United States Department of Agriculture

Natural Resources Conservation Service

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Subject: ENG -- Electromagnetic Induction (EMI) Assistance **Date:** 10 June 1999

To: Janet Oertly
State Conservationist
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Purpose:
To provide electromagnetic induction (EMI) field assistance. A geophysical site investigation was conducted in support of a proposed composting pad at Pennsylvania State University, University Park, Pennsylvania.

Participants:
Jim Doolittle, Research Soil Scientist, USDA-NRCS, Radnor, PA
Scott Heckman, Resource Conservationist, USDA-NRCS, Mill Run, PA
Glen Cauffman, Farm Manager, Pennsylvania State University, State College, PA
Gregg Boyd, Soil Conservation Technician, USDA-NRCS, Mill Run, PA

Activities:
All field activities were completed during on 8 June 1999.

Equipment:
The electromagnetic induction meter used in this study was the EM31, manufactured by Geonics Limited*. This meter is portable and requires only one person to operate. Principles of operation have been described by McNeill (1980a). No ground contact is required with this meter. The EM31 meter provides limited vertical resolution and depth information. Lateral resolution is approximately equal to the intercoil spacing (about 3.9 m). The EM31 meter operates at a frequency of 9,800 Hz and has theoretical observation depths of about 3 and 6 m in the horizontal and vertical dipole orientations, respectively (McNeill, 1980a). Values of apparent conductivity are expressed in milliSiemens per meter (mS/m).

The GEM-300 multifrequency sensor was also used in this study. The GEM-300 is configured to simultaneously measure up to 16 frequencies between 330 and 20000 Hz with a fixed coil separation (1.3 m). Depth of observation is determined by the operating frequency and the conductivity of the soil. Mutifrequency sounding with the GEM-300 allows multiple depths to be profiled with one pass of the meter. Won and others (1998) maintain that the depth of exploration is not governed by the separation between the transmitter and receiver as theorized by McNeill (1980b). These researchers contend that changing the transmitter frequency will change the depth of observation. Won (1980 and 1983) has noted that observation depths are governed by the skin-depth effect: low frequency signals travel farther through conductive mediums than high frequency signal.

To help summarize the results of this study, the SURFER for Windows program, developed by Golden Software, Inc.,* was used to construct two-dimensional simulations. Grids were created using kriging methods with an octant search.

Study Site:
The site is in hayland. The survey area was bounded on the south by a woodland and on the west by a farm road. At the time of this survey, soils were dry. Soil temperature was about 70 $^{\circ}$ F at a depth of about 18 inches.

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* Trade names are used to provide specific information. Their mention does not constitute endorsement by USDA-USDA-NRCS

The topography of the survey area has been simulated in the two-dimensional contour plot shown in Figure 1. In this plot, the contour interval is 0.5 foot. Relief is about 17.5 feet. The surface slopes towards the northwest or the upper left-hand corner of the survey area. A conspicuous sinkhole is apparent in the northeast or upper right-hand corner of the survey area.

The study site is located in areas of Hublersburg silt loam, 3 to 8 percent slopes, and Hagerstown silty clay loam, 3 to 8 percent slopes (Braker, 1981). A sinkhole had been identified and mapped in the area of Hagerstown silty clay loam, 3 to 8 percent slopes. These soils formed in residuum weathered from limestone. Included with these soils in mapping are small areas of soils that have bedrock within depths of 20 to 40 inches. The well-drained Hublersburg soil is very deep (>60 inches) to limestone bedrock. Permeability is moderate. Surface runoff is medium. The Hublersburg soil is a member of the clayey, illitic, mesic Typic Hapludults family. The well-drained Hagerstown soil is underlain by limestone at depths of 40 to 70 inches. Permeability is moderate. Surface runoff is medium. The Hagerstown soils are members of the fine, mixed, semiactive, mesic Typic Hapludults family.

Field Procedures:
A 300 by 400 foot, rectangular grid was established across the site. The grid interval was 50 feet. Survey flags were inserted in the ground at each grid intersection and served as observation points. The relative elevation of each grid intersection was determined with a level and stadia rod. Measurements were taken at each observation point with the EM31 meter placed on the ground surface in both the horizontal and vertical dipole orientations. In addition, measurements were taken at each observation point with the GEM300 sensor held at hip-height in the vertical dipole orientation. At each observation point, inphase, quadrature phase, and conductivity data were recorded with the GEM-300 sensor at three different frequencies (6630, 9810, and 14790 Hz). These frequencies are comparable to the EM38 meter (14800 Hz), the EM31 meter (9800), and the EM34-3 meter (not used in this survey) with an intercoil spacing of 10 m (6400 Hz).

Background:
Electromagnetic induction (EMI) is a noninvasive geophysical tool that can be used for detailed site investigations. Advantages of EMI are its portability, speed of operation, flexible observation depths, moderate resolution of subsurface features, and comprehensive coverage. Results of EMI surveys are interpretable in the field. This geophysical method can provide in a relatively short time the large number of observations that are needed to comprehensively cover sites. Maps prepared from correctly interpreted EMI data provide the basis for assessing site conditions, planning further investigations, and locating sampling or monitoring well sites.

Electromagnetic induction uses electromagnetic energy to measure the apparent conductivity of earthen materials. Apparent conductivity is a weighted, average conductivity measurement for a column of earthen materials to a specific observation depth (Greenhouse and Slaine, 1983). Variations in apparent conductivity are produced by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is influenced by the volumetric water content, type and concentration of ions in solution, temperature and phase of the soil water, and amount and type of clays in the soil matrix (McNeill, 1980b). The apparent conductivity of soils increases with increases in soluble salts, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976).

Electromagnetic induction measures vertical and lateral variations in apparent electrical conductivity. Values of apparent conductivity are seldom diagnostic in themselves, but lateral and vertical variations in these measurements can be used to infer changes in soils and soil properties. Interpretations are based on the identification of spatial patterns within data sets. To assist interpretations, computer simulations are normally used.

Results:
EM31 Meter
Table 1 summarizes basic statistics for the survey conducted with the EM31 meter. At most observation points, apparent conductivity decreased with increasing depth of observation (shallow-sensing horizontal dipole orientation (0 to 3 m) measurement were greater than those of the deeper-sensing vertical dipole orientation (0 to 6 m)). This relationship is associated with the higher water and clay contents of soils. The underlying limestone bedrock is more resistive (less conductive) than the overlying soil materials.

Values of apparent conductivity were relatively low and invariable across the site. Apparent conductivity averaged 3.89 mS/m and 3.30 mS/m in the horizontal and vertical dipole orientations, respectively. In the shallower-sensing, horizontal dipole orientation, one-half the observations had values of apparent conductivity between 3.20 and 4.45 mS/m. In the deeper-sensing, vertical dipole orientation, one-half the observations had values of apparent conductivity between 2.75 and 3.85 mS/m. Values of apparent conductivity are believed to principally reflect variations in soil depth. Areas with lower apparent conductivity are assumed to have shallower depths to bedrock than areas with higher apparent conductivity.

