United States Department of Agriculture

Natural Resources Conservation Service

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Subject: SOI -- Ground-Penetrating Radar Surveys **Date:** February 26, 2002

To: Cecil B. Currin
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PURPOSE:
The primary purpose of this study was to use ground-penetrating radar (GPR) to help characterize cranberry beds and estimate the depth and volume of organic soil materials and the composition of soil map units within these deposits. In addition, comparative studies were conducted using 70 and 120 MHz antennas at several sites. Bedrock investigations were also completed in Wompatuck State Park.

PARTICIPANTS:
Jon Boothvoyd, Professor, University of Rhode Island, Kingston, RI
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James Turenne, Soil Survey Project Leader, USDA-NRCS, West Wareham, MA
Andrew Williams, Soil Scientist (SDQ), USDA-NRCS, Amherst, MA

ACTIVITIES:
All field activities were completed during the period of 11 to 14 February 2002.

RESULTS:

1. Detailed GPR investigations were completed in three cranberry beds. These investigations provided the first opportunity for USDA-NRCS to use RADAN for Windows NT and 3D QuickDraw for RADAN NT software to process and display data collected over organic soils. Some of the results are presented in this report.

2. Comparative studies were conducted with the 120 and 70 MHz antennas. The 70 MHz antenna is easier to operate and maneuver in the field than the 120 MHz antenna. Initially high levels of noise plagued data collected with the 70 MHz antenna. Much of the noise was attributed to the antenna swaying radically in the air when it was suspended from the shoulder of an operator during surveys. Survey procedures were modified and stabilizing poles were fabricated to reduce the noise that was observed in the 70 MHz antenna. Results from stratigraphic studies conducted in southern Rhode Island demonstrate that the 70 MHz antenna can provided greater penetration depth, but with slightly less resolution of subsurface features than the 120 MHz antenna.

3. Bedrock investigations were completed in Wompatuck State Park, Hingham, Massachusetts. Areas of map unit 111C, Chatfield-Rock Outcrop-Canton, rolling, and map unit 110B Canton-Chatfield-Rock Outcrop, undulating were surveyed.

4. Training was provided on the use of RADAN for Windows NT to Jim Turenne and Robert Tunstead.

5. Copies of all radar profiles and transect data have been transmitted to Jim Turenne.

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

With kind regards,

James A. Doolittle
Research Soil Scientist

cc:
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Bedrock Investigation

Bedrock investigations were completed in Wompatuck State Park, Hingham, Massachusetts. Areas of map unit 111C, Chatfield-Rock Outcrop-Canton, rolling, and map unit 110B Canton-Chatfield-Rock Outcrop, undulating, were surveyed. Chatfield and Canton soils are on glaciated plains, hills, and ridges. The moderately deep, well drained, and somewhat excessively drained Chatfield soils formed in till. Crystalline bedrock is at depths of 0.5 to 1.0 m. Chatfield is a member of the coarse-loamy, mixed, superactive, mesic Typic Dystrudepts family. The very deep, well drained Canton soils formed in a loamy mantle underlain by sandy till. Canton is a member of the coarse-loamy over sandy or sandy-skeletal, mixed, semiactive, mesic Typic Dystrudepts family. Table 1 provides a summary of the distribution of soils according to soil depth classes.

Table 1. Summary of Depth to Bedrock Data
Interpreted from GPR Data

Chatfield-Rock Outcrop-Canton, rolling

	Observations	Frequency
Sallow	6	0.25
M. Deep	13	0.54
Deep	1	0.04
V. Deep	4	0.17

Canton-Chatfield-Rock Outcrop, undulating

	Observations	Frequency
Sallow	6	0.14
M. Deep	13	0.29
Deep	1	0.32
V. Deep	4	0.25

Canton-Chatfield-Rock Outcrop, undulating

	Observations	Frequency
Sallow	0	0.00
M. Deep	7	0.78
Deep	0	0.00
V. Deep	2	0.22

USING GPR TO CHARACTERIZED ORGANIC SOILS

Background:

