

REPEATABILITY OF SOIL APPARENT ELECTRICAL CONDUCTIVITY MEASURED BY A COULTER SENSOR

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Apparent electrical conductivity (ECa) measured using an on-the-go coulter sensor offers advantages for mapping soil variability because detailed data can be collected easily and inexpensively using on-the-go ECa sensors. However, there has been little research investigating the repeatability of these sensors, which may be defined as their ability to reproduce the same ECa measurement when operated in the same location under the same operating and field conditions. If the output of the coulter ECa sensor is not repeatable, the accuracy and reliability of the resulting maps and management decisions would be compromised. Therefore, the objective of this study was to evaluate the repeatability of the coulter sensor by comparing ECa data from two passes in barley stubble at two 1.6-ha sites, one with a sandy loam soil texture (Nesson site) and the other, a clay loam soil texture (Montana State University Eastern Agricultural Research Center site). Sampling points were approximately 1.45 m apart in the direction of travel for both passes. The ECa measurements from both passes were compared at shallow (0–30 cm) and deep (0–90 cm) soil depths. The coefficients of variation of ECa measurements for shallow and deep depths from pass 1 were higher than those from pass 2 at both sites. The root mean square error values of ECa measurements between pass 1 and pass 2 at shallow and deep depths for the Nesson site were 0.76 and 0.51 mS m⁻¹, respectively, whereas the root mean square errors for the Montana State University Eastern Agricultural Research Center site were 4.06 and 2.93 mS m⁻¹ at shallow and deep depths, respectively. The repeatability was evaluated using a 95% confidence interval for the differences between ECa measurements of the two passes. Results demonstrate marginally acceptable repeatability between the two passes at shallow depths and acceptable repeatability at deep depths. The reasons for lack of agreement between pass 1 and pass 2 in ECa measurements at shallow depths could have resulted from soil disturbance and compaction caused by the coulter sensor during the pass 1 process. Regardless of discrepancies for shallow depths, the results indicate that the on-the-go ECa sensors can be useful and provide reliable data for describing field spatial variability in precision farming. This study was conducted to represent field conditions under which this equipment will likely be used, and further work is needed to confirm the repeatability of the coulter at shallow depths. (Soil Science 2008;173:35–45)

Key words: Soil mapping, on-the-go sensor, agreement, precision farming, electrical conductivity.

REPEATABILITY is the ability of an instrument to give the same output or reading under repeated and identical conditions (Omega Engineering, 2006). It is the closeness of agreement (precision) between two or more replicates of each measurement. On-the-go apparent electrical conductivity (ECa) coulter sensors provide a convenient way to characterize spatial soil variability. Little information exists regarding these instruments' repeatability, which may be defined as their ability to reproduce the same ECa measurement when operated in the same location under the same operating and field conditions.

Site-specific soil management requires accurate representation of within-field variability of physical and chemical properties. Recently, advanced soil sensors have attracted much attention among farmers in many parts of the world. Farmers need quick, accurate, precise, and affordable sensing technology to measure and map soil properties such as ECa that characterize soil variability in their agricultural fields. To meet this need, on-the-go sensors (electrical and electromagnetic sensors) have been developed and are available commercially. These sensors can record measurements continuously while traveling across a field, and the data can then be used to create detailed soil maps (Mueller et al., 2003; Sudduth et al., 2004; Adamchuk, 2005; Akbar et al., 2005; Farahani et al., 2005; Kravchenko et al., 2005; and Allred et al., 2006). The aforementioned authors concluded that these sensors were effective tools for soil mapping and interpreting soil variability for precision farming. Furthermore, they concluded that spatial data collected using these advanced sensor technologies can be used as a baseline for precision farming and future planning management practices.

Soil ECa offers advantages for mapping soil variability because detailed data can be collected easily and inexpensively; however, to date, there has been little research focused on the repeatability, accuracy, and reliability of the ECa sensors. If the output of the coulter ECa sensor is not repeatable, the concept using ECa for soil mapping would be uncertain. The objective of this study was to use several statistical methods to evaluate the repeatability of the ECa coulter sensor by comparing ECa measurements from two virtually identical passes. We hypothesized that

the ECa measurements from both passes with the sensor would agree sufficiently.

MATERIALS AND METHODS

Description of Study Sites and Data Acquisition

The ECa data were collected on two sites differing in soil texture, with one located in North Dakota and the other located in Montana. The areas evaluated were approximately 1.6 ha in size at each site. The North Dakota site at the Nesson Valley Research farm (Nesson site) is located approximately 37 km east of Williston (48.1640 N, 103.0986 W). The soil is mapped as Lihen sandy loam (sandy, mixed, frigid Entic Haplustoll) consisting of very deep, somewhat excessively or well drained, nearly level that formed in sandy alluvium, glaciofluvial, and eolian deposits.

