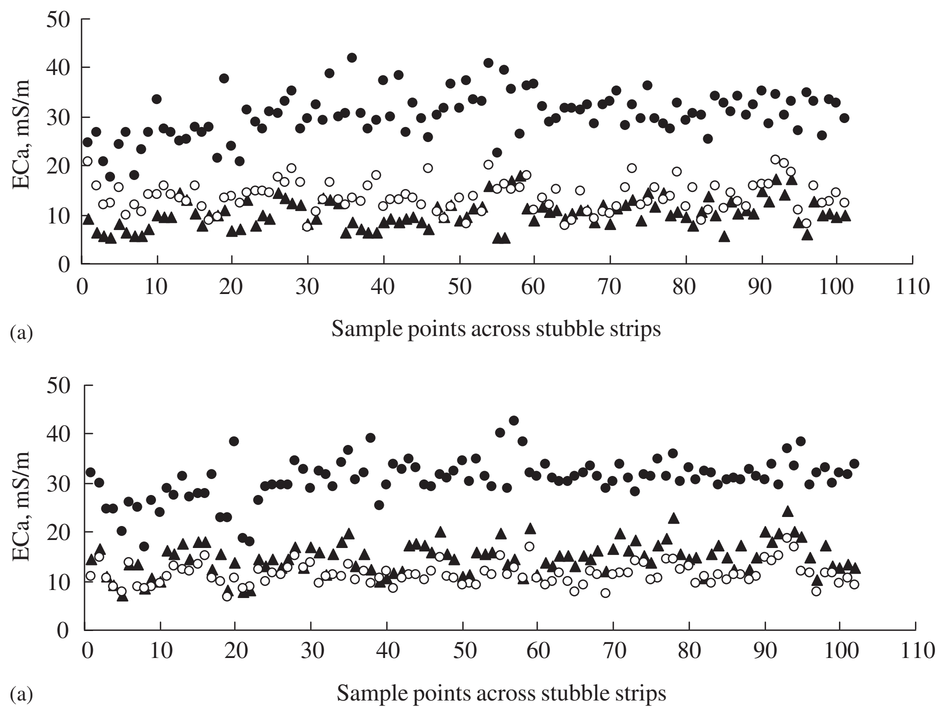


Fig. 6. (a) Shallow and (b) deep apparent soil electrical conductivity (ECa) at 103 sample points across the stubble strips on different mapping dates: ▲, 28 September 2001; ○, 1 April 2002; ●, 22 May 2003

occurred in May 2003 in which ECa in the stubble strips increased by nearly a two to three fold from 10 and 14·4 mS/m (shallow) and 14·9 and 11·9 mS/m (deep) in September 2001 and April 2002, respectively, to 30·1 mS/m (shallow) and 30·9 mS/m (deep) in May 2003.

Table 3 presents a summary of associations between location-specific ECa values from different mapping dates. Associations across time were poor for shallow and poor to average for deep ECa. As given in Table 3, shallow ECa data measured in 12 and 28 September 2001 were weakly correlated with those in April 2002 (correlation coefficient $r = 0{\cdot}28$ and 0·34) and May 2003 ($r = 0{\cdot}39$ and 0·34). Deep ECa data measured in September 2001 were much more strongly correlated with those in April 2002 ($r = 0{\cdot}76$), but data from September 2001 and April 2002 correlated weakly with those in May 2003.

Figure 7 presents a visual comparison of changes in ECa patterns for September 2001 and April 2002, showing high ECa values occurring in a band running from the southeast corner of the field to the northwest through approximately the middle of the field. The maps given in *Fig. 7* use normalised ECa data, called ECa index (ECax) that varies between 0 and 100 (Farahani & Buchleiter, 2004), defined by the per cent ratio of the difference between ECa measured at a point and the whole-field minimum ECa value to the difference between the whole-field maximum and minimum ECa values. This normalisation is particularly helpful when the range of values that define a given ECa delineation change over time. It is noted that normalisation, using the above index or other common approaches such as the standard normal variable, is simply a one-to-one mapping of the original (raw) ECa data, with no effect on the shape of the ECa patterns across the field. The southeast–northwest banding of ECa was observed in both shallow and deep maps on all measurement dates, but was more prominent in deep ECa (*Fig. 7*). Generally, spatial patterns of deep ECa were stronger, sharper, and thus more persistent over time than shallow. This was most likely due to the surface soil layer experiencing more disturbance and climate interactions than subsurface soil.

