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Subject: MGT – Geophysical Investigations

Date: November 5, 2010

To: Joyce Swartzendruber
State Conservationist, NRCS
Bozeman, Montana

File Code: 330-20-7

Purpose:
The purpose of this visit was to provide training on the use of electromagnetic induction (EMI) and complete a high-intensity survey of three fields which are part of the *Judith Basin Groundwater Nitrate Project*. Results from the EMI survey will be used to assess the amounts of nitrates in soils and to develop management zones and nutrient management plans.

Participants:
Rick Caquelin, District Conservationist, USDA-NRCS, Stanford, MT
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Activities:
All activities were completed during the period of October 12-14, 2010.

Summary:

1. Refresher training was provided on the setup and calibration of the EM38 meter, EMI field procedures, data processing and interpretations. The newly developed EM38-MK2 meter and the RTmap38MK2 software program were demonstrated and used in the field survey. Also, participants were provided with an overview of the programs contained in the *ESAP* (*EC_e Sampling, Assessment, and Prediction*) software suite. This software program has been designed for use with EMI data.

2. A high-intensity EMI survey of three fields (total of about 375 acres) resulted in the definition of different soil management zones. Plots of apparent conductivity identified differences in soil types, defined management zones and located an incipient saline seep. Differences in magnetic susceptibility were associated with differences in organic matter, soil moisture, and mineral (due to differences in fertilization) contents.

3. The *ESAP-RSSD* (Response Surface Sampling Design) software was used to generate three different soil sampling schemes and to identify sampling points within the survey area. These schemes are based on the use of a large apparent conductivity (EC_a) data set to identify a sparse number of *optimal* sampling points. Characterization data collected at these sampling points can be used to predict soil physiochemical properties across units of management.

It was the pleasure of Jim Doolittle and the National Soil Survey Center to work with and be of assistance to your fine staff.

/s/ Jonathan W. Hempel

JONATHAN W. HEMPEL
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Technical report on the use of electromagnetic induction (EMI) methods in the *Judith Basin Groundwater Nitrate Study* (October 12-14, 2010).

Jim Doolittle

Background:

The thin loamy soils of the Judith River Basin in central Montana are vulnerable to contamination caused by applications of pesticides and fertilizer. The *Judith Basin Groundwater Nitrate Project*, which is partnered by the Judith Basin and the Fergus Conservation Districts, Montana State University, and USDA-NRCS, focuses on excess levels of nutrients and organics in surface and ground waters, and nitrogen contamination in soils. Presently, NRCS is developing nutrient management plans, and cropping and residue management systems to help manage commercial fertilizer applications. In this study, electromagnetic induction (EMI) was used to produce high-intensity maps of a site near Moccasin, Montana.

Study site:

The study site (47.11351 N Latitude, 109.9039 W. Longitude) is located about 4.1 miles north of Moccasin in Judith Basin County. The site is in cultivation and mapped mostly as Danvers clay loam on 0 to 2 percent slopes (Da), with small included areas of Danvers clay loam on 2 to 4 percent slopes (Db); Utica gravelly loam on 8 to 35 percent slopes (Ub); Winifred clay loam on 4 to 8 percent slopes (Wc);. and Judith gravelly clay loam on 2 to 4 percent slopes (Jm). Figure 1 is the soil map of the study site.