Organic soils cover an estimated 1.6 percent of the United States (Soil Survey Staff, 1999). Once avoided or overlooked, today many peat deposits are being managed to meet agricultural and urban needs (Johnson, 1985). In southeastern Massachusetts, cranberries (Vaccinium macrocarpon Ait.) are produced on peat deposits that range in size from about 0.2 to 80 ha (Burrows, 1976). Areas converted into cranberry beds have level to slightly concave surfaces and are generally confined to basins, broad flats, glacial meltwater channels or periglacial furrows.

Cranberry beds have been extensively modified. At 3 to 5 year intervals, a 2 to 4 cm layer of sand is spread across the surface. This layer of sand is used to cover older growth; counter soil losses do to subsidence; and provide improved drainage, weed, and insect control. A network of drainage ditches has been carved across each cranberry bed to facilitate water management. Earthen dikes subdivide larger cranberry beds into smaller units that are more easily managed.

A prerequisite for the effective use and management of cranberry beds is knowledge of the thickness and volume of peat within basins. The morphometry of cranberry bogs and the degree of peat decomposition influences water needs, nutrient availability, and soil temperature (Doolittle et al., 1990). Renovation or structural upgrades of dike and road systems require knowledge of the depth and underlying topography of the organic/mineral soil contact. Despite the extent of cranberry cultivation in southeastern Massachusetts, few comprehensive surveys have been conducted to determine the actual depth, volume, or geometry of the basin on which the crop is grown. Limited surveys have indicated that the depths of organic soil materials can ranges from less than 1 meter to greater than 12 meters (Deubert and Caruso, 1990). Pushing a metal rod through a column of peat or drilling a small hole to observe the underlying materials are the most commonly used methods to map and inventory peat deposits (Turenne, 1997). As these methods are slow, tedious, and expensive, observations are limited and surveys do not thoroughly cover cranberry beds.

Soil surveys prepared by the USDA provide information on the spatial distribution of organic soils and physical and chemical properties of organic layers. However, this information is depth restricted and therefore of limited value. Depending on the degree of decomposition, soil surveys described and classified organic soil materials to maximum depths of 1.3 or 1.6 m (Soil Survey Staff, 1999). These depth limits are arbitrary and were established for expediency and practical reasons (Soil Survey Staff, 1999; Farnham and Finney, 1965). Therefore, information contained in soil survey reports is inappropriate for estimating the thickness or volume of organic soil materials within cranberry beds (Doolittle et al., 1990).

Today, as the public becomes more awareness to wetland soil processes and the role that cranberry beds play in water quality and carbon cycling, faster, less labor intense, and more comprehensive methods are needed to inventory peat deposits. One geophysical method that has been effectively used to inventory peat deposits is ground-penetrating radar (GPR). Remotec Applications Inc. (1982) and Ulriksen (1980) reported that GPR requires significantly less time and effort than conventional methods to obtain similar information on the depth and volume of peat deposits. GPR has been used to estimate the thickness and volume of peat deposits (Pelletier et al., 1991; Doolittle et al., 1990; Collins et al., 1986; Shih and Doolittle, 1984; Tolonen et al., 1984; Ulriksen, 1982; Welsby, 1988; and Worsfold et al., 1986), distinguish layers having differences in degree of humification and volumetric water content (Lapen et al., 1996; Chernetsov et al., 1988; Worsfold et al., 1986; Tolonen et al., 1984; and Ulriksen, 1982), and to classify organic soils (Collins et al., 1986). In addition, Lowe (1985) used GPR to assess the amount of logs and stumps buried in peat deposits. Welsby (1988) used GPR for post-production surveys of mined peat deposits. Radar records can provide information that have an effect on geotechnical applications such as road design and dike construction on peat deposits (Turenne, 1997; Saarenketo et al., 1992, and Ulriksen, 1982).