3.3. *Soil electrical conductivity explained by texture and water content*

Soil surface (0–0·3 m) clay contents varied between 17% and 37% and sand between 28% and 73% with mean field values of 27% clay and 51% sand contents, with most sample locations classified as sandy clay loam (Table 2). Higher sand contents and lower clay contents were concentrated in the northeast corner of the field, corresponding to the presence of the sandier Kim series soils [*Fig. 1(b)*]. This is consistent with lower θ_v and ECa

Table 3
Summary statistics of volumetric soil water content θ_v, texture (%sand, silt and clay), and chemical properties at sample locations for all measurement dates

Soil property	*Measurement date*	*Cropping strip*	*Shallow (0–0·3 m depth)*			*Deep (0–0·9 m depth)*		
			Mean	*SD*	*Range*	*Mean*	*SD*	*Range*
θ_v, m^3/m^3	12 Sep 01	Fallow	0·18	0·03	0·09–0·24	0·18	0·02	0·10–0·23
	12 Sep 01	Stubble	0·11	0·03	0·03–0·14	0·10	0·02	0·06–0·16
	1 Apr 02	Stubble	0·13	0·03	0·07–0·20	—	—	—
	22 May 03	Stubble	0·21	0·02	0·14–0·26	—	—	—
Sand, %	12 Sep 01	All	51	8	28–73	50	7	33–71
Silt, %		All	22	6	8–38	23	6	8–37
Clay, %		All	27	4	17–37	27	3	15–39
$CaCO_3$, %		All	6·7	4·4	0.0–15.8	8·1	3·1	0·6–22·1
$pH_{1:1}$		All	7·9	0·2	7·4–8·4	8·0	0·2	7·6–8·5
$EC_{1:1}$, mS/m		All	40·6	8·5	24·7–77·4	39·2	6·6	24·8–68·0

Mean, mean of sample locations; SD, standard deviation; range, minimum and maximum values; $CaCO_3$, calcium carbonate; $pH_{1:1}$ and $EC_{1:1}$, the pH and electrical conductivity of 1:1 soil:water ratio.
Number of sample locations in fallow strips = 95. Number of sample locations in stubble strips = 103.