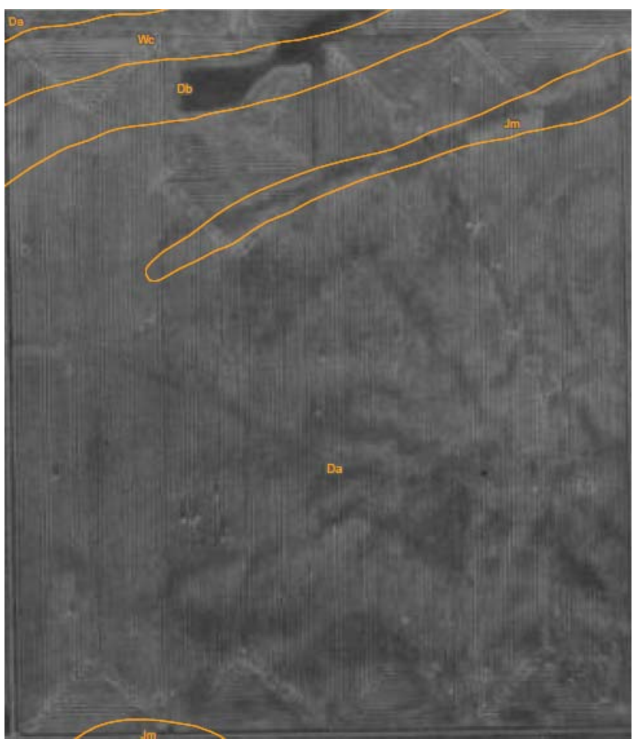

Figure 1. Soil Map of the Moccasin Site from the Web Soil Survey.[1]

[1] Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at http://websoilsurvey.nrcs.usda.gov/ accessed [10/28/2010].

The very deep, well drained Danvers and Judith soils and excessively drained Utica soils formed in alluvium on alluvial fans and stream terraces. Danvers soils formed in materials weathered from mixed rock sources; Judith and Utica soils are calcareous and formed in materials weathered principally from limestone. The moderately deep, well drained Winifred soils formed in residuum weathered from semi-consolidated shale or in alluvium over semi-consolidated shale on sedimentary plains, hills, and escarpments. The taxonomic classifications of these soils are listed in Table 1.

Table 1. Taxonomic classification of the major soils recognized in the Moccasin Study Site

Soil Series	Taxonomic Classification
Danvers	Fine, smectitic, frigid Vertic Argiustolls
Judith	Fine-loamy, carbonatic, frigid Typic Calciustolls
Utica	Sandy-skeletal, carbonatic, frigid Typic Calciustolls
Winifred	Fine, smectitic, frigid Entic Haplustolls

Within the survey site, delineations of Danvers (Db) and Winifred (Wc) soils form a distinct escarpment and Judith soils form a ridge line in the northern portion of the site. The remainder of the site is a level plain, which is mapped mostly as Danvers (Da) soils.

Equipment:
The EM38 and EM38-MK2 meters (Geonics Limited; Mississauga, Ontario) were used in training[2]. The EM38 meter is no longer being produced by Geonics Limited (but is still supported). The EM38 meter has been replaced by the EM38-MK2 meter. The EM38-MK2 provides simultaneous measurement of both quadrature phase (apparent conductivity) and in-phase (apparent susceptibility) components, within two distinct depth ranges. In addition, the EM38-MK2 meter has Bluetooth functionality for wireless data transmission and can be automatic calibrated. Both the EM38 and EM38-MK2 meters require no ground contact. These meters are used to measure the apparent conductivity (EC_a; quadrature component) and/or apparent magnetic susceptibly (inphase component) of soils and earthen materials. Apparent conductivity is typically expressed in milliSiemens/meter (mS/m). Susceptibility is the ratio of the secondary to primary magnetic fields and is expressed in parts per thousand (ppt).

The EM38 meter operates at a frequency of 14,600 Hz and weighs about 1.4 kg (3.1 lbs). This meter has one transmitter and one receiver coil that are spaced 1-m apart. When placed on the soil surface, it has effective penetration depths of about 0.75 m and 1.5 m in the horizontal (HDO) and vertical (VDO) dipole orientations, respectively (Geonics Limited, 1998).

The EM38-MK2 meter operates at a frequency of 14,500 Hz and weighs about 5.4 kg (11.9 lbs). The meter has one transmitter coil and two receiver coils, which are separated from the transmitter coil at distances of 1.0 and 0.5 m. This configuration provides nominal penetration depths of about 1.5 and 0.75 m in VDO, and about 0.75 and 0.40 m in the HDO. In either dipole orientation, the EM38-MK2 meter provides simultaneous measurements of both the apparent conductivity and susceptibility over two depth ranges. Operating procedures for the EM38-MK2 meter are described by Geonics Limited (2007).