Figure 2 contains two-dimension plots of apparent conductivity obtained within the EM31 meter in the horizontal and vertical dipole

orientations. In each plot the isoline interval is 1.0 mS/m. This interval is less than the recognized range in observation errors (2 to 4 mS/m). However, because of the relatively invariable apparent conductivity measured with the EM31 meter within this site, use of a larger interval would provide little or no spatial information.

Table 1

Basic Statistics
EMI Survey
(All values are in mS/m)

Meter	Orientation	Minimum	Maximum	Quartiles 1st	Median	3rd	Average
EM31	Horizontal	1.40	6.60	3.20	3.80	4.45	3.89
EM31	Vertical	0.60	5.40	2.75	3.40	3.85	3.30

Figure 3 is a two-dimensional plot showing the distribution of apparent conductivity overlaid on a three-dimensional surface plot of the study site. The sinkhole is clearly apparent in the upper portion of each plot as it has higher values of apparent conductivity (greater than 4 mS/m) than surrounding, higher-lying areas. Higher values of apparent conductivity are presumed to reflect deeper depths to limestone and the higher clay and moisture contents within this feature. A noticeable band of comparatively low apparent conductivity surrounds the sinkhole. This band is located at slightly higher elevations and is believed to represent soils with shallower depths to bedrock. In the extreme lower corner (0,0) of each plot, spatial patterns of apparent conductivity suggest the possible occurrence of an additional sinkhole.

GEM-300 Multifrequency Electromagnetic Profiler:
Measurements of apparent conductivity collected with the GEM300, though comparable, were slightly higher and more variable than those collected with the EM31 meter. This difference is due, in part, to differences in the depth of observation, volume of earthen material measured, and resolution of each tool. Measurements of apparent conductivity obtained with the GEM300 at 6630 Hz were the most strongly correlated ($r^2 = 0.7203$) with the measurements obtained with the EM31 meter in the vertical dipole orientation. With an average apparent conductivity of 6.6 mS/m, a frequency of 6630 Hz provides a skin depth of about 8 m (Won et al., 1998). Measurements of apparent conductivity obtained with the GEM300 at 9810 Hz were the most strongly correlated ($r^2 = 0.7697$) with the measurements obtained with the EM31 meter in the horizontal dipole orientation. With an average apparent conductivity of 5.4 mS/m, a frequency of 9810 Hz provides a skin depth of about 7 m (Won et al., 1998). Relationships are listed in Table 2.

Table 2
Correlation between
GEM300 and EM31 Measurements of Apparent Conductivity

GEM300	EM31V	EM31H
6630(C)	0.7203	0.7353
9810(C)	0.6921	0.7697
14790(C)	0.6595	0.7132

Table 3 summarizes the results of this survey. While measurements of apparent conductivity obtained at 9810 and 14790 Hz were closely similar, those obtained with the 6630 Hz were slightly higher. This trend suggest that apparent conductivity increases with increasing depth of observation (the lower the frequency, the greater the observation depth). This relationship may reflect changes in lithology and/or increased water content at lower observation depths (greater than 6 m). This relationship does not necessarily

contradict the measurements obtained with the EM31 meter. At 6630 Hz, the GEM300 sensor sounds to a greater theoretical depth (8 m) than the EM31 meter (6 m).

Table 3

Basic Statistics
GEM300 Survey
(All values are in mS/m)

			Quartiles			
Frequency	**Minimum**	**Maximum**	**1st**	**Median**	**3rd**	**Average**
6630	1.6	10.0	6.1	6.6	6.6	6.57
9810	2.3	8.3	4.8	5.4	6.0	5.42
14790	2.7	8.3	5.1	5.5	6.2	5.63

Apparent conductivity data collected with the GEM-300 sensor is shown in Figure 4. In each plot the isoline interval is 1.0 mS/m. The frequency at which data were collected is shown above each plot. The depth of observation is assumed to increase as the frequency decreases. Although values and some patterns vary among these plots, several "anomalies" are apparent on all plots. In each plot, a zone of higher apparent conductivity can be observed within the sinkhole (see "A"). The actual values and spatial patterns of this zone are closely similar in each plot and at each frequency. An area of low conductivity presumed to have relatively shallow depths to bedrock has been labeled "B" in each plot. In each plot, spatial patterns near "C" and "D" suggest the possible presence of additional sinkholes or solution features.

Comparable spatial patterns of apparent conductivity were obtained with the EM31 meter and the GEM300. Each identified areas having higher values of apparent conductivity. These areas are suspected to have greater depths to bedrock. These areas are believed to delineate solution features. Both the EM31 and the GEM300 identified an area of higher apparent conductivity having no noticeable surface expression in the southwestern corner of the study site. Additional solution features may be present in this portion of the study site. Areas with low apparent conductivity are suspected to be underlain by bedrock at shallower depths than areas with higher conductivity. The agreement of these two geophysical tools provides increased confidence in site assessment and demonstrates the advantages of a multi-method approach.

Conclusions:

1. Geophysical interpretations are considered preliminary estimates of site conditions. The results of geophysical site investigations are interpretive and do not substitute for direct ground-truth observations (soil borings). The use of geophysical methods can reduce the number of coring observations, direct their placement, and supplement their interpretations. Interpretations contained in this report should be verified by ground-truth observations.

2. Simulations prepared from correctly interpreted EMI data provide the basis for assessing site conditions. Values of apparent conductivity were low (0.6 to 10 mS/m) within the study site. Spatial patterns evident in the enclosed plots are believed to principally represent variations in the thickness of the soil mantle and depth to bedrock. These patterns suggest the occurrence of solution feature within the proposed site of the composting-pad. Electromagnetic induction provides an indication of the extent of karst conditions that may pose a risk to the environment.

3. The survey at Pennsylvania State University provided a before-built picture of the proposed waste-composting site. Several interpretations were proposed for the spatial patterns appearing in simulated plots of the site. However, as no ground-truth observations were made, these interpretations are tentative.

It was my pleasure to work in Pennsylvania and with members of your fine staff.