The Montana site at the Montana State University Eastern Agricultural Research Center (EARC site) is located approximately 2 km north of Sidney, MT (47.7255 N, 104.1514 W). The soil at the EARC site is classified as Savage clay loam (fine, smectitic, frigid Vertic Argiustolls) consisting of deep, drained, nearly level soils that formed in alluvium parent material.

The ECa measurements were collected on September 8, 2005, at the EARC site and September 19, 2005, at the Nesson site. Two passes (trials) were made with the coulter sensor in barley stubble at each study area as shown in Figures 1 and 2. Each measurement was georeferenced using a Trimble Ag132 Global Positioning System (GPS) with satellite differential correction (OmniSTAR, Inc.; Houston, TX).

Sampling points were approximately 1.45 m apart in the direction of travel. When measurements were taken, soil moisture content was near field capacity at both locations. The ECa data were trimmed according to barley plot size at both fields (see Figs. 3 and 4). A total of 1456 and 1727 data pairs were created for the Nesson and EARC sites, respectively, by pairing one point from the first pass with the nearest point from the second pass using spatial join procedures in the ArcMac software (ESRI, 2006). The distance between the paired measurements of the two passes were between 0 and 1 m, where soil properties were nearly homogeneous within this small distance.

Nesson

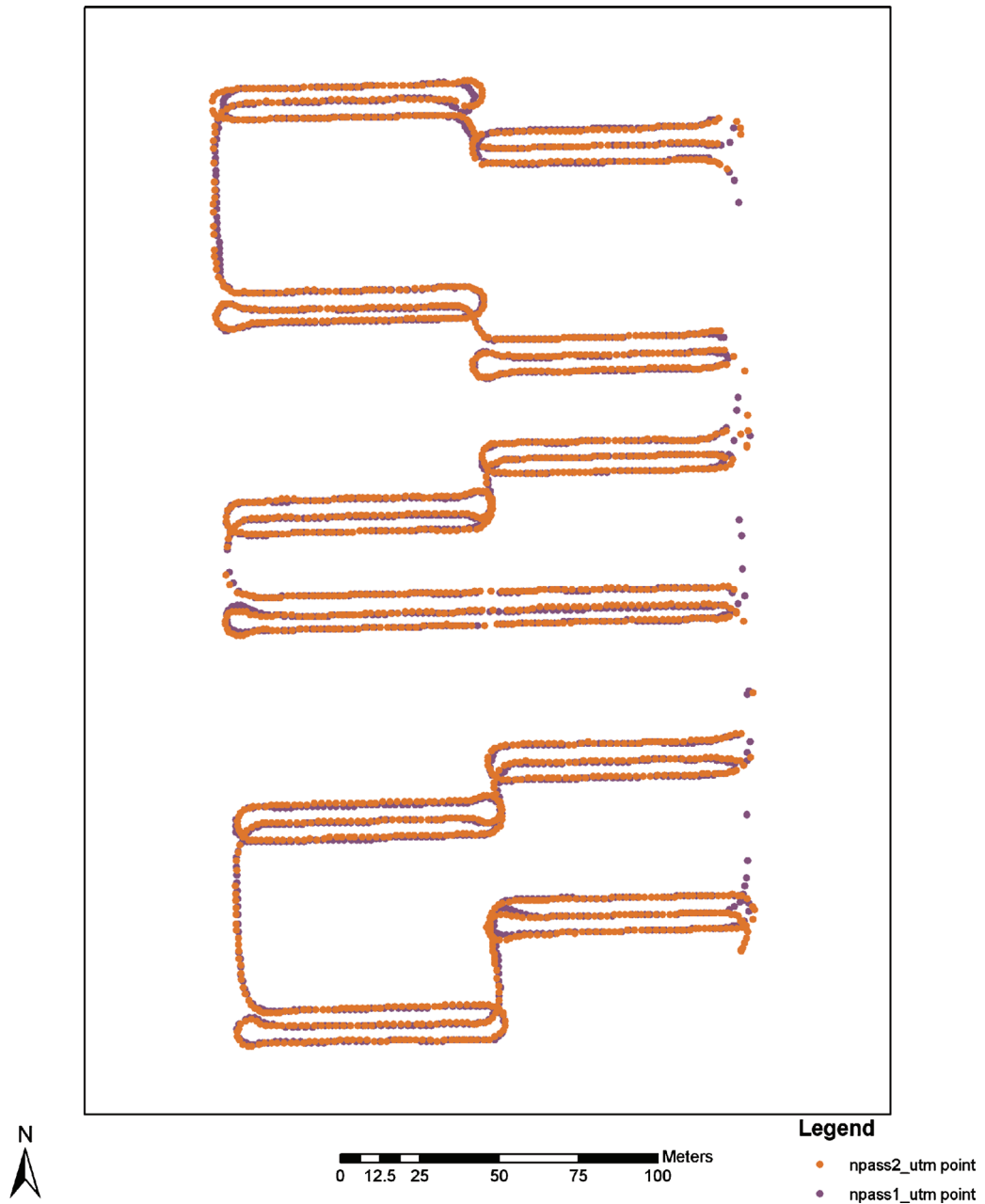


Fig. 1. Two passes of sampling points generated by a coulter ECa sensor at the Nesson site.