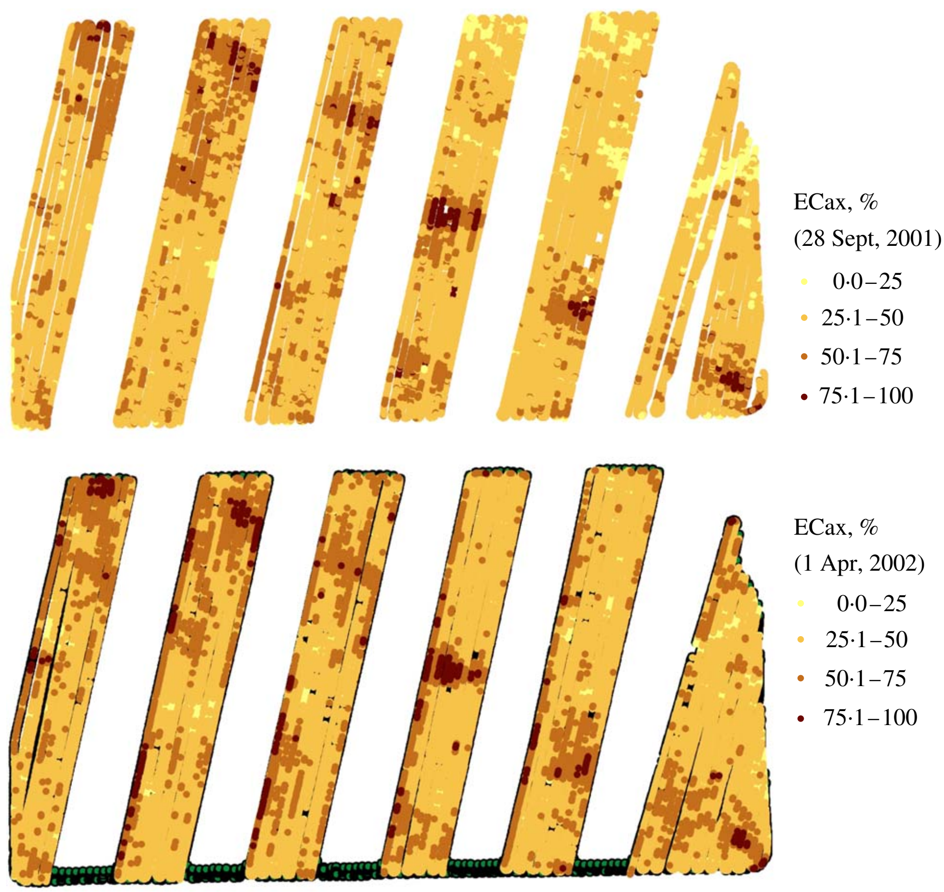


Fig. 7. Maps of apparent soil electrical conductivity index ECax for the deep soil depth (0–0·9 m) across stubble strips on two different dates

values as sands have lower holding capacity and do not conduct electrical current as readily as clay. High clay content, ECa, and θ_v were observed in localised areas of the field indicating correlation between the three. However, correlations between ECa and texture parameters across the entire field were generally low, ranging

Table 4

Correlation coefficients *r* between shallow and deep apparent soil electrical conductivity (ECa) measured on different dates and the corresponding (same depth) soil attributes at 198 sample locations. Shallow ECa is correlated with soil properties from 0 to 0·3 m depth, and deep ECa is correlated with soil properties from 0 to 0·9 m depth

Measurement date	*Cropping strip*	*Soil depth*	*Correlation coefficient (r)*								
			Soil attribute								
			θ_v	*Sand*	*Silt*	*Clay*	ρ_b	*Elev*	*CaCO₃*	$pH_{1:1}$	$EC_{1:1}$
12 Sept 2001	Fallow & stubble	Shallow	0·76	−0·35	0·32	0·31	−0·13	0·18	0·09	−0·18	0·38
	Fallow	Shallow	0·37	−0·16	0·12*	0·17	−0·27	0·35	0·29	−0·18	0·27
	Stubble	Shallow	0·47	−0·25	0·18*	0·25	−0·21	0·39	01·2*	−0·06*	0·36
28 Sept 2001	Stubble	Shallow	0·43	−0·18	0·12*	0·21	−0·10*	0·41	0·20	0·17	0·19
	Stubble	Deep	0·41	−0·28	0·23	0·28	−0·10*	0·49	0·05*	0·15*	0·24
1 Apr 2002	Stubble	Shallow	0·42	−0·04*	0·05*	0·01*	−0·06*	0·0*	—	—	—
	Stubble	Deep	—	−0·19*	0·15*	0·20	−0·07*	0·30	—	—	—
22 May 2003	Stubble	Shallow	0·64	−0·33	0·26	0·33	−0·38	0·42	—	—	—
	Stubble	Deep	—	−0·36	0·29	0·34	−0·19	0·47	—	—	—

*Statistically not significant at 95% confidence level.
Elev, elevation; ρ_b, bulk density; θ_v, volumetric soil water content; $CaCO_3$, calcium carbonate; $pH_{1:1}$ & $EC_{1:1}$, pH and electrical conductivity of 1:1 soil:water ratio.

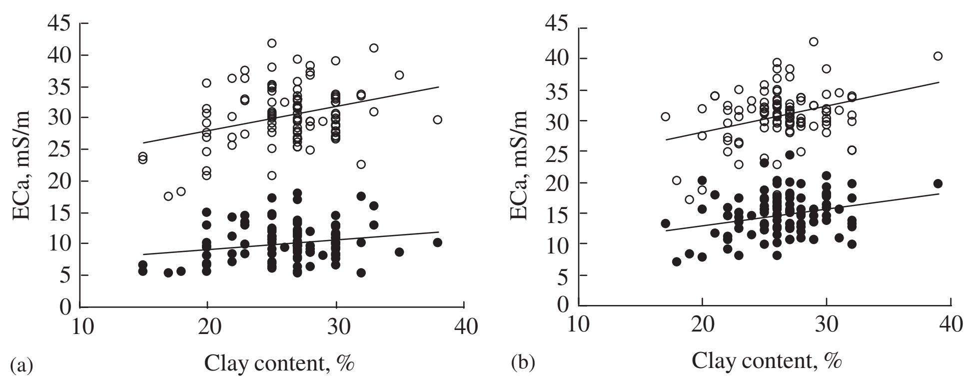


Fig. 8. (a) Shallow and (b) deep apparent soil electrical conductivity (ECa) versus clay content from 103 sample locations across stubble strips on two different mapping dates (and different soil water contents): ●, dry stubble strips on 28 September 2001 (volumetric water content = 0·11 m³/m³); ○, wet stubble strips on 22 May 2003 (volumetric water content = 0·21 m³/m³)