A Trimble AgGPS 114 L-band DGPS (differential GPS) antenna (Trimble, Sunnyvale, CA) was used to georeferenced data collected with the EM38-MK2 meter.[2] An Allegro CX field computer (Juniper Systems, North Logan, UT) was used to record and store both GPS and EMI data[2]. The newly developed RTM38MK2 program (Geomar Software, Inc., Mississauga, Ontario) was used with the EM38-MK2

[2] Manufacturer's names are provided for specific information; use does not constitute endorsement.

meter to display and record both GPS and EC_a data on the Allegro CX field computer.[3] The RTmap38MK2 system provides immediate tracking and viewing capabilities on the Allegro CX computer. With these capabilities, the operator can visually correlate spatial EC_a patterns with soil and landform patterns as surveys progress. In addition, with this software, sites can be more uniformly covered (avoiding skipping areas) and unnecessary overlap of survey lines prevented.

To help summarize the results of the EMI surveys, the SURFER for Windows (version 9.0) software (Golden Software, Inc., Golden, CO) was used to construct the simulations shown in this report.[3] Grids were created using kriging methods with an octant search.

Survey procedures:
At the Moccasin Site, the EM38-MK2 meter was mounted in a plastic sled and towed behind a truck. The meter was operated in the vertical dipole orientation (VDO). The survey was completed by driving the truck at in a back and forth manner across the site at a fairly uniform speed (about 5 m/sec).

All collected EMI and GPS data were entered into an Excel spreadsheet and processed thru the *ESAP* (version 2.35) software program (Lesch et al., 2000). The *Response Surface Sampling Design* software program of *ESAP* was used to generate three different optimal sampling designs for the survey area based on the collected EC_a data.

ESAP:
As a tool for precision agriculture and high intensity soil surveys, spatial-referenced apparent conductivity (EC_a) data have been used to direct soil sampling, refine maps, and provide ancillary measures for spatially varying soil properties that are not easily measured or mapped (Jaynes, 1995; Stafford, 2000). The USDA-ARS Salinity Laboratory (Riverside, California) has developed the *ESAP* (*EC_e Sampling, Assessment, and Prediction*) software for use with EC_a data (Lesch, 2005; Lesch et al., 2000, 1995a, 1995b). The *ESAP* software was developed to predict soil salinity (EC_e) from EC_a data. However, the *ESAP* software can also be used to predict other soil physiochemical properties. The *ESAP* software is designed to combine copious, high-intensity EC_a data with sparse, low-density soil sampling to calibrate suitable predictive equations for the estimation of soil salinity or other soil properties. A goal of this prediction-based sampling approach is to statistically select a small number of sample locations from the EC_a survey data. In order to be effectively used, however, the spatially varying soil property must strongly correlate with EC_a. Amezketa (2007) used *ESAP* to estimate levels of sodicity in saline-sodic soils. Hunsaker et al. (2009) used *ESAP* to infer the spatial variability of basal crop coefficients and crop water use from normalized difference vegetation indices (NDVI) obtain from aerial images. Fitzgerald et al. (2006) used *ESAP* to predict crop height and width attributes from aerial imagery. Eigenberg et al. (2008) used *ESAP* to assess and manage the flow of liquid cattle wastes within vegetative treatment areas.

Directed-Sampling:
The ESAP-*Response Surface Sampling Design* (RSSD) program can generate three different directed-sampling schemes (with 6, 12, or 20 sample locations). The selection of the most suitable sampling design will depend on site and soil conditions, availability of resources, and intended use of the survey information. In this directed-sampling approach, a minimum number of calibration sample locations are selected based on the observed magnitudes and spatial distribution of the EC_a data (Eigenberg et al., 2008). The sampling locations are selected to statistically optimize the estimation of a regression model and to simultaneously maximize the average separation distance among sample locations. Sample locations are representative of the total variation of EC_a and, hopefully, the targeted soil property (Corwin et al., 2006). This directed-sampling approach has been described as an amalgam of a response surface sampling design with a space-filling algorithm (Eigenberg et al., 2008; Lesch, 2005).

[3] Manufacturer's names are provided for specific information; use does not constitute endorsement.

Results:
Table 1 provides the basic statistics for the EC_a data that were collected at the Moccasin site with the EM38-MK2 meter. In general, EC_a increased with increasing depth (measurements obtained in the deeper-sensing, 100-cm intercoil spacing are higher than measurements obtained in the shallower-sensing 50-cm intercoil spacing). For measurements obtained in the shallower-sensing (0 to 75 cm), 50-cm intercoil spacing, EC_a averaged about 17 mS/m, and ranged from about -21 to 205 mS/m. One-half of these measurements were between about 9 and 18 mS/m. For the deeper-sensing (0 to 150 cm), 100-cm intercoil spacing, EC_a averaged about 30 mS/m and ranged from about 8 to 239 mS/m. One-half of the measurements were between about 19 and 30 mS/m.