Description of Coulter Sensor

The coulter sensor ECa mapping system (Veris 3100) consists of six rotating coulter electrodes mounted on a toolbar that can be pulled by a pickup truck (Veris Technologies, 2002). The coulter electrodes 2 and 5 transmit

an electrical current in the soil as arrays. The remaining four coulters (1, 3, 4, and 6) are spaced to measure voltage drop caused by electrical resistance of the soil, and hence electrical conductivity over two depths, 0 to 30 cm (shallow) and 0 to 90 cm (deep). The

EARC

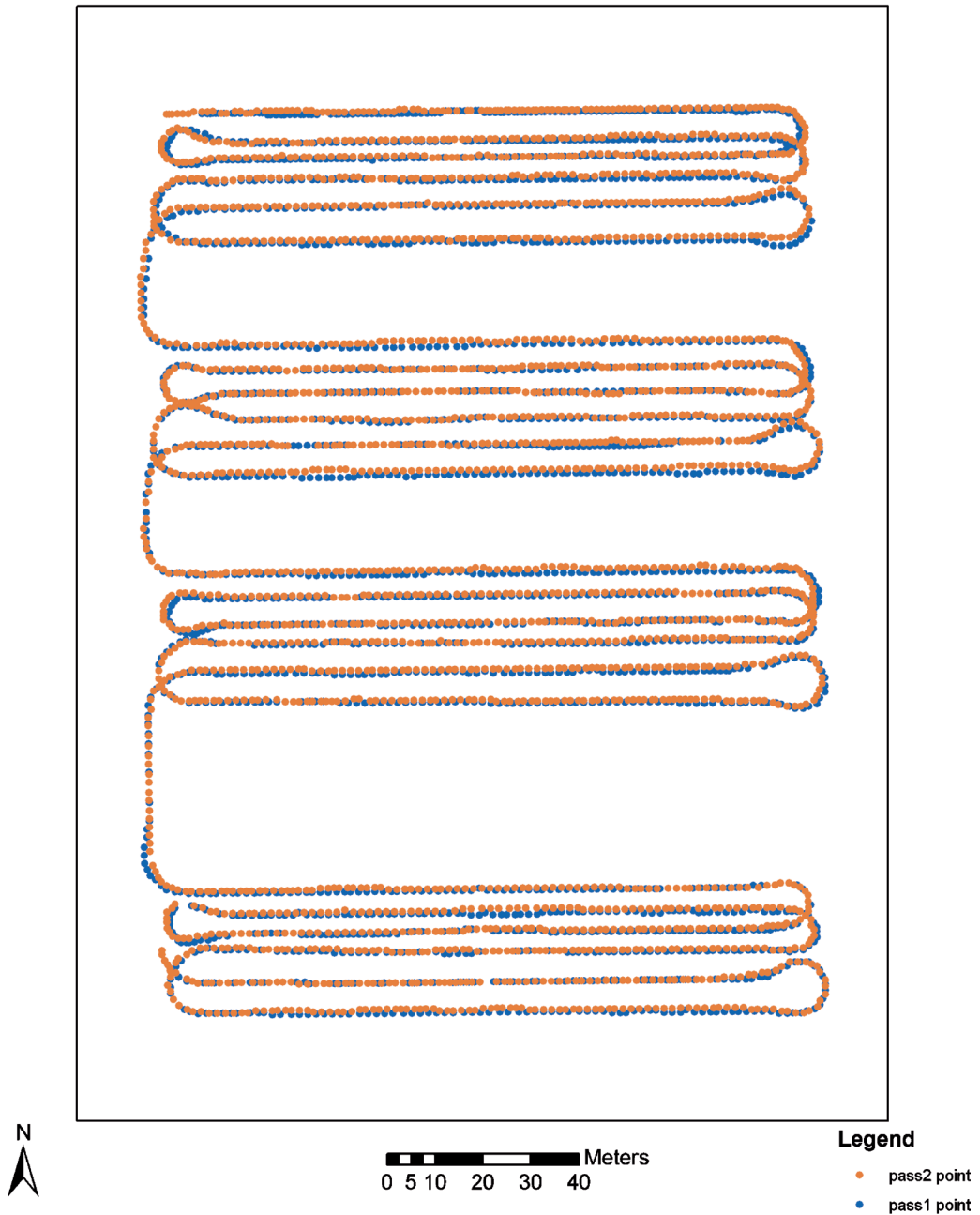


Fig. 2. Two passes of sampling points generated by the coulter ECa sensor at the EARC site.

sensor unit interfaces with a differential GPS to provide georeferenced readings of soil ECa, measured in milliSiemens per meter (mS/m) (Veris Technologies, 2002; Jabro et al., 2006).

Statistical Methods

For each 1.6-ha site, the ECa measurements from both passes of the coulter sensor were compared at shallow and deep soil depths to evaluate the repeatability of the coulter sensor.