With kind regards,

James A. Doolittle
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cc:
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Addendum 1

Data from Survey conducted with the EM31 Meter and the GEM300 Sensor

(elevation is expressed in feet; apparent conductivity is expressed in mS/m)

			EM31 Meter		GEM300 Sensor		
X	Y	Elevation	Horizontal	Vertical	6630(C)	9810(C)	14790(C)
0	0	99.7	6.6	5.4	8.4	6.9	7.6
50	0	99.9	4.4	4.4	6.9	5.3	5.3
100	0	100.6	5.4	3.8	6.7	6.2	6.2
150	0	99.8	5.6	3.0	6.9	5.7	6.0
200	0	99.5	5.0	4.6	6.9	5.2	5.3
250	0	100.7	3.6	3.4	5.2	4.3	4.9
300	0	101.8	3.6	3.0	6.2	4.8	5.2
300	50	99.4	4.6	4.6	6.8	6.2	6.4
250	50	99.4	4.0	4.0	6.5	5.4	5.6
200	50	98.9	4.2	3.4	6.7	4.6	5.2
150	50	98.7	4.4	4.0	6.8	5.8	5.8
100	50	98.1	5.4	5.0	8.3	6.4	6.7
50	50	98.0	5.0	4.2	7.3	6.1	5.4
0	50	97.9	4.2	4.4	6.5	5.4	5.7
0	100	95.4	4.2	3.0	6.5	5.1	5.5
50	100	96.6	4.2	3.8	6.9	5.1	5.3
100	100	97.1	3.8	3.6	6.6	4.4	4.9
150	100	97.0	3.2	3.4	6.7	5.4	5.0
200	100	97.9	3.4	3.0	6.0	4.1	4.9
250	100	99.3	3.2	2.6	6.8	4.6	5.3
300	100	99.5	3.8	3.8	6.9	5.7	5.1
300	150	98.3	2.8	2.8	6.4	4.8	4.4
250	150	96.7	3.4	3.2	5.8	4.8	5.1
200	150	95.8	4.0	3.8	7.2	5.7	5.5
150	150	95.6	3.6	3.2	6.8	5.5	5.5
100	150	95.1	4.6	3.6	6.4	6.1	5.5
50	150	94.0	3.6	3.2	6.5	5.5	5.1
0	150	91.4	4.8	4.8	10.0	6.8	6.5
0	200	88.5	4.8	4.8	7.1	6.6	6.6
50	200	90.2	4.4	3.8	7.2	5.5	6.4
100	200	92.7	3.6	3.4	7.2	5.9	6.0
150	200	93.7	5.0	3.0	6.1	6.7	4.9
200	200	94.5	3.0	2.8	5.8	5.0	5.9
250	200	94.3	3.6	3.4	6.2	4.9	5.1
300	200	96.9	2.8	2.4	6.0	5.1	5.6
300	250	94.3	4.2	3.6	7.1	5.4	6.6
250	250	92.8	4.0	3.2	6.6	6.6	6.2
200	250	91.6	3.2	3.2	6.1	5.1	5.5
150	250	92.3	3.2	2.6	6.1	4.5	4.1
100	250	90.9	2.8	2.2	5.9	5.0	4.5
50	250	89.1	3.8	3.4	6.2	4.9	5.6
0	250	88.2	4.4	3.6	8.0	6.3	6.4
50	300	88.4	3.0	2.6	5.7	4.6	5.3
100	300	89.7	2.6	1.8	6.3	5.4	5.7
150	300	91.4	2.8	2.4	5.5	4.4	5.0
200	300	88.8	3.6	4.0	6.6	5.7	6.5
250	300	91.3	4.2	3.2	7.5	6.1	7.0
300	300	92.8	5.2	5.4	8.3	8.3	7.7
300	350	90.3	4.6	5.2	8.2	7.9	8.3
250	350	87.4	5.4	4.2	7.4	6.9	7.4
200	350	87.4	4.6	3.4	6.4	5.9	6.2

			EM31 Meter		GEM300 Sensor		
X	Y	Elevation	Horizontal	Vertical	6630(C)	9810(C)	14790(C)
150	350	90.5	2.2	1.6	4.5	3.9	4.1
100	350	88.4	3.4	2.4	5.8	4.8	5.3
50	400	84.3	4.2	3.0	6.5	5.7	6.1
100	400	86.2	3.6	0.6	6.6	5.9	6.2
150	400	90.6	1.4	0.8	1.6	2.3	2.7
200	400	89.6	2.0	2.2	5.5	4.4	4.8
250	400	91.1	2.6	1.2	5.2	3.7	4.1
300	400	92.9	3.6	1.6	6.5	5.1	5.5

* Trade names are used to provide specific information. Their mention does not constitute endorsement by USDA-USDA-NRCS.

EMI Survey of Composting-Pad Site
Pennsylvania State University
Relative Topography