Table 2. Basic statistics for EC_a data collected with the EM38-MK2 meter at the Moccasin Site in Judith Basin County.

	EM38-MK2-100cm	EM38-MK2-50cm
Number	9290	9290
Minimum	7.85	-20.9
25%-tile	18.91	8.79
75%-tile	30.43	18.05
Maximum	238.71	205.43
Mean	30.04	16.84

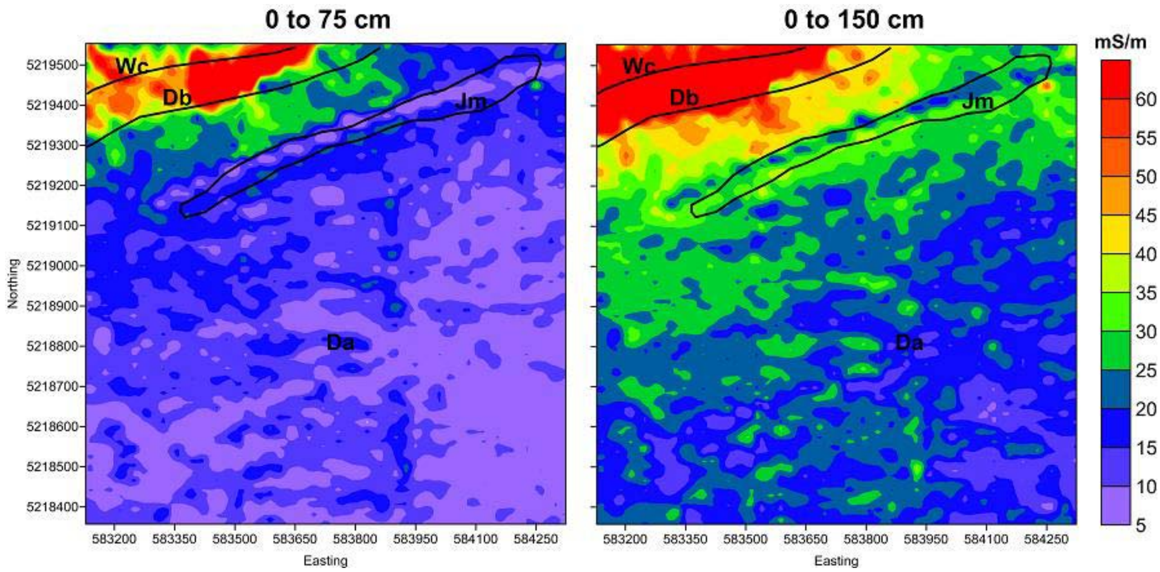

Figure 2. These plots of apparent conductivity were generated from data collected with the EM38-MK2 meter operated in the VDO at the Moccasin site. The depth of effective penetration is shown above each plot.

Figure 2 contains plots of the EC_a data collected at the Moccasin site. Effective penetration depths for the 50- and 100-cm intercoil spacing are 75 and 150 cm, respectively. In both plots, similar color scales and ramps have been used. Soil boundary lines have been digitized from Web Soil Survey data[4]. While EC_a values vary spatially and with depth, overall spatial patterns are similar in both plots. A majority of the site has comparatively low EC_a (< 35 mS/m), which is representative of Danvers and Judith soils. The extreme northwest corner of the site has comparatively high (> 40 mS/m) EC_a. The higher clay content of the Winifred soils account for some of the higher recorded EC_a, but values greater 70 mS/m are considered anomalous and suggests the accumulation of soluble salts. In this portion of the survey area, there were more than 630 EC_a measurements greater than 70 mS/m (recorded with the deeper-sensing (0 to 150 cm), 100-cm intercoil spacing). Increased levels of soluble salts in the soil profile are suspected to have contributed to these exceptionally high EC_a values. This area of higher EC_a values is associated with a prominent escarpment. The suspected underlying shale bedrock could form a restrictive layer, which causes water to move laterally and discharge along the escarpment. Here, evaporative discharge would produce saline seeps. The spatial relationship of EC_a with topography and the occurrence of saline seeps are captured in the three-dimensional wireframe image shown in Figure 3. The EC_a data used in this plot are for the 0 to 150 cm depth interval. Compare with similar data shown in Figure 2 (right-hand plot), a wider range and more inclusive scale have been used in Figure 3.