Nesson

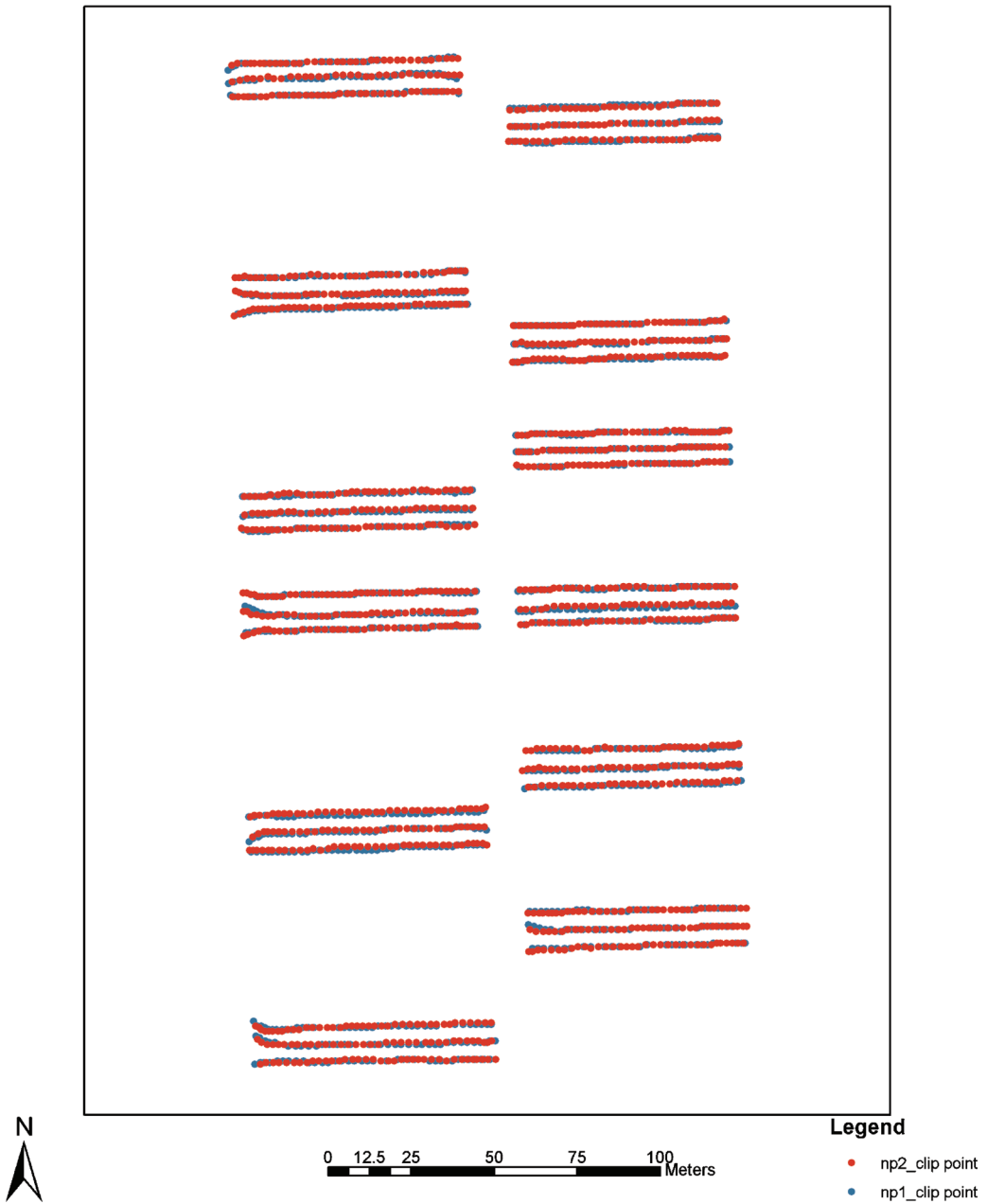


Fig. 3. Two passes of trimmed sampling points for the Nesson site.

All statistical analyses were performed on trimmed data (see Figs. 3 and 4).

Several statistical procedures were explored to assess the agreement between ECa measurements from the two passes of the coulter sensor. The descriptive statistics (mean, minimum, maxi-

um, and coefficient of variation (CV)) of ECa were determined using SAS software (SAS Institute, 2003). The CV was also used to express variability on a relative basis.