from 0·01 to 0·36 (Table 4). For instance, shallow ECa measured in April 2002 showed no correlation with textural parameters. As shown in *Fig. 8* for two different mapping dates, soil ECa and clay relationships were temporally variable. Even though ECa *versus* clay relationships improved at higher water contents (*i.e.*, May 2003), the association still remained relatively weak ($r = 0{\cdot}34$). *Figure 8* show a large variability in ECa at a given clay content, implying the influence of other soil parameters than clay content alone. For the conditions examined in this study, none of the ECa maps developed over time represented a useful surrogate map of clay, a significant limitation to the use of ECa mapping as a tool to delineate texture in site-specific management.

As discussed previously for 12 September data, there were contrasting ECa differences between the fallow and stubble strips caused by the differing water content regimes between the drier stubble strips and the wetter fallow strips. For the other measurement dates, temporal differences between θ_v values for the top 0·3 m soil in the stubble strips measured in September 2001 (0·11 m³/m³) and April 2002 (0·13 m³/m³) were significant and consistent with the increased shallow ECa from 10·3 to 14·4 mS/m during winter. Although θ_v was not measured below 0·3 m soil depth in April 2002, the inability to probe the subsurface soil implied decreased water content below that previously measured in September 2001 (0·11 m³/m³). That observation is consistent with the trend of deep ECa decreasing from 14·9 to 11·9 mS/m between September 2001 and April 2002. Results imply an over-winter recharge, sufficient only to partially increase near surface θ_v. Results suggest an approximate 1·5 mS/m decrease in ECa per 0·01 m³/m³ decrease in θ_v.

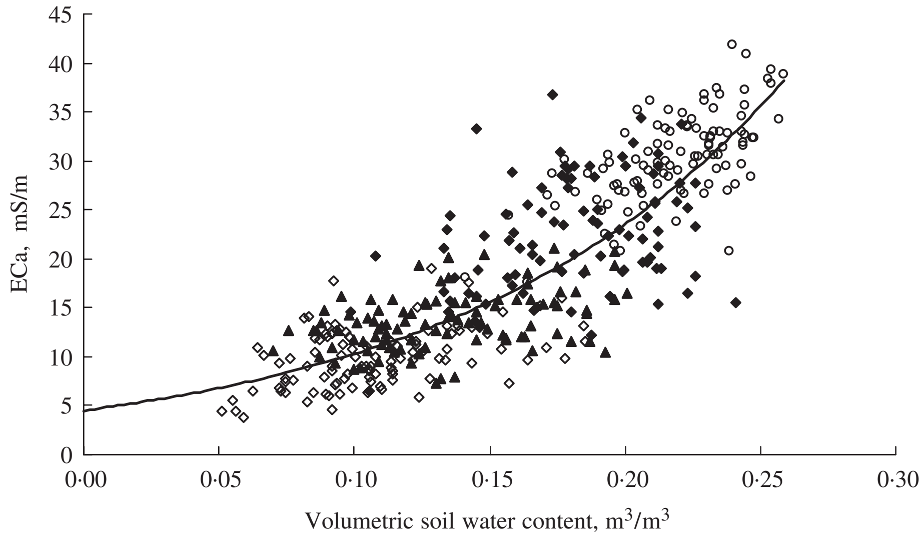


Fig. 9. Shallow apparent soil electrical conductivity (ECa) versus volumetric soil water content at different mapping dates [Eqn (1) describes the fitted line]: ◆, fallow strips 12 September 2001; ◇, stubble strips 12 September 2001; ▲, stubble strips 1 April 2002; ○, stubble strips 22 May 2003