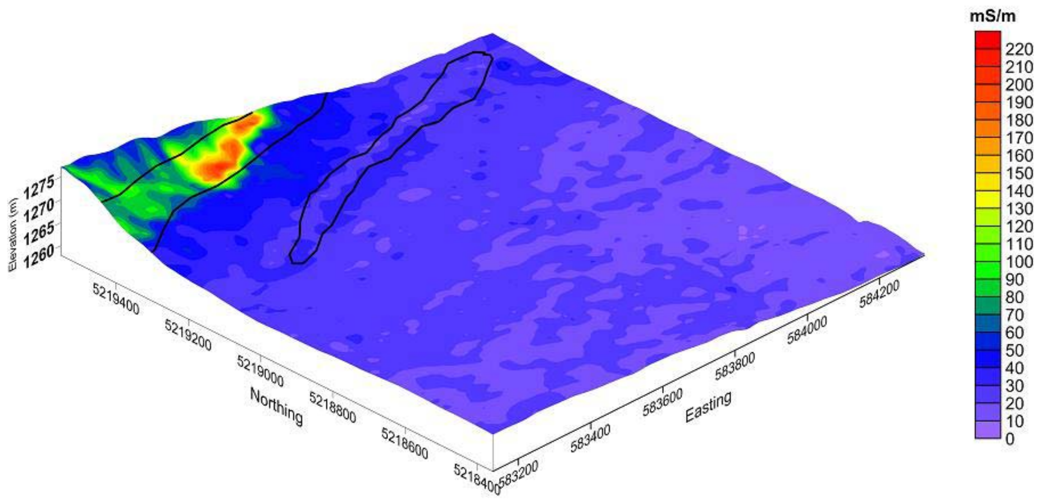

Figure 3. In this three-dimensional map, a plot of apparent conductivity data collected with the deeper-sensing (0 to 150 cm), 100-cm intercoil spacing of the EM38-MK2 meter has been overlain on a wireframe map of elevations recorded with the AG114 GPS antenna.

Figure 4 contains plots of the inphase data collected with the EM38-MK2 meter over two soil depth intervals at the Moccasin site. In the plot of shallower data (left-hand plot), each of the three fields produces slightly different inphase responses and is therefore identifiable. Bevan (1994) observed that plowing can have a subtle affect on electrical conductivity, with values changing with the direction of plowing due to the alignment of soil particles. North-south trending spatial patterns (the direction of cultivation) are evident in these plots. Compared with the subsoil, surface layers often have greater magnetic susceptibility due to higher organic contents (Bevan, 1994). Differences in the physical structure of the plow layer, and where present, the plow pan will affect soil moisture contents, which may be detectable with EMI. Each of the three fields is under different rotations and therefore, organic

[4] Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at http://websoilsurvey.nrcs.usda.gov/ accessed [9/29/2010].

residue, surface moisture, soil compaction, and mineral (due to differences in fertilization) are expected to differ. In either plot, but especially in the plot of deeper inphase data (Figure 4, right-hand plot), a buried pipeline or drainage line is evident. This feature crosses the two easternmost fields in a north-northwest to south-southeast direction.

The three individual fields are more easily recognized in the plots of apparent magnetic susceptibility (Fig. 4) than in the plots of apparent conductivity (Fig. 2). On the other hand, differences in soil types are more easily recognized in the plots of apparent conductivity (Fig. 2) than in the plots of apparent magnetic susceptibility (Fig. 4).