While profiling depths as great as 8.1 to 10 m have been reported in organic soils (Worsfold et al., 1986, and Ulriksen, 1980), GPR is not equally suitable for use on all organic soils. Soils having high electrical conductivity rapidly attenuate radar energy, restrict penetration depths, and severely limit the effectiveness of GPR. The electrical conductivity of organic soils is directly related to the concentration of total dissolved ions in the pore water (Theimer et al., 1994). For organic soils, the concentration of ions in the ground water is the principal factor influencing electrical conductivity. In addition, Theimer and others (1994) noted that the electrical conductivity is closely related to the chemistry of the underlying mineral sediments. Because of this relationship, electrical conductivity often increases towards organic/mineral soil interfaces (Theimer et al., 1994).

In general, GPR is more effective in acidic, low nutrient organic soil materials than in alkaline, high nutrient organic soil materials. Generally, profiling depths are greater in oligotrophic bogs than in minerotrophic fens (Malterer and Doolittle, 1984). Oligotrophic bogs are nutrient poor and have lower concentrations of the basic cations (calcium, magnesium, and potassium) than many nutrient enriched minerotrophic fens. In some fens, such as coastal marshes, high concentrations of dissolved salts completely absorb the radar’s electromagnetic energy and restrict observation depths to less than 0.5 m.

STUDY SITES:

Two cranberry beds in Carver Township, Plymouth County, Massachusetts were surveyed with GPR. Canal Bed (41^{o}50’9’N Latitude and 70^{o} 42’2’ W Longitude) has an area of about 33,127 square meters (3.3 ha). Bergman Bed (41^{o}48”18’N Latitude and 70^{o} 41”46’ W Longitude) has an area of about 7978 square meters (0.8 ha). Both beds were mapped as Freetown coarse sand. The very deep, very poorly drained Freetown soil formed in more than 1.3 m of highly decomposed organic material. Freetown soils are in depressions or on level areas on uplands and outwash plains. Freetown soil is a member of the dysic, mesic Typic Haplosaprists family. Included in mapping are small areas of Swansea soil and areas with less than 0.4 m of organic soil materials. The very poorly drained Swansea soils formed in 0.4 to 1.3 m of highly decomposed organic material over sandy mineral. Swansea soil is a member of the sandy or sandy-skeletal, mixed, dysic, mesic Terric Haplosaprists family.

MATERIALS AND METHODS

Equipment:

The radar unit is the Subsurface Interface Radar (SIR) System-2000, manufactured by Geophysical Survey Systems, Inc.[1] Morey (1974) and Doolittle (1987) have discussed the use and operation of GPR. The SIR System-2000 consists of a digital control unit (DC-2000) with keypad, VGA video screen, and connector panel. A 12-volt battery powered the system. This unit is backpack portable and, with an antenna, requires two people to operate. The 120 MHz antenna was used in this study. Scanning time varied with site conditions but ranged from 200 to 400 nanoseconds (ns).

The coordinates of all observation points were obtained with Rockwell Precision Lightweight GPS Receivers (PLGR).[1] This receiver was operated in the continuous and the mixed satellite modes. The Massachusetts State Plane coordinate system was used. Horizontal datum is the North American 1983. Horizontal units are expressed in meters.

To help summarize the results of this study, the SURFER for Windows (version 7.0) program, developed by Golden Software, Inc.,[1] was used to construct two- and three-dimensional simulations. Grids were created using kriging methods with an octant search.

Field Methods:

A 240 by 90 m grid was established across Canal Bed. The grid consisted of eleven lines that were spaced at 24 m intervals and varied in length from 30 to 90 m. Observation flags were spaced at 10 m intervals along each line. This provided ninety-six observation points. The coordinates of each observation point were identified with GPS. An additional 44 points were recorded with GPS. These points were used to define the outline of the bed. These points were assigned an organic thickness of 0.0 m.