As given in Table 4, ECa correlation with soil properties was highest with θ_v ($r = 0{\cdot}37$–$0{\cdot}76$) at all mapping dates. As θ_v in the stubble strips increased from one mapping to the next, so did absolute values of ECa, with shallow ECa and θ_v values of 10·3 mS/m and 0·11 m^3/m^3 in September 2001 and 30·1 mS/m and 0·21 m^3/m^3 in May 2003, respectively. Soil ECa correlations with θ_v were significantly higher on a whole field-basis (*i.e.,* combined fallow and stubble data from 12 September) than either fallow or stubble. For instance, correlation coefficient between ECa and θ_v was 0·76 for the combined fallow and stubble data (measured 12 September), but correlation was reduced to 0·37 and 0·47 when ECa *versus* θ_v was compared separately for fallow and stubble strips, respectively (Table 4). In this study, different regression functions were identified between ECa and θ_v at each mapping date and also between stubble and fallow strips that were mapped on the same day (12 September), implying that none of the single-mapping functions could be a reliable predictor of θ_v from ECa maps over time. As shown in *Fig. 9*, a more defined ECa *versus* θ_v relationship is established when combining spatial data from all mapping dates, *i.e.*, in the form of the following exponential equation (coefficient of determination $r^2 = 0{\cdot}71$)

$$\sigma_a = 4{\cdot}504 e^{8{\cdot}2635\theta_v} \qquad (1)$$

where σ_a is the apparent soil electrical conductivity in mS/m, and θ_v is the soil volumetric water content (m^3/m^3). In this study, higher clay content and θ_v values were observed together in some areas of the field indicating co-linearity, but the correlation between the two was weak and varied with time, being higher in September 2001 and May 2003 ($r = 0{\cdot}26-0{\cdot}46$) than April 2002 ($r = 0{\cdot}03-0{\cdot}17$). It is noted that some parts of θ_v variations are due to variability in soil texture (*i.e.,* clay content) and organic matter while other parts are likely due to variations in elevation.

3.4. *Soil electrical conductivity explained by elevation and other soil properties*

Correlations between ECa and elevation were mostly significant (except for April 2002) and surprisingly positive at all mapping dates, with r values ranging from 0·18 to 0·49 (Table 4). That is opposite to other comparable dryland studies with significant hill slope topography (Kachanoski *et al.*, 1988, 1990; Khakural *et al.*, 1998; Nugteren *et al.*, 2000) in which negative correlations were reported. They found elevation to be a co-linear variable with water content, being higher at lower elevations and lower on summit. In this study elevation was found to be weakly correlated with θ_v (and clay) with r values below 0·2.

As expected, variations in soil properties of $CaCO_3$, $pH_{1:1}$, and $EC_{1:1}$ between fallow and stubble strips were insignificant. In this study, ECa correlated weakly with $CaCO_3$ ($r = 0{\cdot}05-0{\cdot}29$) and $pH_{1:1}$ ($r = -0{\cdot}06$ to $-0{\cdot}18$), although carbonates were previously speculated as an important parameter increasing ECa in an irrigated field near Gibbon, Nebraska (Luchiari *et al.*, 2000). Correlation between ECa and $EC_{1:1}$ (a measure of soluble salts) was on the scale of texture relations with ECa (weak to

Table 5
Actual and normalised (to a common temperature of 25 °C) shallow ECa at different mapping dates

Date	*Cropping strip*	*Average air temperature, °C*	*Soil temperature, °C*	*Actual ECa, mS/m*	*Normalised ECa, mS/m*
12 Sept 2001	Fallow	17·8	13·8	22·5	27·3
12 Sept 2001	Stubble	17·8	13·8	10·3	12·5
28 Sept 2001	Stubble	17·0	15·3	10·0	11·9
1 Apr 2002	Stubble	10·8	5·6	14·4	19·7
22 May 2003	Stubble	16·0	17·9	30·1	34·1

moderate) and ranging from 0·19 to 0·51. Although positive correlations between bulk density ρ_b and ECa were expected (*i.e.*, decreasing ECa with increasing porosity due to decreased particle-to-particle contact), negative correlations ($r = -0{\cdot}1$ to $-0{\cdot}38$) were found (Table 4). Inconsistent results between ECa and ρ_b have been reported in literature, among which Banton *et al.* (1997) concluded that ECa appeared to be most influenced by soil constituents (*i.e.,* clay minerals) than by structure (*i.e.,* porosity).