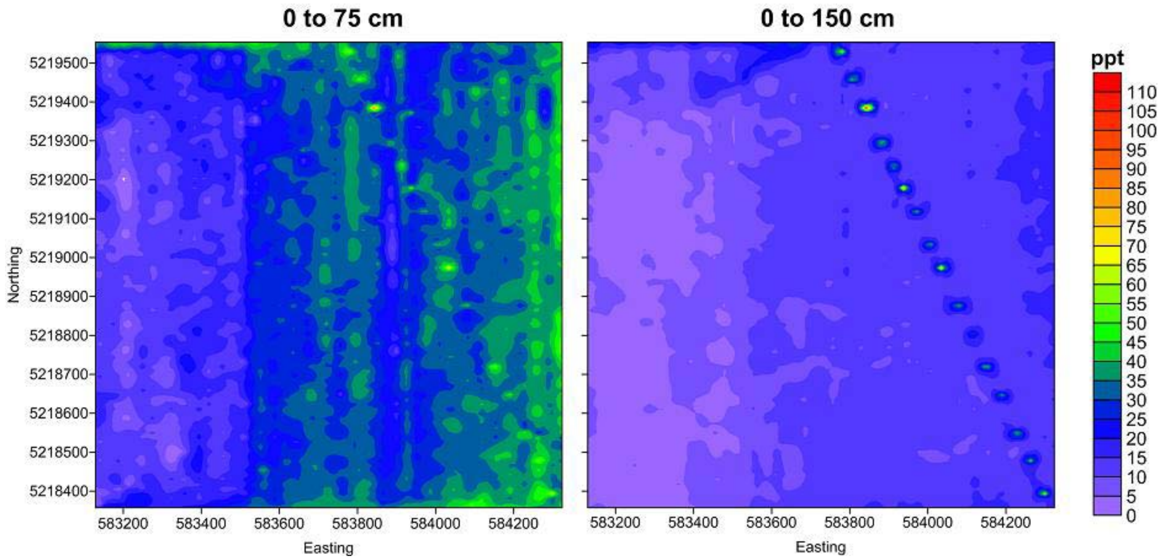

Figure 4. These plots of apparent susceptibility were generated from data collected with the EM38-MK2 meter operated in the VDO at the Moccasin site. The depth of effective penetration is shown above each plot.

Response Surface Sampling Design:

The *Response Surface Sampling Design* software program of *ESAP* was used to generate three (6, 12, and 20) optimal soil sampling designs for the Moccasin site based on the collected EC_a data. The first step in this program is to center, scale, and decorrelate the raw EC_a data. Decorrelation analysis identifies outliers (highly anomalous EC_a measurements). The decorrelation algorithm will automatically center and scale the raw EC_a data. The decorrelated EC_a data are measured in standard deviation units. In using the decorrelation algorithm, default settings of 3.5 and 4.5 standard deviations are used for site masking and outlier detection, respectively. The validation algorithm is used to either mask or delete outlier sites. In an iterative manner, the signal decorrelation and validation algorithms were invoked with outliers deleted.

Figures 5, 6, and 7 are plots showing the optimal sampling points for three different sampling schemes generated by the RRSD program based on the collected EC_a data. In each of these plots, the locations of observation points along the traverse lines are shown. The observation number for each of the sampling points is also provided. In the Compendium to this report, Tables 3, 4 and 5 respectively lists the coordinates and EMI data for the six, twelve, and twenty point optimal sampling schemes.

The RSSD treated most of the EC_a data collected in the northwest portion of the site as anomalous outliers. As shown in Figures 5 thru 7, the validation program deleted these outliers from consideration in the selection of the optimal soil sampling points. In effect, the RSSD program has identified an atypical area that containing excess amounts of soluble salts, contrasting soils, and requires different management practices.