An irregular shaped, 120 by 25 m grid was established across Bergman Bed. The grid consisted of six lines that varied in length from 80 to 120 m, and spaced 5 m apart. Observation flags were spaced at 10 m intervals along each line. This provided seventy-one observation points. The coordinates of each observation point were identified with GPS. An additional 32 points were recorded with GPS. These points were used to define the outline of the bed. These points were assigned an organic thickness of 0.0 m.

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

Pulling the 120 MHz antenna along each traverse line completed a radar survey file. As the antenna was pulled passed each flagged observation point, the operator impressed a vertical reference line on the radar profile to identify the observation point.

CALIBRATION OF GPR

Ground-penetrating radar is a time scaled system. This geophysical tool measures the time it takes electromagnetic energy to travel from an antenna to an interface (i.e., soil horizon, stratigraphic layer) and back. To convert travel time to depth requires knowledge of the velocity of pulse propagation. Several methods are available to determine the velocity of propagation. These methods include use of table values, common midpoint calibration, and calibration over a target of known depth. The last method is considered the most direct and accurate method to estimate propagation velocity. The procedure involves measuring the two-way travel time to a known reflector on a radar profile and calculating the propagation velocity by following equation (after Morey, 1974):

$$V = 2D/T \qquad [1]$$

Equation [1] describes the relationship of the average propagation velocity (V) to the depth (D) and two-way pulse travel time (T) to a reflector.

At four observation points within the Canal Bed the depth to the organic/mineral interface was measured. Depths ranged from 3.35 to 6.1 m. A strong ($r = 0.99$) and significant (.001 level of significance) relationship was found between the two-way travel time and the measured depth to the organic/mineral interface. At each observation point, the measured depth (D) and the two-way radar pulse travel time to the organic/mineral interface were used to estimate the velocity of propagation. At the four observation points, the estimated velocity of propagation averaged 0.43 m/ns and ranged from 0.038 to 0.054 m/ns.

At three observation points within the Bergman Bed the depth to the organic/mineral interface was measured. Depths ranged from 0.9 to 2.1 m. A strong ($r = 0.95$) and significant (.001 level of significance) relation was found between the two-way travel time and the measured depth to the organic/mineral interface. At each observation point, the measured depth (D) and the two-way radar pulse travel time to the organic/mineral interface were used to estimate the velocity of propagation. The estimated velocity of propagation averaged 0.44 m/ns and ranged from 0.038 to 0.049 m/ns.

Because of the spatiotemporal variability in propagation velocities, a predictive equation based on depths to the organic/mineral soil interface and the two-way travel times was developed for each GPR survey. The measured depth and the two-way travel time to the organic/mineral soil interface at the sampled observation points were compared. A least square line was fitted to the data for each survey and used to predict the depth to organic/mineral soil interface at all observation points. The relationship is expressed as:

$$D = b + aT \qquad [2]$$

Where D is the depth to the organic/mineral soil interface, T is the two-way travel time to the organic/mineral soil interface reflection, b is the intercept term, and a is the slope of the line.

For the two beds surveyed, using predictive equations, the average difference between the measured and the predicted depth to the organic/mineral soil interface at the seven sampled observation points was 0.19 m with a maximum difference of 0.41 m. Half of the predicted organic/mineral soil interface depths were within 0.04 to 0.31 m of the measured values.

INTERPRETATIONS:

A representative radar profile from Canal Bed is shown in Figure 1. In Figure 1 the depth scale is in meters. The black vertical lines at the top of the radar profile represent equally spaced (10 m) observation points. The vertical scale is exaggerated about 3.5 times. Abrupt and strongly contrasting changes in water content makes the organic/mineral interface distinguishable on this radar profile. In Figure 1, this interface forms a conspicuous reflector and varies in depth from about 1.2 to 5.4 m.