The other important soil variable causing changes in ECa is temperature (McKenzie *et al.*, 1989; Nugteren *et al.*, 2000) with ECa increasing by approximately 1·9% per degree centigrade (Corwin & Lesch, 2003). This could be significant for the shallow depth, which exhibits the greatest temperature variation. Due to lack of on-site soil profile temperature data, ECa measurements across time were not adjusted to a reference temperature for comparison. Average soil temperature (5 cm depth) measurements from two nearby automated weather stations (Table 5) were used to obtain rough estimates of the effect of soil temperature on ECa. The soil temperature data show a range of 5·6–17·9 °C for all mapping dates. According to Table 5, normalising the shallow ECa data to a common temperature of 25 °C yields an ECa range of 11·9–34·1 mS/m as compared to the non-normalised range of 10–30·1 mS/m. It is obvious that the estimated range of temperature variations between spring and autumn would not alter the ECa trend. These near surface (5 cm depth) soil temperature represents extreme variations in temperature and thus the effect of temperature variations on deep ECa is expected to be much smaller.

3.5. *Multivariate linear and spatial regressions*

Initially, multivariate linear regressions were performed on all ECa data sets. Each individual regression included all measured soil properties as independent variables. The residuals from all linear regressions were tested with a Moran's I test and, if found to be spatially correlated, spatial auto-regressions were performed. Spatial regressions were necessary for all data sets, except shallow ECa data from fallow strips on 12 September 2001. The linear regression of ECa data for the fallow strips included elevation, θ_v, and $EC_{1:1}$ as significant predictors ($r^2 = 0{\cdot}23$). Spatial regression of stubble ECa data from 12 September resulted in elevation and θ_v as significant predictors of ECa ($r^2 = 0{\cdot}62$). For the combined fallow and stubble data from 12 September, the spatial regression (including only terms significant at the 95% confidence level) of log-transformed data resulted in elevation and θ_v as significant predictors of whole-field shallow ECa ($r^2 = 0{\cdot}87$).

As discussed in detail by McCutcheon (2003), the data used in this study were found spatially correlated and application of spatial regression techniques resulted in θ_v and elevation as major predictors of ECa at all mappings. Of particular importance is the fact that spatial regression did not identify any textural parameters as significant predictors of ECa. Results from this study are consistent with Johnson *et al.* (2001) findings under similar soils, climate, and dryland cropping systems in eastern Colorado, who reported ECa maps to provide an overall picture of spatial variability of soil condition, but not suitable for mapping any particular soil parameter.

Findings are supported by theory (Rhoades *et al.*, 1989) showing the relationship between ECa and soil stable properties (such as clay content) to be governed by the status of the soil transient property of θ_v at the time of the ECa mapping. Soil ECa showed significant variability across space and time demanding more advance geostatistical analysis [*i.e.*, space–time analysis (Rouhani & Wackernagel, 1990), and kriging and co-kriging (Lesch *et al.*, 1995; Vaughan *et al.*, 1995; Pozdnkakova & Zhang, 1999)], than practiced herein. The goal of this study was a more holistic quantification of ECa variability to highlight practical difficulties with the use of ECa mapping in site-specific management. In-depth analysis of space–time variability and theoretical considerations of ECa formulation in non-saline soils are recommended for future studies.

4. Conclusions

For the field and during a single mapping, apparent soil electrical conductivity (ECa) differed between fallow and stubble strips with soil water content as the main factor dictating the difference. The dynamic nature of soil water content from one mapping to the next caused soil ECa and clay relationships to be temporally variable. Results suggest that soil water content most influenced ECa with all other measured soil properties nearly equally, but weakly, correlating with ECa. For the soils and soil water content regimes examined in this study, none of the ECa maps developed over time represented a useful surrogate map of clay, a significant limitation to the use of ECa mapping as a tool to delineate texture in site-specific management.

The main obstacle in the use of ECa maps is not the ECa mapping techniques, but the lack of more focused examination of the spatial and temporal variability of ECa and an appreciation for its complex interactions with stable and transient soil properties at low salt concentrations. Results suggest that generalization of ECa *versus* soil property relationships and temporal extrapolations of empirical relations from limited data are unwise. For soils and dryland conditions similar to those examined in this study, delineating ECa maps for variable rate application seems to have limited utility, but offers a potential method of mapping the relative spatial patterns of soil water content. That may prove to be a plausible method of using on-the-go ECa mapping devices (*i.e.*, ahead of planters) to predict soil water for site-specific seeding rate adjustment.

