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FACTORS INFLUENCING SPATIAL VARIABILITY OF SOIL APPARENT ELECTRICAL CONDUCTIVITY

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ABSTRACT

Soil apparent electrical conductivity (EC_a) can be used as a precision farming diagnostic tool more efficiently if the factors influencing EC_a spatial variability are understood. The objective of this study was to ascertain the causes of EC_a spatial variability in soils developed in an environment with between 50 and 65 cm of annual rainfall. Soils at the research sites were formed on calcareous glacial till parent materials deposited approximately 10,000 years ago. Soil samples (0–15 cm) collected from at least a 60 by 60 m grid in four fields were analyzed for Olsen phosphorus (P) and potassium (K). Elevation was measured by a carrier phase single frequency DGPS and EC_a was measured with an EM 38 (Geonics Ltd., ON, Canada) multiple times between 1995 and

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1999. Apparent electrical conductivity contained spatial structure in all fields. Generally, the well drained soils in the summit areas and the poorly drained soil in the toeslope areas had low and high EC_a values, respectively. The landscape differences in EC_a were attributed to: (i) water leaching salts out of summit areas and capillary flow combined with seepage transporting water and salts from subsurface to surface soils in toeslope areas; (ii) lower water contents in summit than toeslope soils; and (iii) water erosion which transported surface soil from summit/shoulder areas to lower backslope/footslope areas. A conceptual model based on these findings was developed. In this model, topography followed a sine curve and EC_a followed a cosine curve. Field areas that did not fit the conceptual model were: (i) areas containing old animal confinement areas; (ii) areas where high manure rates had been applied; and (iii) areas where soils were outside the boundary conditions of the model, i.e., soils not developed under relatively low rainfall conditions in calcareous glacial till with temperatures ranging between mesic and frigid. This research showed that the soil forming processes as well as agricultural management influenced EC_a and that by understanding how landscape position influences salt loss and accumulation, water redistributions following precipitation, and erosion areas that do not fit the conceptual model can be identified. This information can be used to improve soil sampling strategies.

INTRODUCTION

Apparent electrical conductivity (EC_a), as measured with an electromagnetic (EM) sensor, has been used as an diagnostic tool for soil sampling for several reasons (1–10). First, EC_a is an integrated measure of many soil properties (clay content, water content, tillage, varying depths of conductive soil materials, salinity, metals, bulk density, and temperature). Second, the soil properties integrated by EC_a are related to crop productivity. Third, advances in EM sensor technology have reduced the costs of obtaining EC_a information. Fourth, EC_a maps have been used to identify anomalous areas in fields. A more complete discussion on how to use EM sensors to identify management zones is available in Franzen and Kitchen (3) and Franzen et al. (11). A concept behind this paper is that EC_a can be used as a precision farming diagnostic tool more efficiently if the factors influencing EC_a spatial variability are understood. The objective of this study was to ascertain the causes of EC_a spatial variability in soils developed in an environment with between 50 and 65 cm of annual rainfall.

MATERIALS AND METHODS

Spatial Variability

All fields used in this study were located in Eastern South Dakota. The 30-year rainfall average for the Moody, Brookings, and Flandreau fields was 55.8 cm and the average rainfall for the Beresford field was 63 cm (12). The crop rotation for all fields was corn (*Zea mays*) followed by soybean (*Glycine max*). The dominant soils and coordinates of the these fields are shown in Table 1. All fields contained old animal confinement areas or areas where manure had been applied. In the 65 ha Moody and Brookings fields: (i) a no-till system was followed, (ii) nitrogen (N) and P fertilizers were band applied, (iii) the crop row spacing was 57 cm, (iv) old (>50 years) animal confinements were located within the fields, and (v) manure had not been applied for the previous 15 years. The 60-ha Flandreau field had a row spacing of 76 cm, manure was applied annually, a chisel plow was used as the primary tillage implement, N and P fertilizers were broadcast applied. The 43-ha Beresford field had a row spacing of 76 cm, used a ridge tillage system where and N and P fertilizer were broadcast or band applied, and had a history of manure applications.