The root mean square error (RMSE; see Eq. 1) was used to determine the total difference

EARC

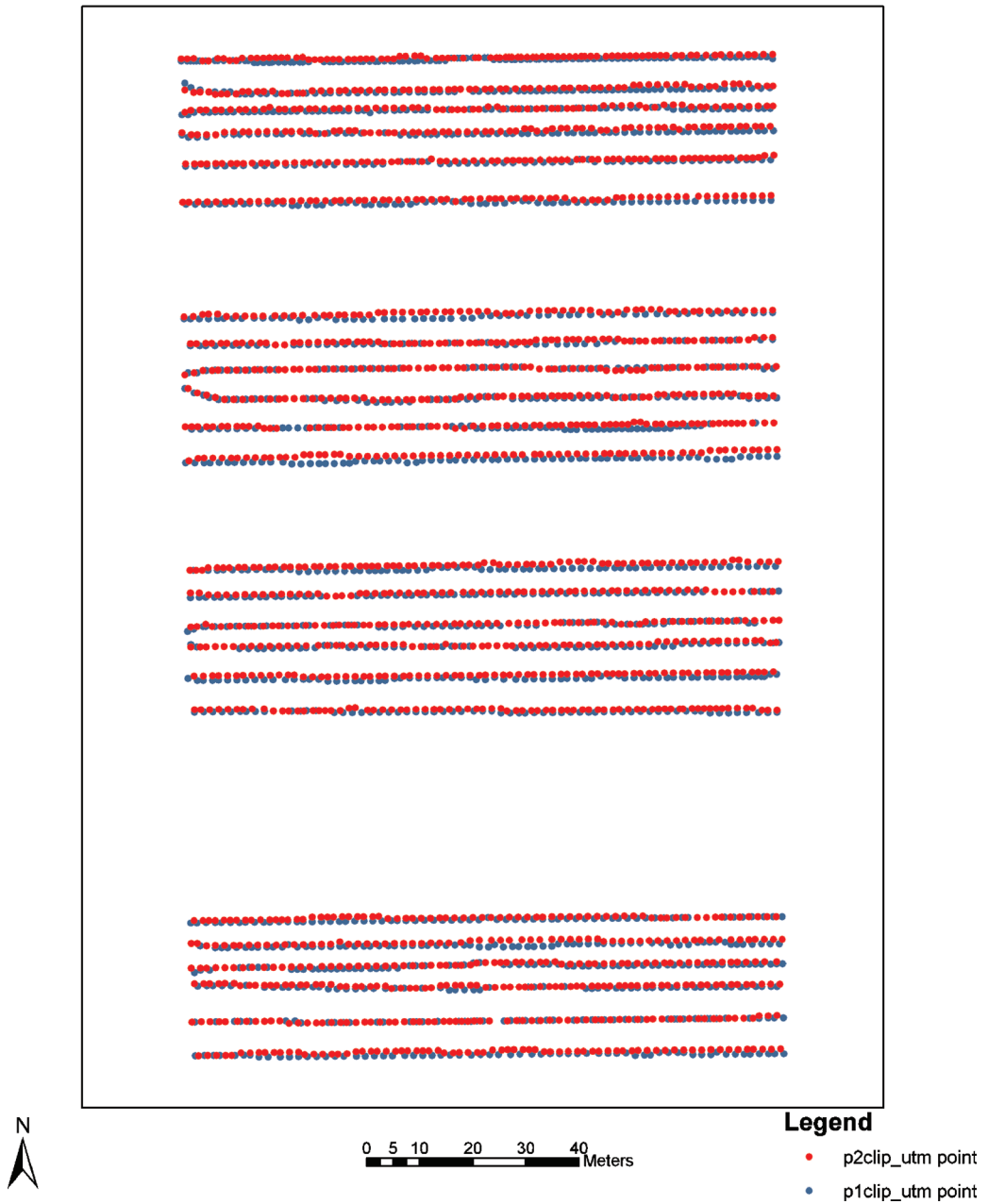


Fig. 4. Two passes of trimmed sampling points for the EARC site.

between ECa measurements of the first (pass 1) and second (pass 2) passes. The RMSE may be considered as an index of the total error (repeatability error) between two passes. A smaller RMSE indicates better agreement between the two passes. The RMSE was performed on pairs located at the same or nearly

the same point coordinates using spatial join procedures.

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^n (Pass1ECa_i - Pass2ECa_i)^2 \right]^{0.5} \quad (1)$$

where n is number of measurements.

Furthermore, the procedure suggested by Altman and Bland (1983) and Bland and Altman (1986) was used to further understand the observed differences between a pair of ECa measurements. The two sets of measurements from pass 1 and pass 2 along with the line $x = y$ were graphed so as to determine whether the measurements were comparable and closely scattered around the 1:1 line (identity line). Differences between a pair of measurements (pass 1 + pass 2) were also plotted against their mean values ((pass 1 \pm pass 2)/2) to determine if the ECa measurements were comparable. If ECa measurements from both passes are analogous, differences should be small, centered around zero, and show no systematic variation in the differences against the means of the measurement pairs. Altman and Bland (1983) and Bland and Altman (1986) concluded that these two methods are the most informative ways of displaying the results when comparing two methods of measurements and assessing their repeatability.

RESULTS AND DISCUSSION

Descriptive Statistics

The arithmetic mean, CV, and minimum and maximum values of ECa measurements from pass 1 and pass 2 at the Nesson and EARC sites are listed in Table 1. The CV values of ECa measurements for shallow and deep depths from pass 1 were higher than the CV values from pass 2 at both sites, except for the deep ECa at the EARC site. However, the ECa CV values between the two passes were larger at the shallow depth than those found in deep depths at both sites (Table 1). These results indicate less repeatability and more variation in ECa measurements between the two passes at shallow depths than deep depths.