Peat deposits display considerable anisotropy in moisture content, bulk density and often have uneven or sloping layer boundaries (Hanninen, 1992). Differences in moisture contents have allowed some to distinguish layers with differences in degree of humification, bulk density and dielectric permittivity (Hanninen, 1992, Chernetsov et al., 1988, and Tolonen et al., 1982). However, in other surveys, peat layers could not be clearly associated with radar reflections (Worsfold al., 1986, and Remotec Applications Inc., 1982). In Figure 1, weak planar reflectors are evident within the peat. While the more uniform reflections are presumed to represent noise, the more irregular or wavy reflectors suggest layering within the peat (see "B' in Figure 1). A field drain was crossed at "A" and produced echoes on the radar profile.

Often transitional layers composed of both organic and mineral soil materials form at the lower boundary of peat deposits. As these transitional layers have moisture contents that are intermediary between the organic soil materials above and the mineral materials below, they do not produce high amplitude reflections and are therefore more difficult to distinguish. In Figure 1, these features appear in the lower part of each of the three conspicuous concavities.

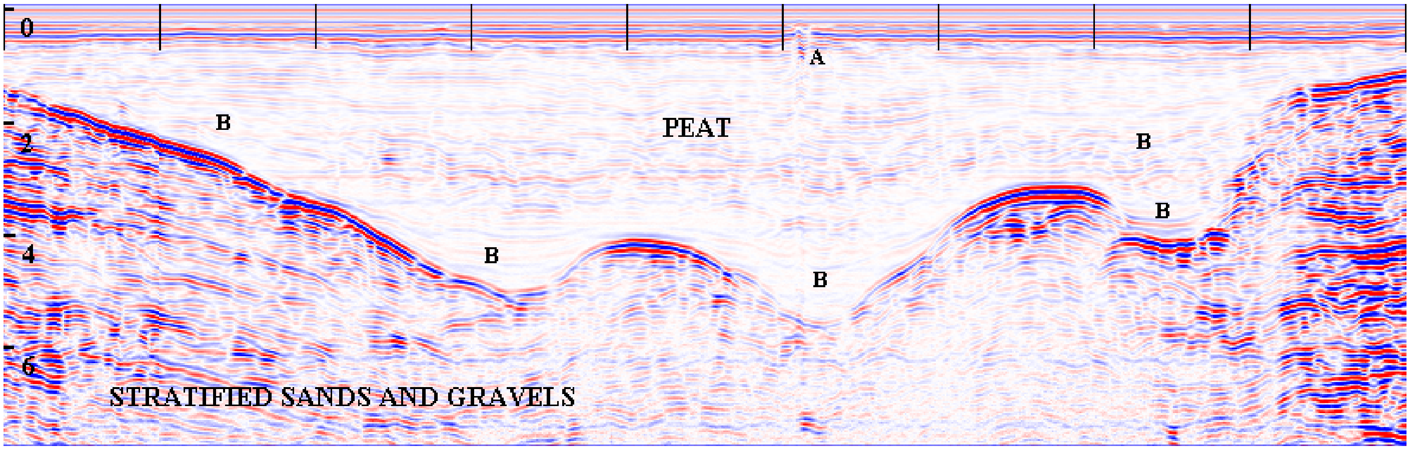

Figure 1. The organic/mineral soil interface is readily discernible and easily traced laterally along a radar profile from Canal Bed. Depth scale is in meters.

RESULTS:

Canal Bed:

One hundred and forty observations were obtained at Canal Bed. Of these, 44 were used to define the perimeter of the bed and were assigned a peat thickness of 0.0 m. Based on 140 observations, the average depth of organic materials is 2.09 m with a range of 0 to 6.32 m. One half of the observations had organic materials that ranged from 0.0 and 3.43 m thick. Thirty-one percent of the observation points had organic soil materials less than 0.4 m thick. Eleven percent of the observation points had organic soil materials between 0.4 and 1.52 m thick and represents Swansea soils. Fifty-eight percent of the observation points had organic materials greater than 1.52 m thick and represents Freetown soils.