Contour Interval = 0.5 Feet

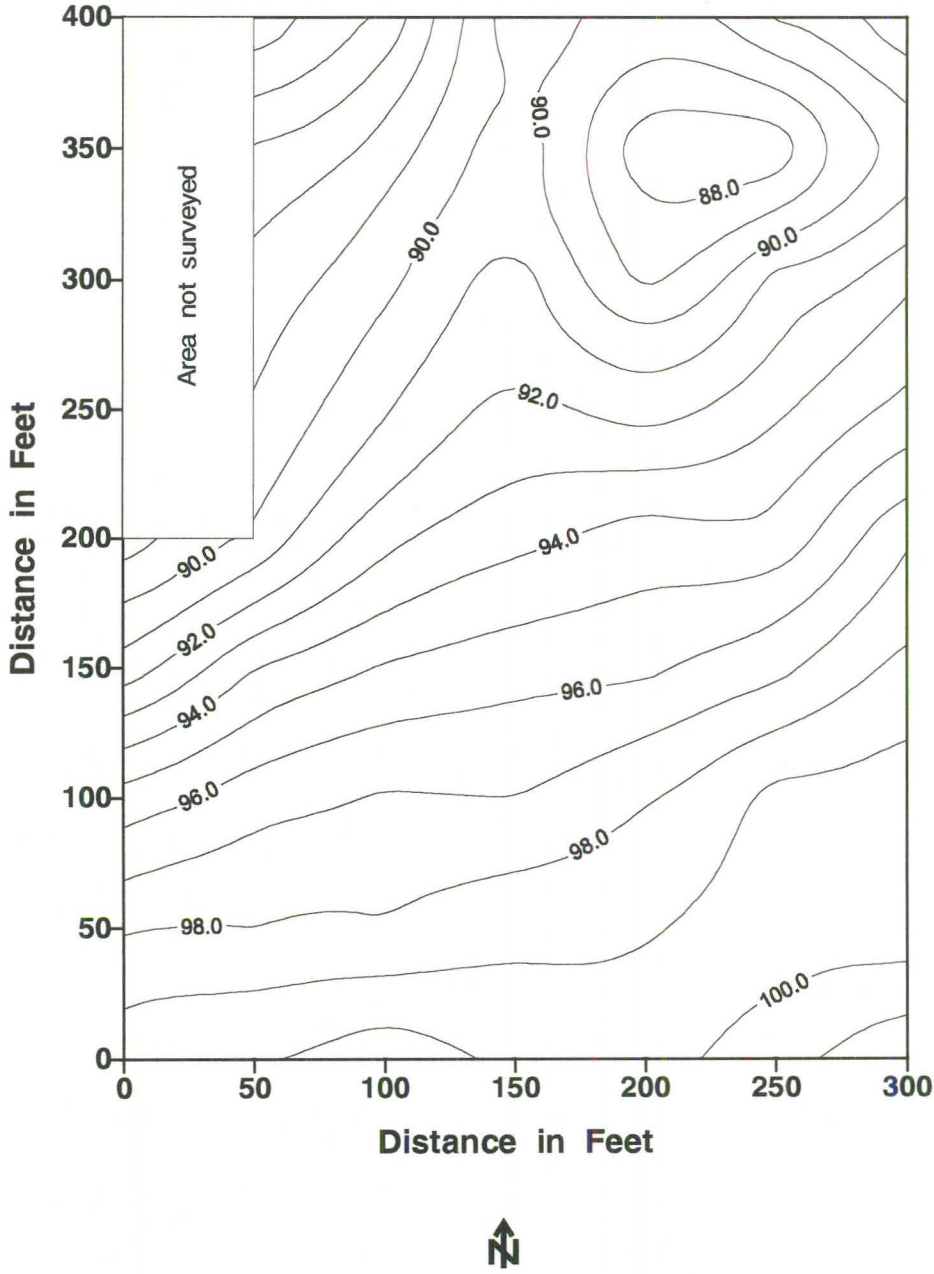


Figure 1

EMI Survey of Composting-Pad Site
Pennsylvania State University
EM31 Meter

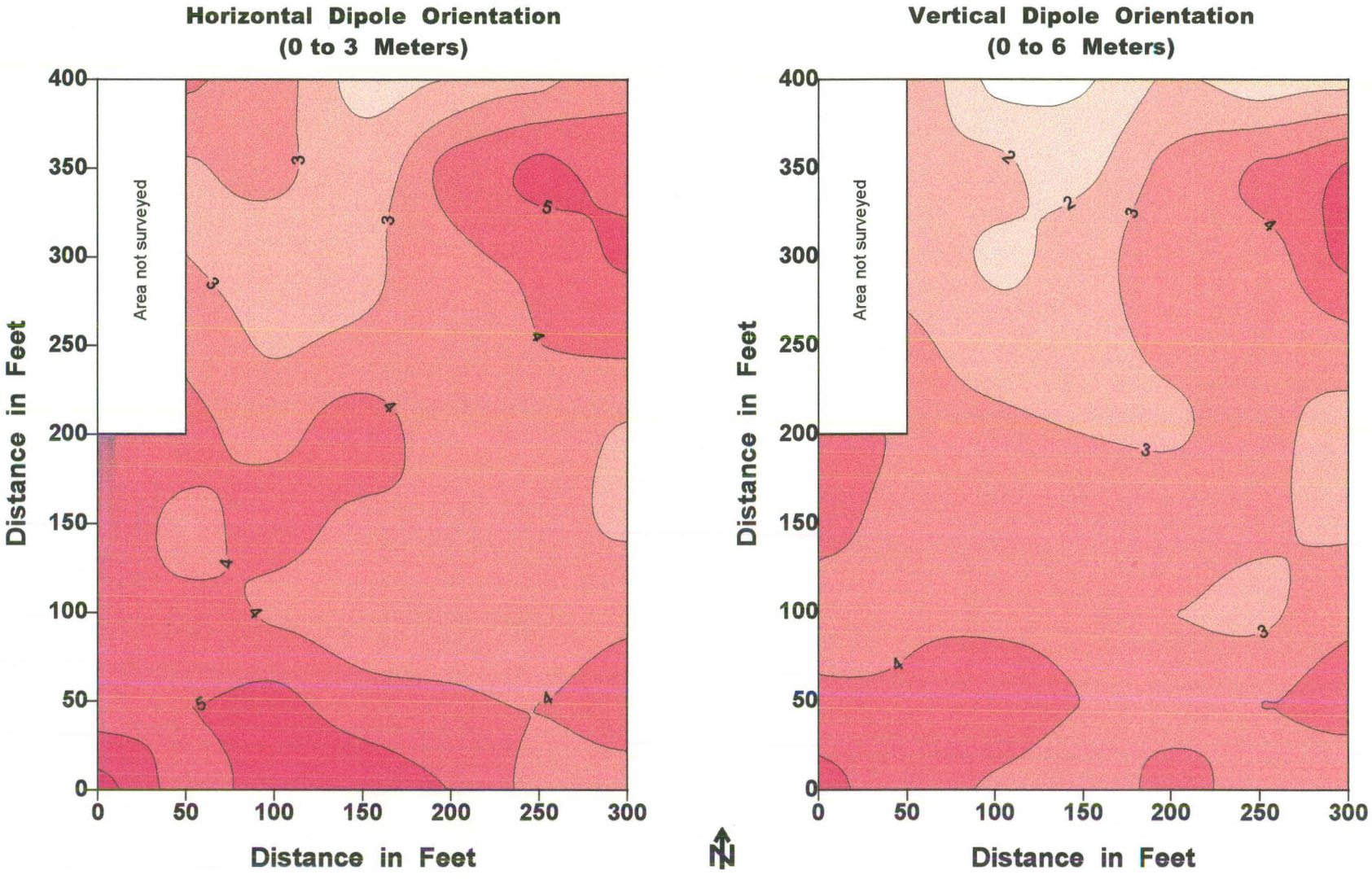
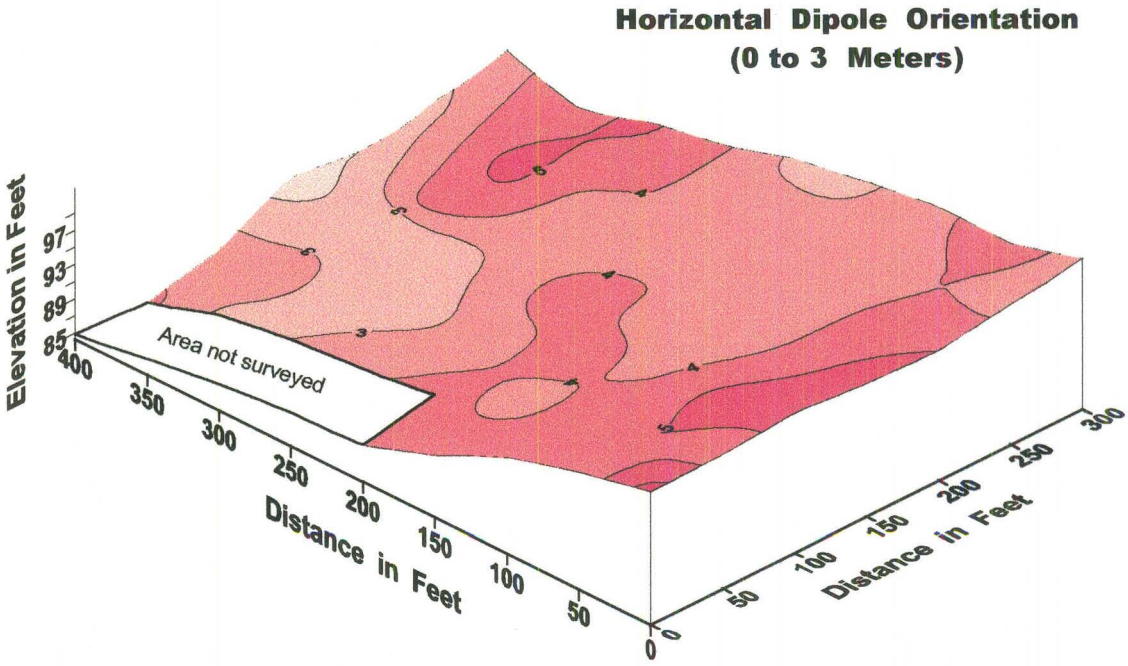