At Moody, 598 soil samples (0–15 cm) were collected from a 30 by 30 m grids in May 1995. At Brookings, 418 soil samples were collected from a 30 by 60 m grid in May 1996. At Flandreau, 115 soil samples were collected from a 60 by 60 m grid in the spring of 1997. At Beresford, 115 soil samples were collected from a 60 by 60 m grid in the spring of 1997. At Brookings, Moody, and Beresford each composite sample contained 15 individual cores collected at sample points located every 11.4 cm along a 170 cm transect perpendicular to the row (13). At Flandreau, 15 individual cores were randomly collected from a 1 m^2 area surrounding each grid point. Sample points were located using a differentially corrected global positioning system (DGPS). Dried soil samples (35°C) were ground (2 mm) and analyzed for Olsen P, K, and pH (14–16). Soil EC was determined on saturated paste extract (17). At each grid point, the soil phases were determined following standard National Resource and Conservation Service methods (18).

A Leica (Leica, Inc.; Norcross, GA) carrier phase single frequency DGPS with a vertical error of approximately 2 cm was used to measure elevation. Data acquisition mode was real time kinematic and the rover's differential correction was obtained from a base station located at a field corner. Apparent electrical conductivity (EC_a) at each grid point was measured by an EM 38 (Geonics Ltd.; Mississauga, ON, Canada) (4). At Moody, EC_a was measured in the spring of 1995, 1996, 1997, and 1998 and in the fall of 1997 and winter of 1998. At Brookings, EC_a was measured in the spring of 1997, 1998, and 1999. At Flandreau and Beresford, EC_a was measured in the spring of 1997 and 1998.

Table 1. Soil Phases, Landscape Position, Parent Materials, and Classification of Soils Located in the Four Fields

Name & Location	Soil Phase	Landscape Position	Parent Material	Classification
Moody	Kranzburg	Summit/shoulder	Loess/glacial till	Fine-silty, superactive, frigid Calcic Hapludoll
44° 10′ 15″ N	Vienna/Venagro	Summit/shoulder	Loamy eolian/glacial till	Fine-loamy, mixed, superactive, frigid Calcic Hapludoll
96° 37′ 25″ W	Waubay	Backslope	Silty glaciofluvial/glacial till	Fine-silty, mixed, superactive, frigid Aquic Hapludoll
	Badger/Cubden	Footslope/toeslope	Local alluvium of glacial till	Fine-silty, frigid Aeric Calciaquoll
	Lamour	Footslope/toeslope	Sitly alluvium	Fine-silty superactive, calareous, frigid Cumulic Endoaquolls
Brookings	Barnes/Vienna	Summit/shoulder	Loamy eolian/glacial till	Fine-loamy, mixed, superactive, frigid Calcic Hapludoll
44° 13′ 41″ N	Brookings	Backslope	Silty glaciofluvial/glacial till	Fine-silty, superactive, frigid Cumulic Hapludoll
96° 39′ 04″ W	McIntosh	Footslop/toeslope	Local alluvium/glacial till	Fine-silty, frigid Aeric Calciaquoll
	Lamour	Footslope/toeslope	Sitly alluvium	Fine-silty superactive, calareous, frigid Cumulic Endoaquolls

Flandreau	Moody	Summit/backslope	Loess/glacial till	Fine-silty, mixed, superactive, mesic Udic Haplustoll
$44^\circ\ 3'\ 43''$ N	Shindler	Summit/backslope	Glacial till	Fine-silty, mixed, superactive, mesic Udorthentic Haplustoll
$96^\circ\ 38'\ 37''$ W	Trent	Backslope/footslope	Silty local alluvium	Fine-silty, mixed, superactive, mesic Pachic Haplustoll
	Wakonda	Footslope/toeslope	Silty local alluvium	Fine-silty, mixed, superactive mesic Aeric Calciaquoll
	Chancellor	Footslope/toeslope	Silty local alluvium	Fine, smectitic, mesic Vertic Argiaquoll
Beresford	Egan	Summit/backslope	Loess/glacial till	Fine-silty, mixed, superactive, mesic Udic Haplustoll
$43^\circ\ 3'\ 3''$ N;	Ethan	Shoulder/backslope	Glacial till	Fine-loamy, mixed, superactive, mesic Typic Calciustoll
$96^\circ\ 53'\ 22''$; N	Viborg	Backslope/footslope	Loess/glacial till	Fine-silty, superactive, msic Pachic Haplustoll
	Chancellor	Footslope/toeslope	Silty local alluvium	Fine, smectitic, mesic Vertic Argiaquoll