Figure 2 is a two-dimensional simulation of Canal Bed based on radar interpretations. The organic materials have filled two kettles that are interconnected by a 3 m deep channel. None of these subsurface features was apparent from visual observations conducted on the soil surface. With the exception of a bench-like area on the northwest side of the cranberry bed, slopes appear relatively steep. The bench-like feature represents a sizeable area of thinner (< 1.5 m) organic soil materials. Although too small to be delineated on soil survey maps, this shelf represents a rather large area of Swansea soil and soils with less than 0.4 m of organic soil materials. The cranberry bed is about 33,127 sq m. The volume of organic soil materials within Canal Bed is 80,682 cubic meters.

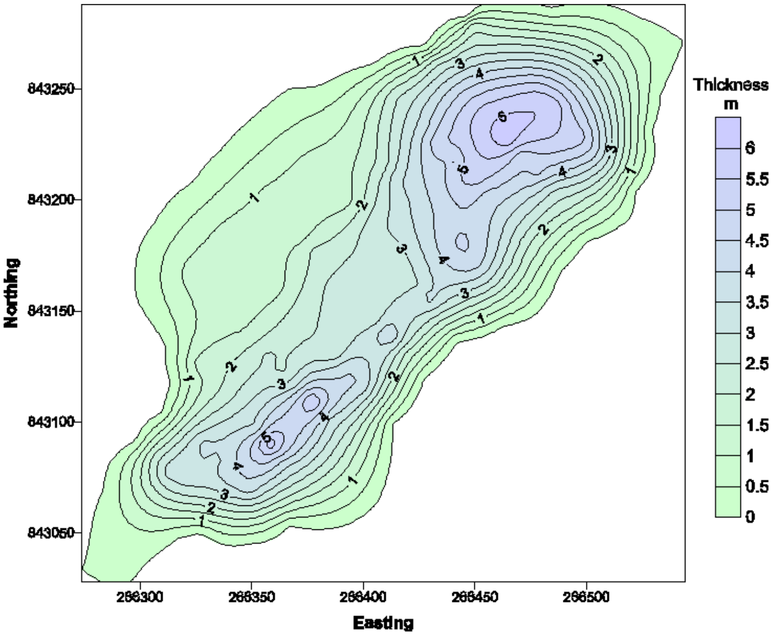

Figure 2. Thickness of organic soil materials within Canal Bed. All scales are in m.

Bergman Bed:
One hundred and three observations were obtained at Bergman Bed. Of these, 32 were used to define the perimeter of the bed and were assigned a peat thickness of 0.0 m. Based on 103 measurements; the average depth of organic soil materials is 0.65 m with a range of 0 to 2.22 m. One half of the observations had between 0.0 and 0.82 m of organic soil materials. Thirty-one percent of the observation points had organic soil materials less than 0.4 m thick. Fifty-three percent of the observation points had organic soil materials between 0.4 and 1.52 m thick and represents Swansea soil. Sixteen percent of the observation points had organic materials greater than 1.52 m thick and represents Freetown soil.

Figure 3 is a two-dimensional simulation of Bergman Bed based on radar interpretations. With the exception of a small kettle in the southeast corner, organic soil materials within this bed are generally less than 1 m thick. Slopes are generally slight. The area of the bed is about 7,978 sq m. The volume of peat within the bed is an estimated 4,287 cubic meters.