References

Auerswald K; Simon S; Stanjek H (2001). Influence of soil properties on electrical conductivity under humid water regimes. Soil Science, **166**(6), 382–390

Banton O; Seguin M K; Cimon M A (1997). Mapping field-scale physical properties of soil with electrical resistivity. Soil Science Society of America Journal, **61**(4), 1010–1017

Cockx L; Van Meirvenne M; Hofman G (2004). The use of electromagnetic induction in delineating nitrogen management zones. In: Proceedings of the Seventh International Conference on Precision Agriculture (Mulla D J, ed) (unpaginated CD-ROM), ASA, CSSA, SSSA, St. Paul, MN, USA

Corwin D L (2005). Geospatial measurements of apparent soil electrical conductivity for characterizing soil spatial variability. In: Soil-Water-Solute Characterization: An Integrated Approach (Àlvarez-Benedí J; Muñoz-Carpena R, eds), pp 55–69. CRC Press, Boca Raton, FL, USA

Corwin D L; Lesch S M (2003). Application of soil electrical conductivity to precision agriculture: theory, principles, and guidelines. Agronomy Journal, **95**(3), 455–471

Dalgaard M; Have H; Nehmdahl H (2001). Soil clay mapping by measurement of electromagnetic conductivity. In: Third European Conference on Precision Agriculture (Grenier G; Blackmore S, eds), Vol. 1, pp 367–372. Montpellier, France

Doolittle J A; Indorante S J; Potter D K; Hefner S G; McCauley W M (2002). Comparing three geophysical tools for locating sand blows in alluvial soils of southeast Missouri. Journal of Soil and Water Conservation, **57**(3), 175–182

Earl R; Taylor J C; Wood G A; Bradley I; James I T; Waine T; Welsh J P; Godwin R J; Knight S M (2003). Soil factors and their influence on within-field crop variability: part I: field observation of soil variation. Biosystems Engineering (Special Issue on Precision Agriculture), **84**(4), 425–440

Earl R; Wheeler P N; Blackmore B S; Godwin R J (1996). Precision farming—the management of variability. Landwards, **51**(4), 18–23

Farahani H J; Buchleiter G W (2004). Temporal stability of soil electrical conductivity in irrigated sandy fields in Colorado. Transactions of the ASAE, **47**(1), 79–90

Farahani H J; Buchleiter G W; Brodahl M K (2005). Characterization of apparent soil electrical conductivity variability in irrigated sandy and non-saline fields in Colorado. Transactions of the ASAE, **48**(1), 155–168

Gee G W; Bauder J W (1986). Particle size analysis. In: Methods of Soil Analysis: part I (Klute A, ed), pp 383–411. Madison, WI, USA

James I T; Waine T W; Bradley R I; Taylor J C; Godwin R J (2003). Determination of soil type boundaries using electromagnetic induction scanning techniques. Biosystems Engineering (Special Issue on Precision Agriculture), **86**(4), 421–430

Johnson C K; Doran J W; Duke H R; Wienhold B J; Eskridge K M; Shanahan J F (2001). Field-scale electrical conductivity mapping for delineating soil condition. Soil Science Society of America Journal, **65**(6), 1829–1837

Kachanoski R G; deJong E; van Wesenbeeck I J (1990). Field scale patterns of soil water storage from non-contacting measurements of bulk electrical conductivity. Canadian Journal of Soil Science, **70**(3), 537–541

Kachanoski R G; Gregorich E G; van Wesenbeeck I J (1988). Estimating spatial variations of soil water content using non-contacting electromagnetic inductive methods. Canadian Journal of Soil Science, **68**(4), 715–722

Khakural B R; Robert P C; Hugins D R (1998). Use of non-contacting electromagnetic inductive method for estimating soil moisture across a landscape. Communications in Soil Science Plant Analysis, **29**(11), 2055–2065

King J A; Dampney P M R; Lark M; Mayr T R; Bradley R I (2001). Sensing soil spatial variability by electro-magnetic induction (EMI): its potential in precision farming. In: Third European Conference on Precision Agriculture (Grenier G; Blackmore S, eds), Vol. 1, pp 419–424. Montpellier, France

Lesch S M; Corwin D L (2003). Using the dual-pathway parallel conductance model to determine how different soil properties influence conductivity survey data. Agronomy Journal, **95**(2), 365–379

Lesch S M; Strauss D J; Rhoades J D (1995). Spatial prediction of soil salinity using electromagnetic induction techniques 1. Statistical prediction models: a comparison of multiple linear regression and cokriging. Water Resources Research, **31**(2), 373–386

Levine and Associates (2002). CrimeStat II: A spatial statistics program for the analysis of crime incident locations. Ned Levine & Associates, Houston, TX, and the National institute of Justice, Washington D.C.