Figure 2

EMI Survey of Composting-Pad Site
Pennsylvania State University
EM31 Meter



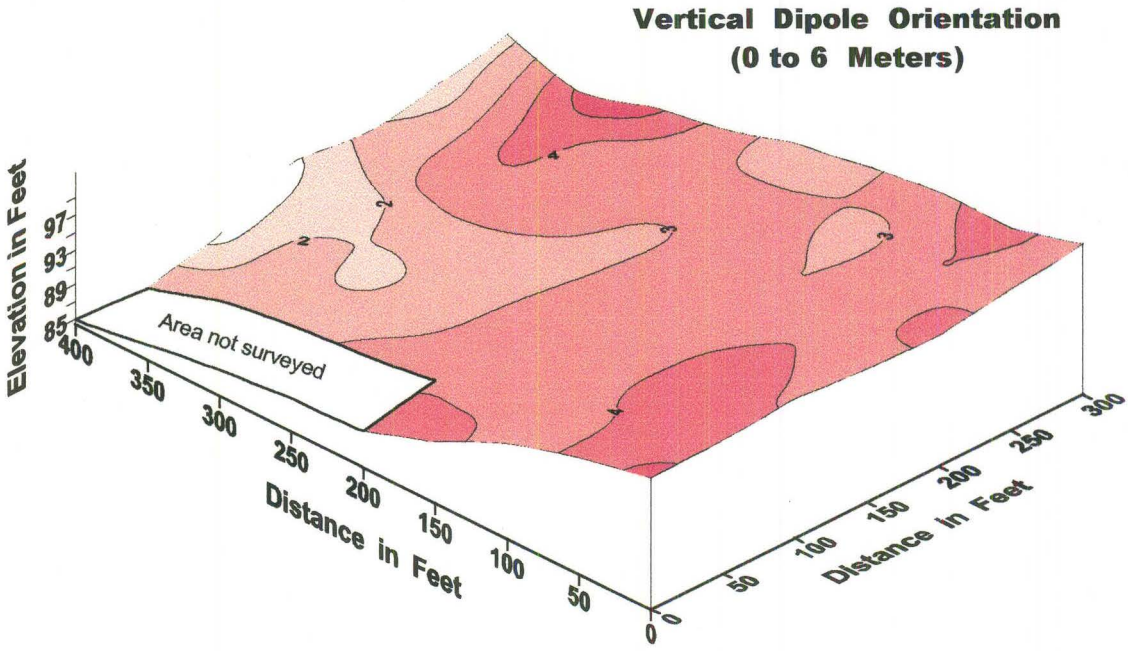


Figure 3

EMI Survey of Composting-Pad Site
Pennsylvania State University
GEM300 Sensor

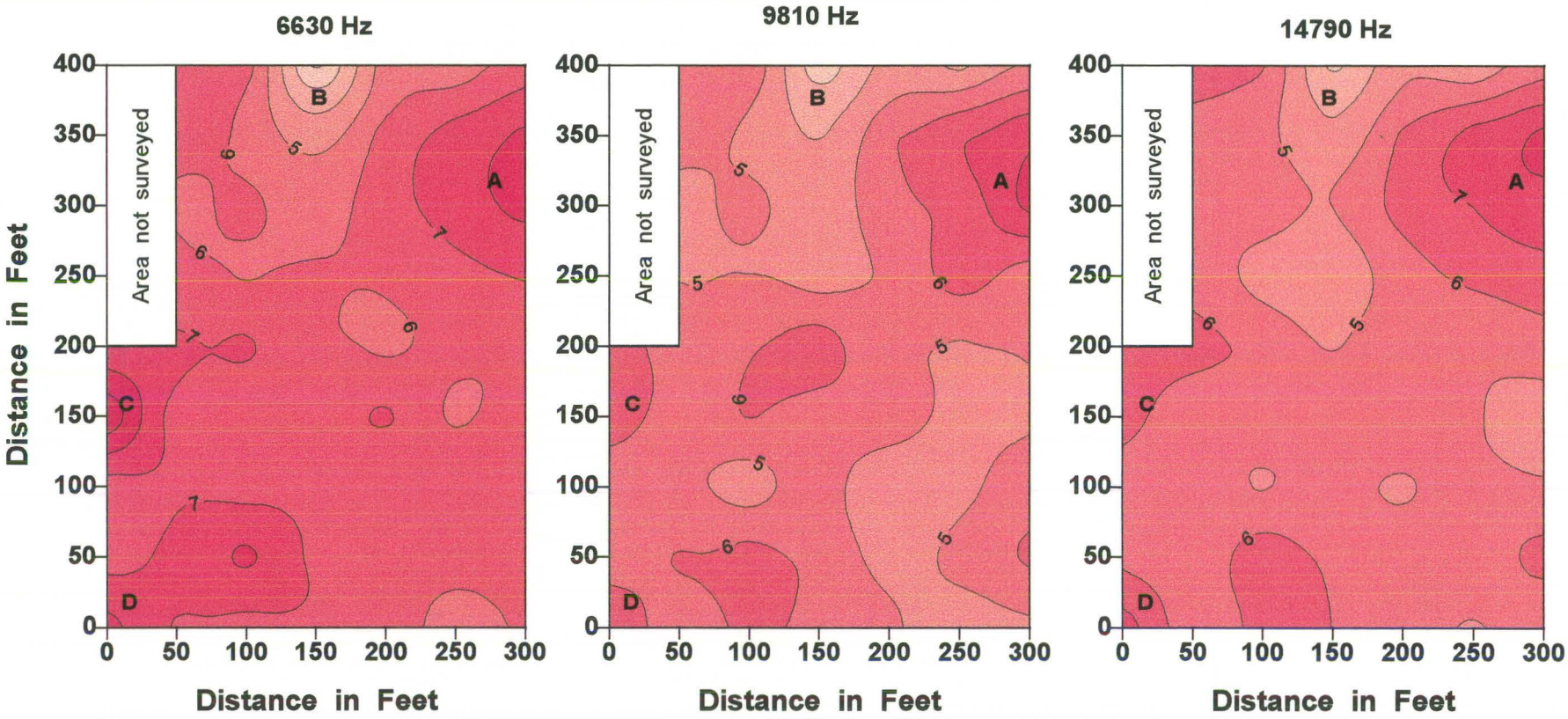


Figure 4

EMI Survey of Composting-Pad Site
Pennsylvania State University
Relative Topography