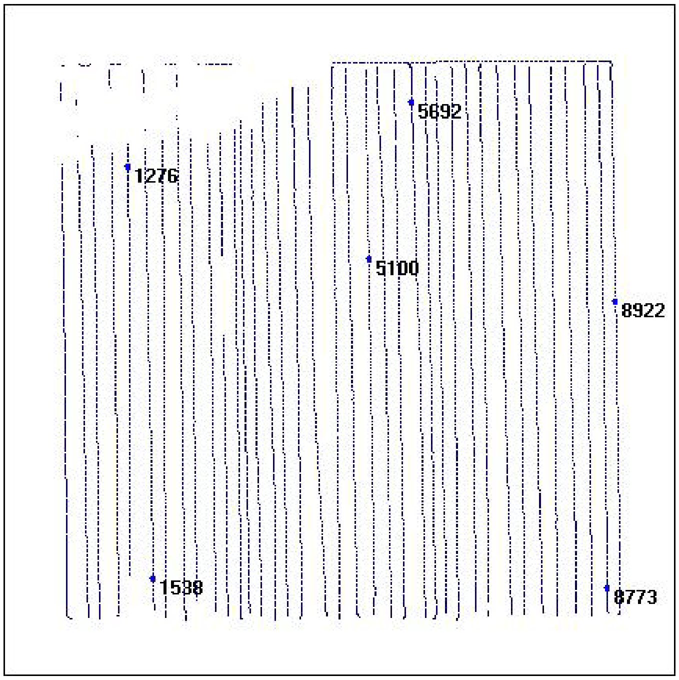

Figure 5. Plot of the six optimal sampling locations generated by the ESAP-RSSD program and based on EC_a data collected with the EM38-MK2 meter.

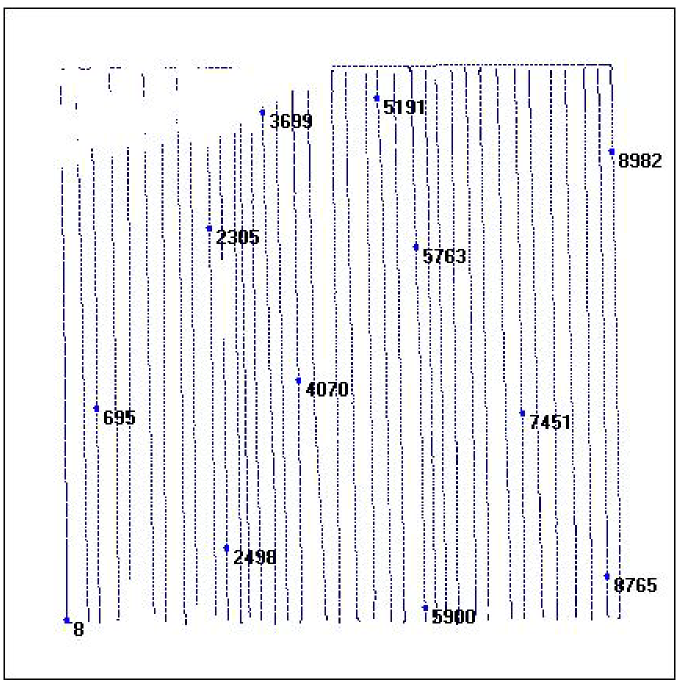

Figure 6. Plot of the twelve optimal sampling locations generated by the ESAP-RSSD program and based on EC_a data collected with the EM38-MK2 meter.

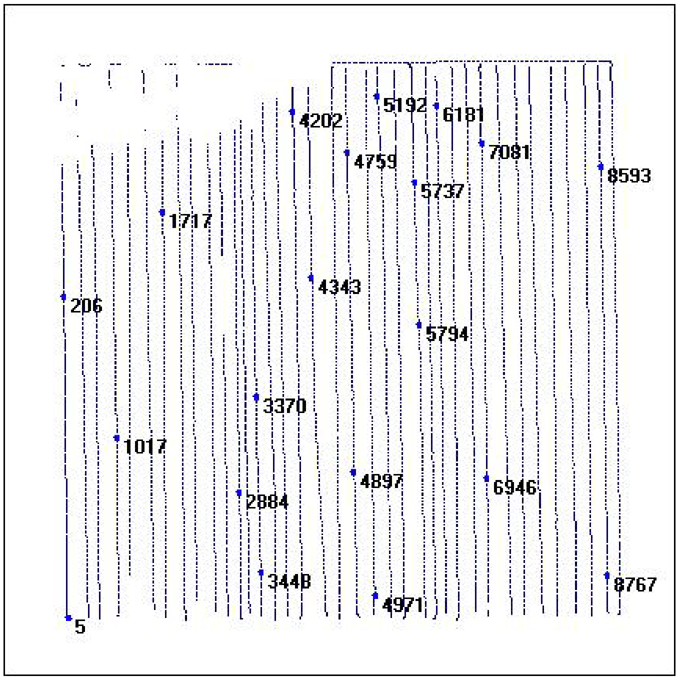

Figure 7. Plot of the twenty optimal sampling locations generated by the ESAP-RSSD program and based on EC_a data collected with the EM38-MK2 meter.