Root Mean Square Error (Repeatability Error)

The RMSE values of ECa measurements between pass 1 and pass 2 at shallow and deep depths for the Nesson site were 0.76 and 0.51, respectively, whereas the RMSE for the EARC site were 4.06 and 2.93 at shallow and deep depths, respectively (Table 2). The RMSE at deep depths were smaller compared with those of shallow depths for both fields, which indicates better repeatability and less variation in ECa measurements between the two passes at deep depths.

Coefficient of Correlation

Correlation coefficients (r) were calculated to compare the ECa measurements from pass 1 to those from pass 2 for both depths and sites (Table 2). The r values were 0.928 and 0.934 for shallow and deep depths at the Nesson site, respectively, whereas r values were 0.924 and 0.985 for shallow and deep depths at the EARC site, respectively. The ECa data from the two passes were strongly and significantly correlated ($P < 0.01$), however, these high correlations do not always show that the measurements are in good agreement and closely comparable. Therefore, the use of r and its test of significance can be biased, irrelevant, and misleading for assessing the degree of agreement between the ECa measurements of two passes because r is a measure of degree of association between the measurements of the two passes and not the agreement between them (Altman and Bland, 1983).

Line of Identity (1:1) and the Difference Method

The ECa measurements from pass 1 and pass 2 for both shallow and deep depths at both sites were plotted along with the line $x = y$ (1:1 line) to determine whether the measurements are

TABLE 1

Statistical analyses of ECa (mS m^{-1}) data for two soil depths (0–30 cm and 0–90 cm) collected during two separate, but nearly identical, passes (pass 1 and pass 2) at the Nesson and EARC sites

Statistics	Nesson site [†]				EARC site [‡]			
	Shallow ECa		Deep ECa		Shallow ECa		Deep ECa	
	Pass 1	Pass 2	Pass 1	Pass 2	Pass 1	Pass 2	Pass 1	Pass 2
Mean	9.4	9.6	6.9	6.9	31.9	32.4	39.1	38.4
CV, %	20.8	18.7	20.3	19.1	33.1	31.3	42.6	42.4
Minimum	0.9	3.5	0.7	2.6	8.4	8.6	5.1	5.0
Maximum	16.5	16.7	11.2	11.0	80.4	77.7	77.7	79.7

[†]No. observations = 1456.

[‡]No. observations = 1727.

TABLE 2

Statistical analyses of ECa (mS m^{-1}) data for two soil depths (0–30 cm and 0–90 cm) for two passes (pass 1 and pass 2) at the Nesson and EARC sites

Statistics	Nesson site [†]		EARC site [‡]	
	Shallow ECa	Deep ECa	Shallow ECa	Deep ECa
R	0.928	0.934	0.924	0.985
RMSE	0.76	0.51	4.06	2.93

[†]No. observations = 1456.

[‡]No. observations = 1727.

comparable (Figs. 5A–D). The identity graphs provide a visual assessment of the relationship for the purpose of comparing the ECa measurements from the two passes. These plots show that most of the data points are uniformly and closely clustered near the 1:1 line with a few clear outliers that are scattered away from the line (Figs. 5A–D).

Bland and Altman (1986) recommended another method for assessing measurement repeatability. They suggested that the relationship of the difference between the two measurements and their mean value may be more informative and precise than the identity line approach for assessing the statistical agreement between two repeated measurements (Figs. 6A–D). These graphic presentations can show if a relationship exists between the ECa measurements' error of two passes and their true value. The mean of the measurements of both passes is considered the best estimate of the true value. In all cases, there was no obvious relationship or significant trend between the difference in ECa measurements of the two passes and their mean value.

Before using the difference method, the distribution of differences between the passes at both depths and locations was also checked for normality by constructing histograms (not shown). The histograms of the differences indicated that data were well described by a normal distribution for all cases, allowing use of the criterion of 95% confidence limits of the difference between two passes for evaluating the repeatability of the coulter sensor.

The differences between a pair of measurements (pass 1–pass 2) were plotted against their mean values ((pass 1 + pass 2)/2) for both depths and sites (Figs. 6A–D). The middle line is the mean difference between ECa measurements of pass 1 and pass 2. The upper and lower lines represent the 95% confidence interval (agreement limits) around the mean difference value. Bland and Altman (1986) suggested that these

depictions are useful because they are much easier to use to assess the magnitude of disagreement between repeated measurements, to detect outliers, and to determine if there is any trend in the data.

This analysis uses a criterion that indicates that sensor repeatability is statistically acceptable if 95% of the differences lie between the upper and lower limits (approximately ± 2 SD around the mean difference); otherwise, the repeatability is unacceptable in repeated measurements of ECa.