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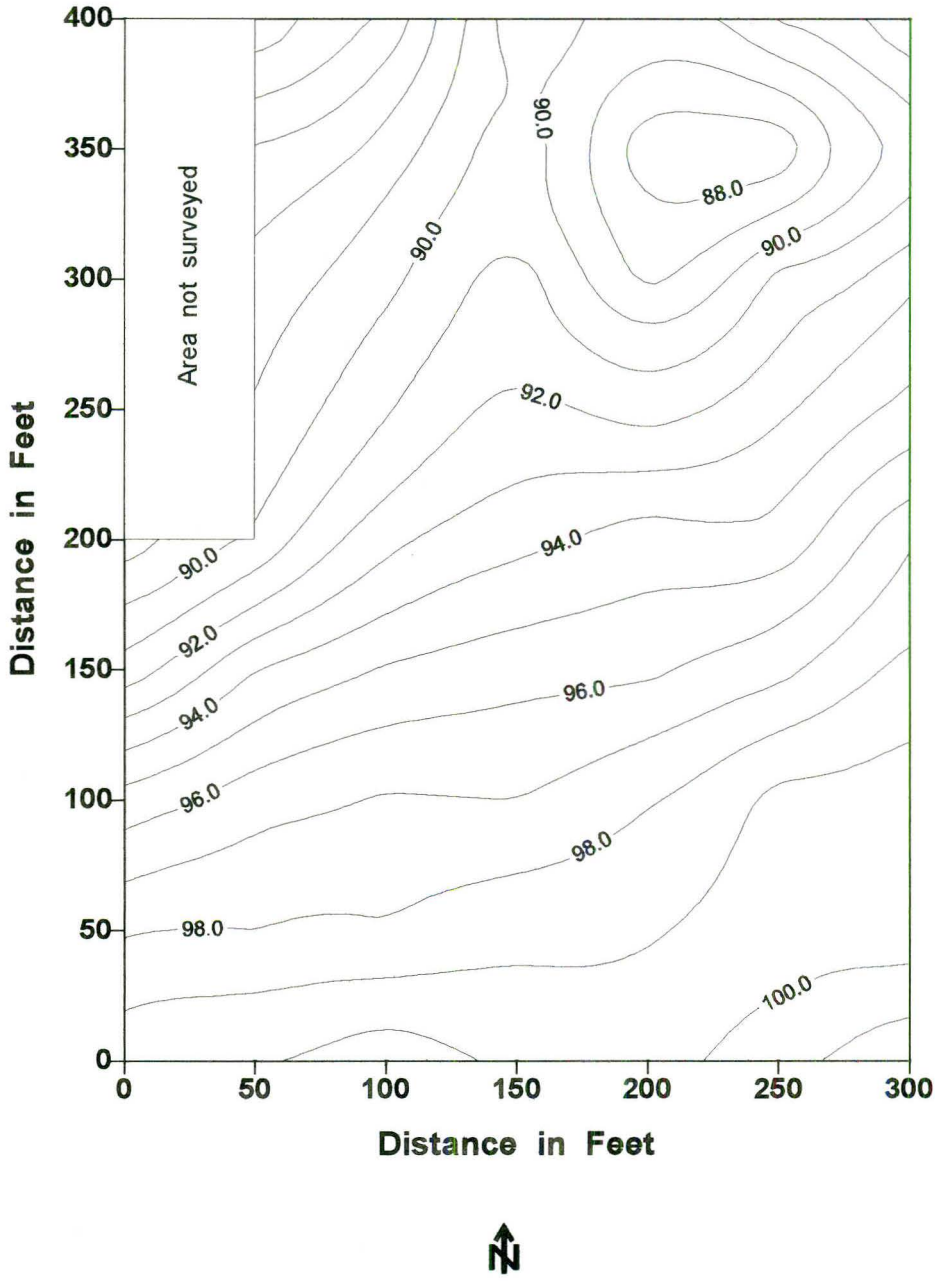