Luchiari Jr A; Shanahan J; Francis D; Schlemmer M; Schepers J; Liebig M; Schepers A; Payton S (2000). Strategies for establishing management zones for site specific nutrient management. In: Proceedings of the Fifth International Conference on Precision Agriculture (Robert P C; Rust R H; Larson W E, eds) (unpaginated CD-ROM), ASA, CSSA, SSSA, Madison, WI, USA

Lund E D; Christy C D; Drummond P E (2000). Using yield and soil electrical conductivity (ECa) maps to derive crop production performance information. In: Proceedings of the Fifth International Conference on Precision Agriculture (Robert P C; Rust R H; Larson W E, eds) (unpaginated CD-ROM), ASA, CSSA, SSSA, Madison, WI, USA

McCutcheon M C (2003). Spatial relations between soil electrical conductivity and soil properties in a dryland wheat-fallow cropping system. M.S. Thesis, Colorado State University, Fort Collins, CO, USA, 957pp

McKenzie R C; Chomistek W; Clark N F (1989). Conversion of electromagnetic inductance readings to saturated paste extract values in soils for different temperature, texture, and moisture conditions. Canadian Journal of Soil Science, **69**(1), 25–32

Neter J; Kutner M H; Nachtsheim C H; Wasserman W (1996). Applied Linear Statistical Models. McGraw Hill, Boston, MA, USA

Nugteren W A; Malo D D; Schumacher T E; Schumacher J A; Carlson C G; Clay D E; Clay S A; Dalsted K J; Ellsbury M M (2000). Hillslope chronosequence of electromagnetic induction readings as influenced by selected soil properties. In: Proceedings of the Fifth International Conference on Precision Agriculture (Robert P C; Rust R H; Larson W E, eds) (unpaginated CD-ROM), ASA, CSSA, SSSA, Madison, WI, USA

Pozdnkakova L; Zhang R (1999). Geostatistical analyses of soil salinity in a large field. Precision Agriculture, **1,** 153–165

Rhoades J D; Manteghi N A; Shouse P J; Alves W J (1989). Soil electrical conductivity and soil salinity: new formulations and calibrations. Soil Science Society of America Journal, **53**(2), 433–439

Rhoades J D; Raats P A; Prather R J (1976). Effects of liquid-phase electrical conductivity, water content, and surface conductivity on bulk soil electrical conductivity. Soil Science Society of America Journal, **40,** 651–655

Rouhani S; Wackernagel H (1990). Multivariate geostatistical approach to space–time data analysis. Water Resources Research, **26**(4), 585–591

Sheets K R; Hendrickx J M H (1995). Noninvasive soil water content measurement using electromagnetic induction. Water Resources Research, **31**(10), 2401–2409

Sherrod L A; Dunn G; Peterson G A; Kolberg R L (2002). Inorganic carbon analysis by modified pressure-calcimeter method. Soil Science Society of America Journal, **66**(1), 299–305

Stombaugh T S; Shearer S A (2000). Equipment technologies for precision agriculture. Journal of Soil and Water Conservation, **55**(1), 6–11

Taylor J C; Wood G A; Earl R; Godwin R J (2003). Soil factors and their influence on within-field crop variability; part II: spatial analysis and determination of management zones. Biosystems Engineering (Special Issue on Precision Agriculture), **84**(4), 441–453

USGS (1999). Aerial photo taken 4 October 1999, digitized 26 September 2001, source file 'S.severance_CO.ver_1.04010426.NWS.1159229'. Accessed on Terraserver USA on 13 September 2003. <http://terraserverusa.com/image.aspx?t=1&s=12&x=641&y=5618&z=13&w=1>

Vaughan P J; Lesch S M; Corwin D L; Cone D G (1995). Water content effect on soil salinity prediction: a geostatistical study using cokriging. Soil Science Society America journal, **859,** 1146–1156