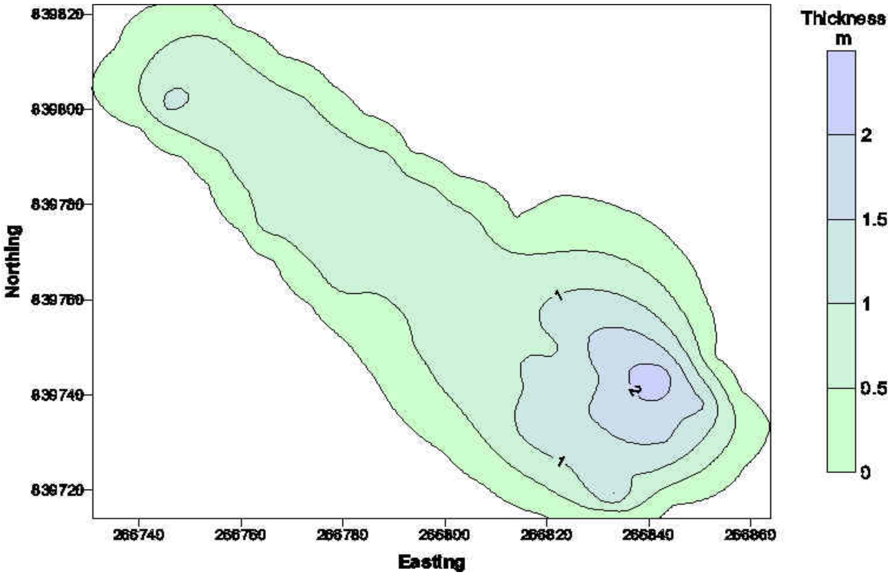

Figure 3. Thickness of organic soil materials within Bergman Bed. All scales are in m.

Figure 4 contains three-dimensional surface net diagrams of the topography of the organic/mineral soil interface within Canal and Bergman beds. While aerial photographs and soil maps provide information on the area of organic soils materials, these tools provide little information on the subsurface geometry or the volume of peat within these beds. Computer simulations based on radar interpretations provide easily understood graphic summaries of the area, volume, and subsurface form of peat deposits. Each plot in Figure 4 provides a unique perspective into the geometry of the peat deposit. These simulations may assist users of this information to better manage or assess the properties of these cranberry beds.

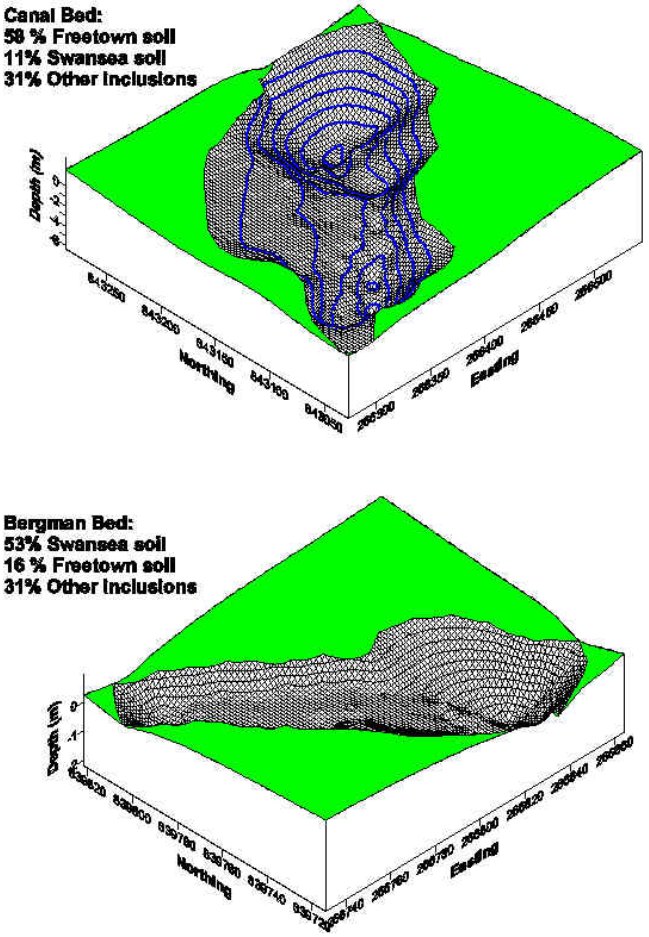

Figure 4. Three-dimensional surface net diagrams of Canal and Bergman beds. All scales are in m.