EC and Water Contents Impacts on EC_a

At a fifth site located near South Dakota State University (SDSU) (44.31 N and 96.67 W), the relationship between EC_a and soil water was evaluated. Soils at this site were developed in calcareous glacial till with an average rainfall of 54.9 cm. At this site, EC_a was measured and soil samples (0 −15 cm) were collected from three sampling points, located at the summit landscape position, on 6 July 1998, 30 July 1998, and 20 April 1999. Soil samples were analyzed for gravimetric water content. At Moody and Brookings soil water contents and EC_a was also measured at periodic intervals during the summers of 1999 and 2000. Spatial dependence of K, P, and pH for Moody are reported in Chang et al. (19).

RESULTS AND DISCUSSION

Site Characterization

Soil phases, latitude and longitude coordinates, and parent materials for soils in the Brookings, Moody, Flandreau, and Beresford fields are shown in Table 1. Selected soil chemical and physical characteristics of representative soil phases are shown in Table 2. Common features at all sites were that: (i) the soils developed under a semi-arid environment (<65 cm of annual rainfall) in calcareous glacial till deposited approximately 10,000 years ago; (ii) pH values in surface horizons in the summit and shoulder areas were generally less than those measured in footslope and toeslope areas; (iii) summit and shoulder soils generally had lower EC, gypsum, and free carbonate contents than footslope and toeslope soils; and (iv) summit soils had faster drainage than toeslope/footslope soils.

Spatial EC_a Variation

The strong EC_a spatial dependence, observed at all fields, indicates that EC_a values become more dissimilar with increasing distance between sampling points (Fig. 1). Spatial dependence may have been caused by soil forming processes, summits areas that tended to be dryer than footslopes areas, a positive correlation between soil water and EC_a, and erosional processes that transport clays and organic matter from summit to footslope areas.

Table 2. Selected Soil Physical and Chemical Properties of the Surface Horizon in Representative Soil Phases in the Moody, Brookings, Flandreau, and Beresford Fields

Field	Soil Phase	Landscape Position	EC ($mS\,m^{-1}$)	pH	Textural Class[a]	Free $CaCO_3$	Drainage Class
Moody	Vienna	Summit/backslope	<30	6–7	l to cl	No	Well
	Cubden	Foot/toeslope	40–70	7.5–8.3	scl to cl	Yes	Somewhat to poorly drained
Brookings	Brookings	Summit/backslope	<30	5.1–6.6	l to scl	No	Well
	McIntosh	Foot/toeslope	30–40	5.5–7.9	sl to scl	No	Somewhat to poorly drained
Flandreau	Moody	Summit/backslope	30–40	5.2–5.6	l to scl	No	Well
	Chancellor	Foot/toeslope	30–50	5.4–7	l to scl	No	Somewhat to poorly drained
Beresford	Egan	Summit/backslope	<50	5.6–5.9	l to scl	No	Well
	Chancellor	Foot/toeslope	50–110	6.2–7.3	l to scl	Yes	Somewhat to poorly drained

[a] l = loam, cl = clay loam, scl = silty clay loam.