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Compendium:

Table 3. The six-point sampling scheme for the Moccasins Site generated from the ESAP-RSSD program.

Obs	Easting	Northing	100cm_ECa	100-inphase	50cm-ECa	50-inphase
1276	583272.7	5219327.0	43.91	4.57	24.18	14.69
1538	583327.8	5218448.5	11.29	-0.04	-0.39	11.29
5100	583787.2	5219130.9	24.80	14.65	13.09	38.13
5692	583879.7	5219464.4	38.48	12.81	26.88	20.78
8773	584298.0	5218429.1	13.98	13.83	6.99	37.34
8922	584314.6	5219039.2	22.66	15.86	11.64	44.10

Table 4. The twelve-point sampling scheme for the Moccasins Site generated from the ESAP-RSSD program.

Obs	Easting	Northing	100cm_ECa	100-inphase	50cm-ECa	50-inphase
8	583144.7	5218367.1	21.64	5.39	15.20	9.26
695	583207.4	5218821.1	32.03	2.81	18.63	3.75
2305	583447.5	5219203.8	29.53	2.93	11.88	15.82
2498	583484.5	5218520.7	10.63	3.40	-0.90	18.52
3699	583559.9	5219451.7	42.54	9.06	23.32	32.81
4070	583636.9	5218879.7	17.97	9.34	7.97	28.87
5191	583806.3	5219482.4	47.19	14.77	30.16	33.79
5763	583888.0	5219164.3	37.46	13.16	25.63	18.91
5900	583907.3	5218395.5	13.16	14.30	6.02	29.34
7451	584114.6	5218810.8	26.56	21.45	14.65	35.78
8765	584297.5	5218463.5	9.49	10.70	1.33	29.41
8982	584308.3	5219366.8	25.00	16.64	13.13	42.58

Compendium:

Table 5. The twenty-point sampling scheme for the Moccasins Site generated from the ESAP-RSSD program.

Obs	Easting	Northing	100cm_ECa	100-inphase	50cm-ECa	50-inphase
5	**583147.2**	**5218363.2**	**20.78**	**5.86**	**14.77**	**12.03**
206	**583136.9**	**5219051.1**	**31.45**	**5.27**	**19.84**	**7.73**
1017	**583249.1**	**5218748.6**	**18.01**	**2.30**	**6.37**	**18.52**
1717	**583348.0**	**5219230.5**	**36.17**	**3.36**	**21.60**	**14.80**
2884	**583511.7**	**5218632.2**	**11.05**	**3.98**	**-0.51**	**13.24**
3370	**583546.5**	**5218837.7**	**17.85**	**9.69**	**7.89**	**31.56**
3448	**583557.2**	**5218461.6**	**23.32**	**9.96**	**14.30**	**29.22**
4202	**583625.9**	**5219444.4**	**42.03**	**10.70**	**22.89**	**34.84**
4343	**583666.2**	**5219091.0**	**22.81**	**11.91**	**11.91**	**31.05**
4759	**583741.1**	**5219358.2**	**37.89**	**10.98**	**25.90**	**27.77**
4897	**583756.4**	**5218674.6**	**15.90**	**9.14**	**8.01**	**25.94**
4971	**583800.2**	**5218410.3**	**24.57**	**11.17**	**12.50**	**34.26**
5192	**583806.4**	**5219478.4**	**47.77**	**15.00**	**30.55**	**33.71**
5737	**583883.8**	**5219294.7**	**27.97**	**83.83**	**11.17**	**70.86**
5794	**583894.7**	**5218990.1**	**14.96**	**10.66**	**7.85**	**11.09**
6181	**583932.3**	**5219458.5**	**31.45**	**13.24**	**18.13**	**25.74**
6946	**584040.4**	**5218664.2**	**13.09**	**12.93**	**4.30**	**26.37**
7081	**584027.7**	**5219378.0**	**26.13**	**13.87**	**11.80**	**38.98**
8593	**584282.0**	**5219327.4**	**33.71**	**15.66**	**18.32**	**36.17**
8767	**584297.5**	**5218454.9**	**8.91**	**11.05**	**0.47**	**39.30**