Figures 6A, B show a comparison of difference in ECa measurements at shallow depths between pass 1 and pass 2 against the mean of the measurements for the Nesson and EARC sites, respectively. These statistics showed that 94.4% and 94.5% of the differences in ECa measurements were within the 95% confidence interval of the mean difference for both Nesson and EARC sites, respectively. These statistical results demonstrate marginally acceptable repeatability between the two passes at the shallow depth for both locations based on the evaluation criterion used in this study. The discrepancies in ECa measurements between pass 1 and pass 2 were between -1.65 and 1.27 for the Nesson site and between -8.6 and 7.6 for the EARC site (Figs. 6A, B). However, at deep depths, the degrees of agreement were acceptable and better than those estimated at shallow depths. Figures 6C, D show that 95.3% and 95.1% of the differences in ECa measurements fell within the 95% confidence interval of the mean difference for both the Nesson and EARC sites, respectively. The ranges of agreement limit were between -1.01 and 0.994 for the Nesson site and -6.88 and 5.56 for the EARC site, which indicated that more than 95% of cases were between these limits for each site at the deep depth. It is obvious that the ranges of variation between pass 1 and pass 2 at shallow depths were larger than those found in deep depths at both sites as indicated by the limits of agreement (Figs. 6A–D).

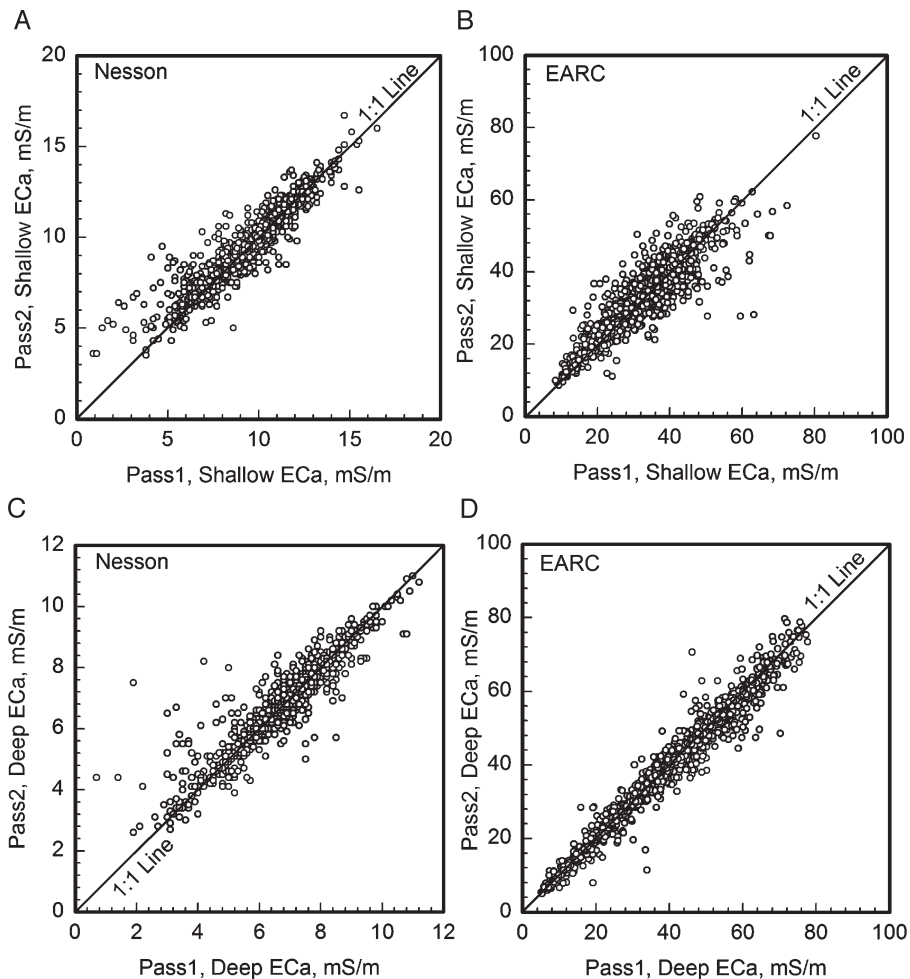


Fig. 5. Comparison of two passes using the 1:1 line relationship for the shallow depth (0–30 cm) at the Nesson site (A), at the EARC site (B), and for the deep depth (0–90 cm) at the Nesson site (C) and at the EARC site (D).

The lack of agreement between pass 1 and pass 2 in ECA measurements at shallow depths could have resulted from soil disturbance and compaction caused by the first pass with the coulter sensor. This process could have affected soil surface conditions (i.e., soil-coulter contact) for pass 2 and consequently ECA measurements during this mapping trial. The inconsistency and variation between pass 1 and pass 2 could also be attributed to the roughness of the soil surface during pass 1 operation compared with a smoother surface during the pass 2 mapping process. Another possible source of error is the occasional divergence between the two passes as indicated in Figures 3 and 4. These path discrepancies could be the result of either driver error or inherent inaccuracy (up to 1 m) of the

DGPS receiver. Furthermore, the repeatability error could also be related in some way to the sensor's operational, voltage, or electrical current characteristics, although we found no evidence to support this.