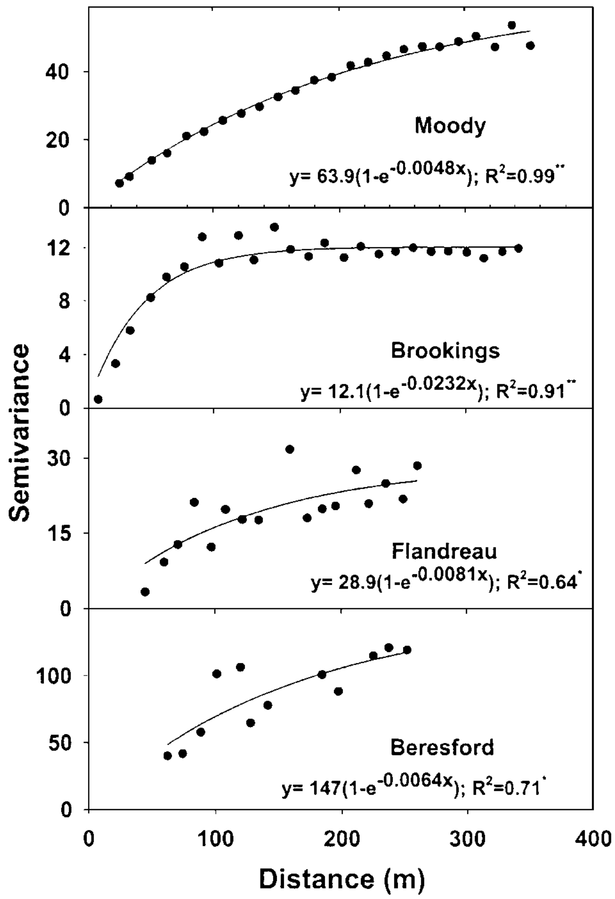

Figure 1. Semi-variograms for EC_a in Moody, Brookings, Flandreau, and Beresford.

Soil Forming Processes

In semi-arid landscapes, the amount of $CaCO_3$ and $CaSO_4$ remaining in the soil profile is dependent on the landscape position and age of the profile. The landscapes used in this study were relatively young, (<10,000 years old) and substantial amounts of salt remained in the landscapes. Generally, saturate paste EC values were higher in footslope than summit soils (Table 2). Landscape differences in saturated paste EC resulted from carbonates and gypsum removal from summit soils by percolating water and carbonate and gypsum accumulation in footslope and toeslope soils from capillary flow and seepage (20). This process was previously discussed in Malo and Worcester (20). Salt removal from summit soils and accumulation in footslope soils most likely was responsible the positive correlations between pH, saturated paste EC, and EC_a (data not shown). For example at Moody, linear equations relating pH, saturated paste EC, and EC_a were:

$$EC(mS/m) = -30 + 10\,(pH); \quad r = 0.63^{**} \tag{1}$$

$$EC_a(mS/m) = 25 + 0.40\,(EC); \quad r = 0.62^{**} \tag{2}$$

$$EC_a(mS/m) = -3 + 6.5\,(pH); \quad r = 0.66^{**} \tag{3}$$

Dryer Summit Than Footslope Areas

Dryer summit than footslope areas can be caused by runoff which reduces the amount of water which can infiltrate into summit soils and/or capillary movement and seepage which increases soil water contents in lower backslope and footslope areas. At Brookings and Moody, water contents in footslope areas were either higher or similar to summit soils at all sampling dates 1999 and 2000 (21). For example, the water content in samples collected from the 0–15 cm depth on 13 July 1999 from the summit and footslope areas in the Brookings field were 0.19 and 0.25 g water g^{-1} soil, respectively. Rockström et al. (22) had similar results and reported that backslope soils had greater soil water contents than summit soils. Jaynes et al. (23) in Iowa also had similar results and suggested that EC_a could be used to identify areas subject to water stress.

Relationship Between Soil Water and EC_a

Increased water contents of footslope areas was partially responsible for higher EC_a in footslope areas because EC_a was positively correlated to the soils water content at SDSU, Brookings, and Moody (24). For example in the summit area at SDSU, EC_a and water content measured at different dates during the 1998 and 1999 growing seasons were highly correlated and the linear equation between these parameters was:

$$\text{water content}\,(g/g\ soil) = -0.54 + 0.020\,(EC_{a(mS/m)}); \quad r = 0.93^{**} \tag{4}$$

Hanson and Kaita (5) had similar results.

Erosional Processes

The transport of clay and organic matter from summit to footslope areas by water erosion may also have been partially responsible for higher EC_a values in footslope than summit areas. Evidence supporting erosional losses of clay and organic matter from summit areas includes that: surface soils in the lower backslope were thicker than those observed in the shoulder and summit areas; at Moody and Brookings organic C concentrations were lower in summit and shoulder areas than footslope areas (25); and at Moody $\delta\,^{13}C$ values were lower in footslope areas than shoulder areas (25). In Iowa, Jaynes et al. (23) and Burras and Scholtes (26) had similar results and reported that erosional processes that transport clays and organic matter from summit to footslope areas can result in higher EC_a values in footslope than summit areas. Sudduth et al. (10) had opposite results and reported that in Missouri, low EC_a values in low areas and high values in summit areas were attributed to parent material and topsoil depth differences.