Figure 1

EMI Survey of Composting-Pad Site
Pennsylvania State University
EM31 Meter

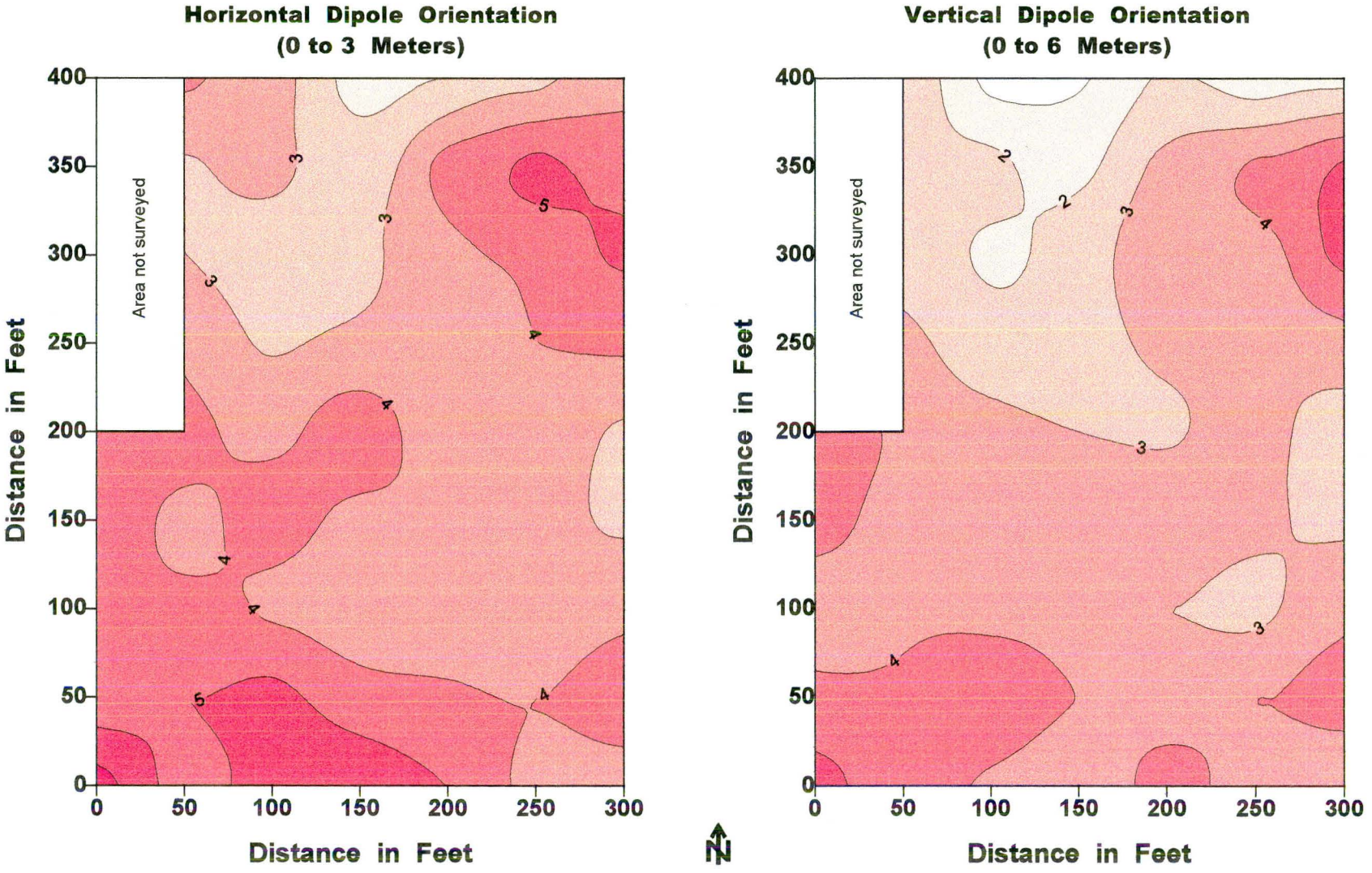
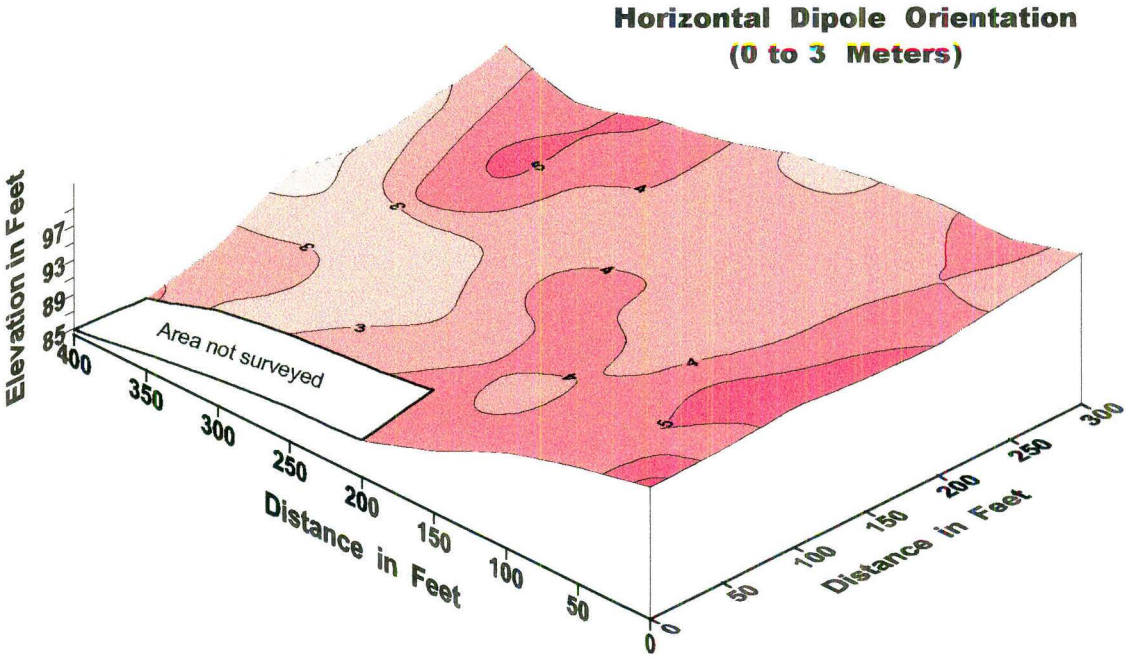