Differences in soil-coulter contact from pass 1 to pass 2 are the most likely cause of the variation observed because the operation of the coulter sensor does cause substantial soil disturbance to a depth of about 5 cm. This would more likely affect the repeatability of the shallow ECA measurements because the percentage of soil affected at this depth is much higher than for the deeper soil measurements. The differences between the two passes might be lessened if some additional operation were performed between the two passes to refirm the soil

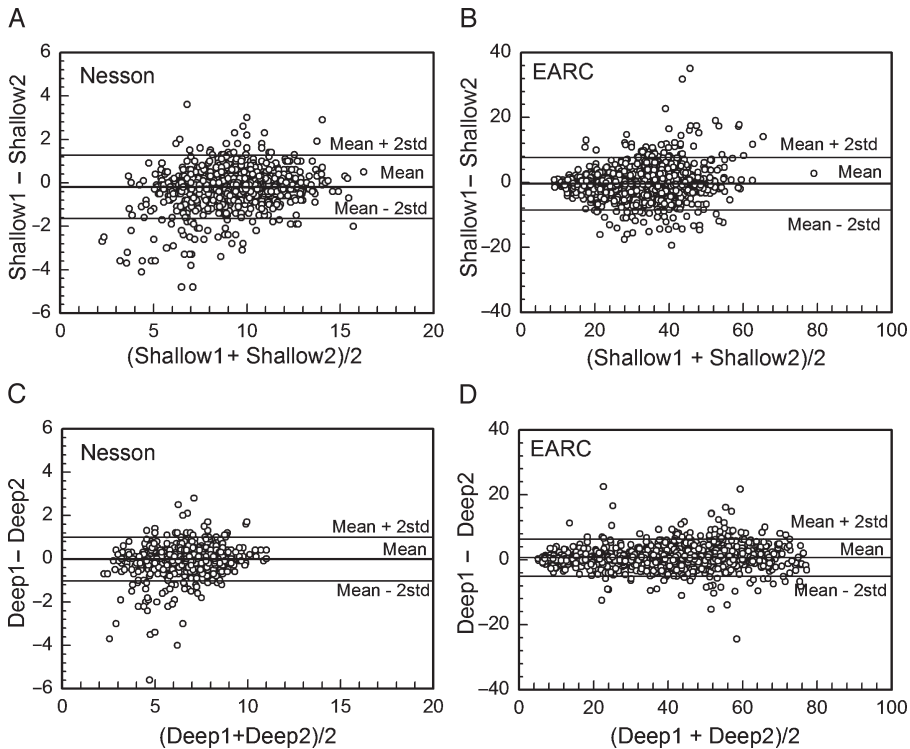


Fig. 6. Relationship between difference and mean of ECa measurements for pass 1 and pass 2 at the shallow depth (0–30 cm) at the Nesson site (A), at the EARC site (B), and at the deep depth (0–90 cm) at the Nesson site (C) and at the EARC site (D).

surface. The disadvantage of such an approach is that the firming operation would likely flatten the standing stubble, which may also affect the subsequent readings. It is also unlikely that the firmness of the soil after such an operation would be the same as before the first pass. Another option would be to perform the soil firming operation before both passes. We would expect this to increase variability within both passes because of increased contact by the coulters with flatten crop residue, which may cause an insulating effect.

Despite the lack of agreement in measured ECa between two passes at the shallow depth, generally, the results of this study suggest that the coulters-type sensor is reliable and capable of measuring soil ECa to characterize spatial soil variations within fields for precision agriculture purposes.

CONCLUSIONS

Both CV and RMSE results indicated less agreement and more variations in ECa measurements between the two passes at shallow depths than deep depths. The repeatability was evaluated

by calculating a 95% confidence interval for the difference between ECa measurements of the two passes against their mean. This method was more informative than the identity relationship method for comparing repeated measurements.

Based on the evaluation criterion used in this study, the results demonstrate marginally acceptable repeatability between the two passes at shallow depths and acceptable repeatability at deep depths at both fields. The lack of agreement between pass 1 and pass 2 in ECa measurements at shallow depths could have resulted from soil disturbance and compaction caused by the coulters sensor during the pass 1 operation. The variation between pass 1 and pass 2 could also be attributed to the roughness of soil surface during pass 1 compared with a smoother surface during the pass 2 mapping process.

In this study, soil disturbance caused by the first pass may have affected the agreement between the two passes; however, the study was designed and conducted in this way so as to represent field conditions under which this equipment would likely be used. Because few, if any, studies of this nature have been reported in

the literature, our study provides important preliminary results that support the hypothesis that a coulter-based ECa sensor is a useful tool for mapping spatial variability of soil properties. Additional work, including a more rigorous research approach and precautions to minimize confounding factors, is needed to confirm the repeatability of this instrument at shallow depths.

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