Temporal EC_a Variability

As discussed above, because EC, soil water, and clay content tended to be higher in footslope than summit areas and these factors were positively correlated to EC_a, EC_a tends to be lower in summit than footslope areas at all sites (Fig. 2). Wetting or drying of the landscape did not change these results. Stability in EC_a patterns resulted in: (i) footslope areas with high EC_a values at all sampling dates; (ii) summit areas with low EC_a values at all sampling dates; and (iii) EC_a values at the different sampling date being positively correlated to each other (data not shown). For example, the linear relationship between EC_a values collected at 160 points in May 1997 (wet) and October 1997 (dry) at Moody,

$$EC_{a(mS/m)}\,(\mathrm{Oct.}) = 1.31 + 0.91\,EC_{a(mS/m)}(\mathrm{May}); \quad r = 0.95^{**} \tag{5}$$

shows that EC_a values were higher in May than October, and that areas with high EC_a values in May also had high values in October.

These findings were used to construct a simple conceptual model relating topography to EC_a. In the conceptual model, topography followed a sine curve while EC_a followed a cosine curve (Fig. 3). The conceptual model was in agreement with the findings of Malo and Worchester (20). However, not all areas of the fields followed the conceptual model. For example, in Moody, Brookings, Beresford, and Flandreau there were areas where differential management occurred, i.e., manure spill or the location of an old animal confinement area. Many of these areas had higher EC_a values than adjacent areas in the same

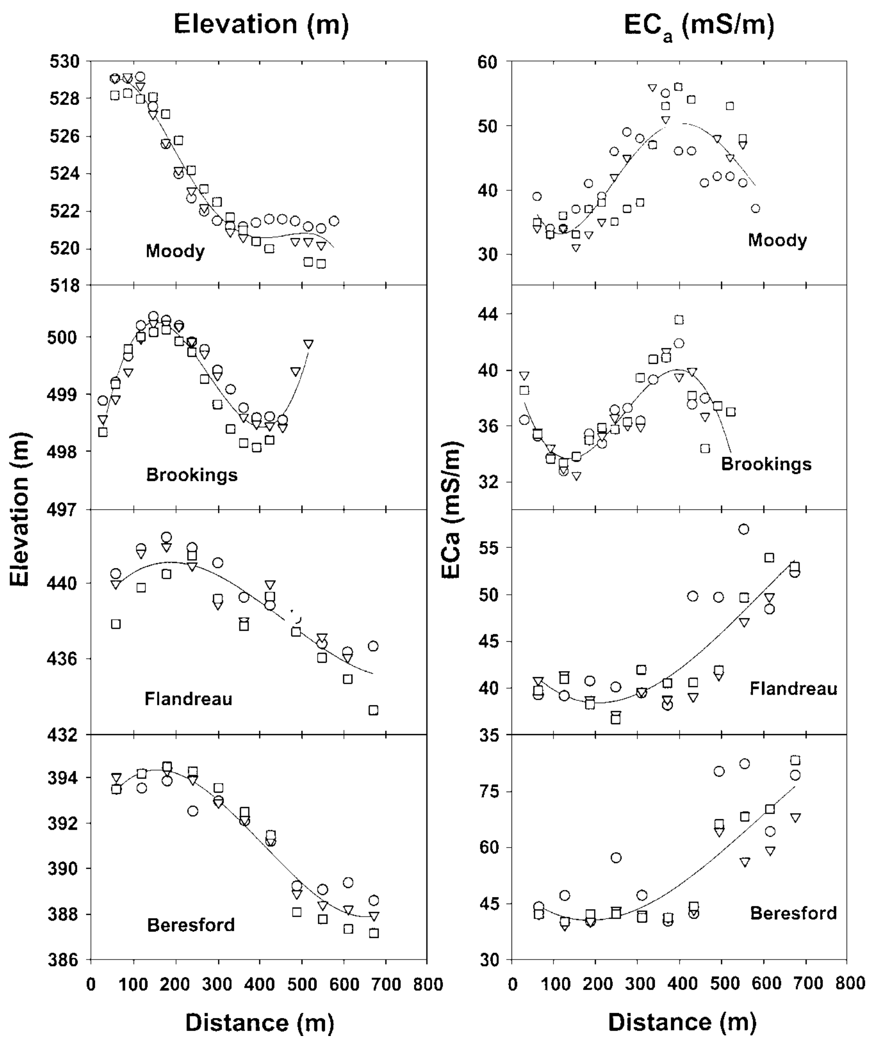

Figure 2. The relationship between EC_a and elevation collected from three different transects (□, ○, ▽). Transects do not contain areas where animals were confined.