Figure 2

EMI Survey of Composting-Pad Site
Pennsylvania State University
EM31 Meter



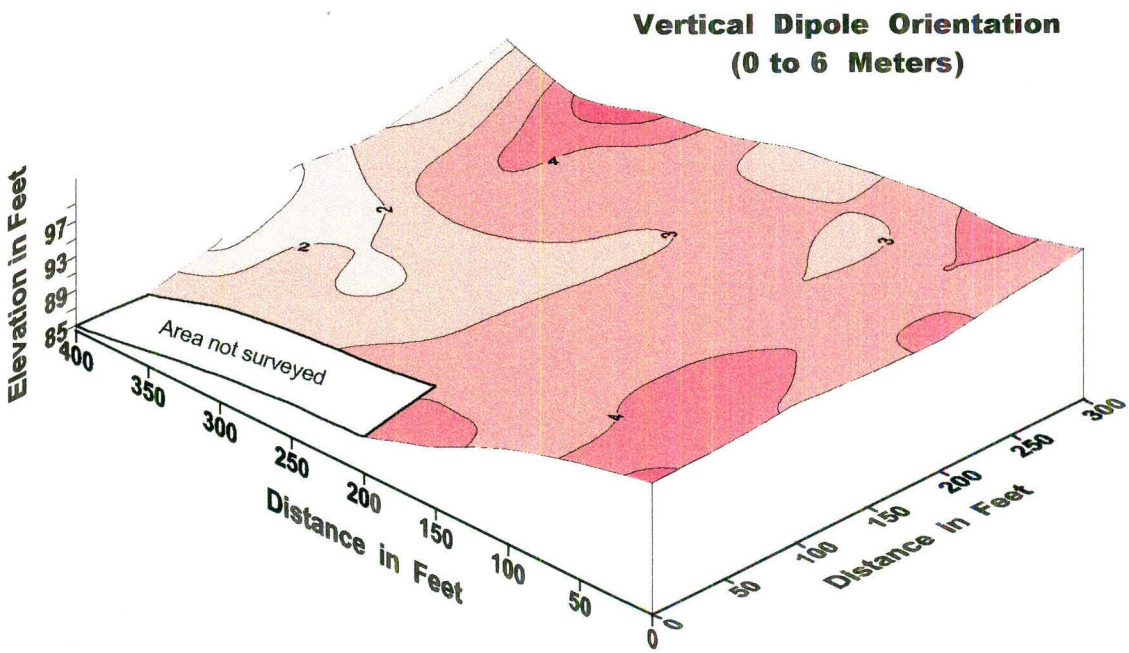


Figure 3

EMI Survey of Composting-Pad Site
Pennsylvania State University
GEM300 Sensor

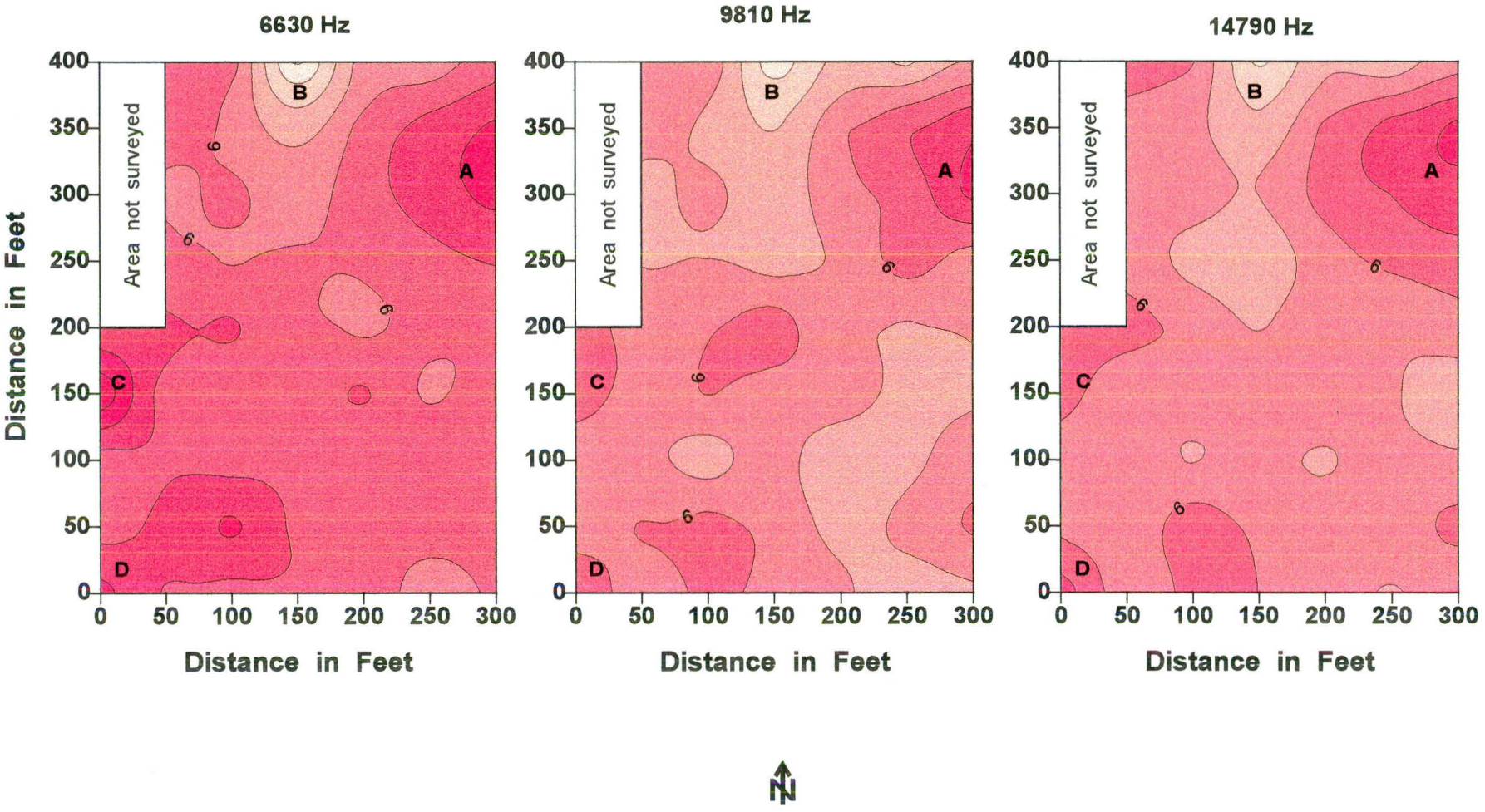


Figure 4

EMI Survey of Composting-Pad Site
Pennsylvania State University
GEM300 Sensor

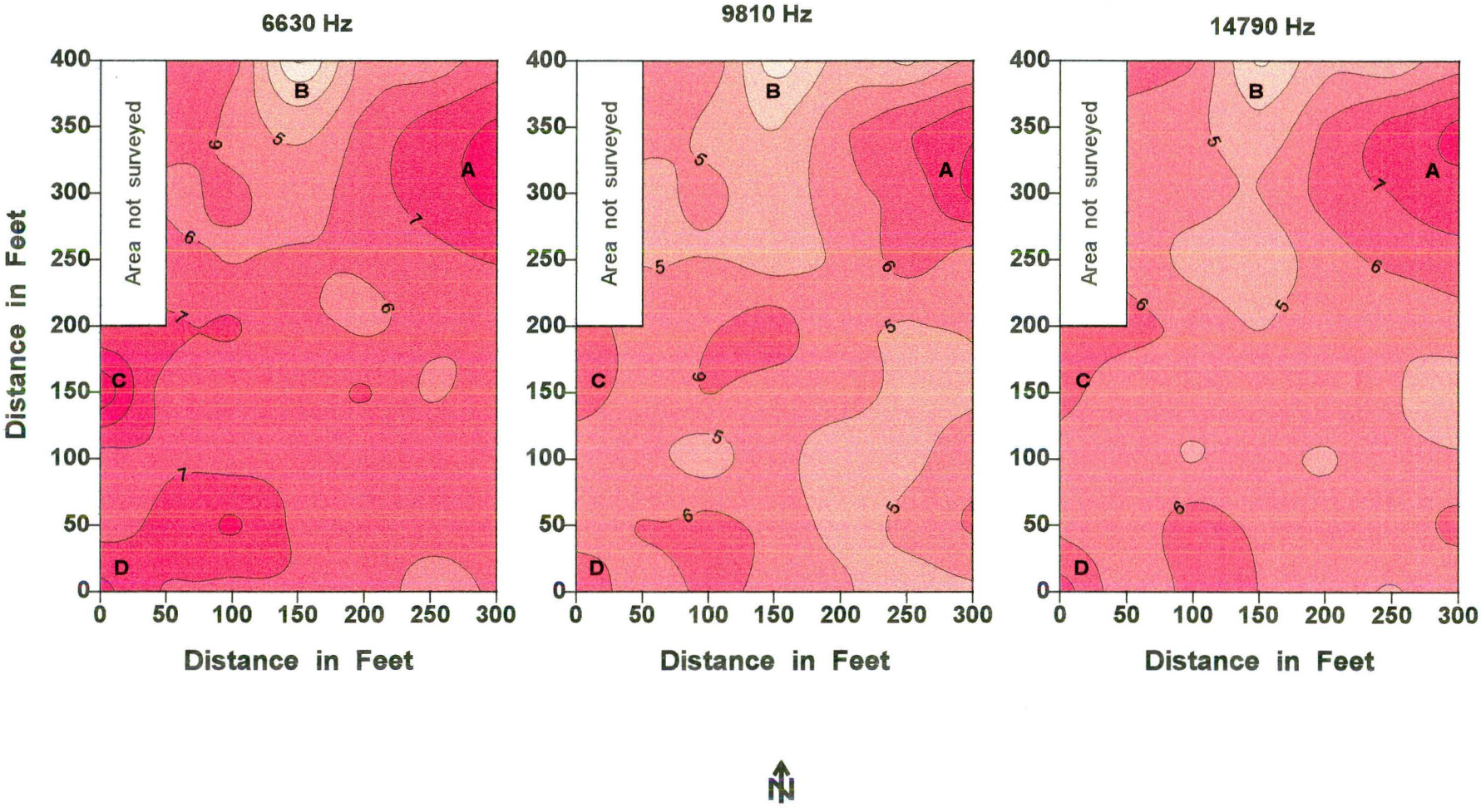


Figure 4