landscape position (Table 3). Higher EC_a values may have resulted from increased water holding capacity, salt concentration, or organic matter content of soil within the differentially managed area. Regardless of the reason, Table 3 shows that EC_a and Olsen P and K concentrations at Moody, Brookings, Flandreau, and Beresford were higher inside the old animal confinement area or

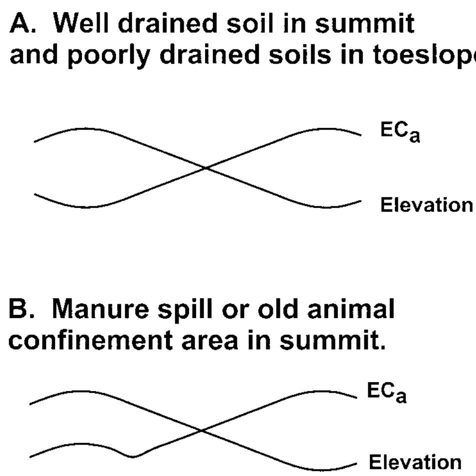

Figure 3. A conceptual model relating EC_a and elevation for areas of the fields shown in Fig. 2.

manure spill site than outside of the area of differential management. By superimposing the EC_a map on a topography map it may be possible to identify areas that follow the conceptual model and areas that may be differentially influenced by previous management. Enterprise analysis of Moody showed that if areas differentially influenced by management can be identified, then they should be sampled separately from the rest of the field (25).

CONCLUSIONS

Apparent electrical conductivity contained spatial structure in all fields. Regardless of sampling date, the well drained summit soils generally had lower EC_a values than the poorly drained toeslope soils. Landscape differences in EC_a were attributed to: (i) water leaching salts out of summit areas and capillary flow combined with seepage transporting water and salts from subsurface to surface soils in toeslope areas; and (ii) lower water contents in summit than toeslope soils. A conceptual model based on these findings was developed. In this model, topography followed a sine curve and EC_a followed a cosine curve. Areas of the fields that did not fit the conceptual model were: (i) areas where old animal confinement sites had been located; (ii) areas where high manure rates had been applied; and (iii) areas where the soils were outside the boundary conditions of the model, i.e., soils not developed under low rainfall conditions in calcareous

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Table 3. The Influence of Landscape Position on EC_a on the Mean Concentration of Olsen P and K in an Area Where Manure Was Applied, Previously Contained an Old Animal Confinement Area (ACA), and Adjacent Areas Where Manure Was Not Applied (None) in Four South Dakota Fields

				P		K		EC	
Field	Landscape Position	Prior Treatment	Number of Samples	Mean (μg g Soil^{-1})	CI[a] (μg g Soil^{-1a})	Mean (μg g Soil^{-1})	CI (μg g Soil^{-1})	Mean (mS m^{-1})	CI (mS m^{-1})
Moody	Summit	Old ACA	30	29.2	3.5	287	30	30.9	0.45
	Summit	None	28	10.2	1.0	201	19	28.3	0.74
	Toeslope	None	30	14.5	3.0	73	30	36.9	2.04
Brookings	Backslope	Old ACA	15	60.8	24.9	645	233	42.6	2.56
	Backslope	None	15	15.7	3.0	177	24	37.8	1.54
Flandreau	Backslope	Manure spill	11	19.7	5.7	262	37	48.6	2.88
	Backslope	No-manure	11	15.5	1.8	206	10	42.8	2.42
Beresford	Backslope	Manure spill	15	51.5	19.6	464	127	50.7	4.88
	Backslope	No-manure	13	10.2	2.6	265	42	43.6	2.31
	Toeslope	No-manure	9	11.3	2.7	303	28	48.2	4.48

[a] The 95% confidence intervals for each mean are located under CI.

glacial till with temperatures ranging from mesic to frigid. By superimposing the EC_a map on a topography map it may be possible to identify areas differentially influenced by previous management. Related research at Moody showed that fertilizer recommendations can be improved by not compositing samples from these areas with bulk samples from the rest of the field (19,22).

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