Alternative methods of displaying data

Although computer simulations based on radar interpretations do provide useful information on the area, volume, and subsurface form of peat deposits, many cranberry growers found these presentations difficult to spatially relate to their beds. As a consequence, Jim Turenne integrated two-dimensional computer graphic images with aerial photograph using ArcView. The remarkable union of these technologies is shown in Figure 5. Growers find the visual imagery more familiar, and easier to comprehend and orientate than the more conventional computer graphic presentations.

An emerging approach to GPR interpretations is the use of three-dimensional visualization of radar data. Under favorable conditions, GPR and 3D imaging can provide new information and perspectives into cranberry beds. Three-dimensional images facilitate the examination of subsurface structures and forms that are impossible to view in the field. The Massachusetts State NRCS Office and the National Soil Survey Center recently purchased RADAN for Windows NT software for the three-dimensional visualization of radar data.

To construct three-dimensional images, a bed is intensively surveyed with parallel GPR traverses (see Figure 5 for location of observation points along parallel GPR traverses). Generally these lines should be closely spaced (0.5 to 1 m apart). However, because of the size of cranberry beds and the lucid and consistent imagery from the organic/mineral soil interface, economy dictates wider spacing of 5 to 30 m. Data from these lines are processed into a three-dimensional image through the RADAN Windows NT software. Once processed, arbitrary cross-sections, insets, and time slices can be quickly viewed and extracted from the three-dimensional data set. The flexibility of three-dimensional visualizations can facilitate the interpretation of spatial relationships and the analysis of subsurface features within cranberry beds. This imaging technique enables users to quickly view the subsurface from nearly any perspective.

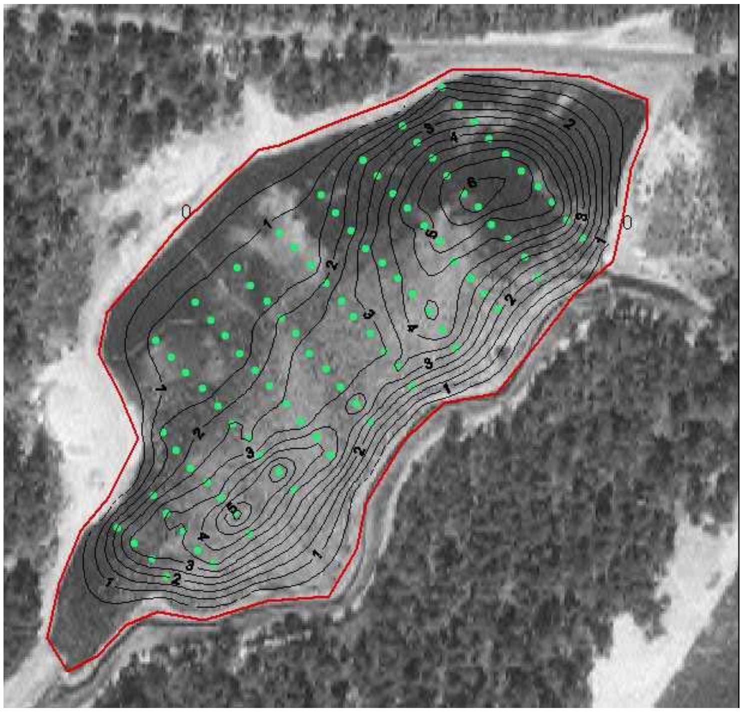

Figure 5. Two-dimensional contour plot of peat thickness overlain on a digitized aerial photograph of Canal Bed. Jim Turenne using ArcView created images.

Figure 6 is a fence diagram of eight parallel radar profiles that were collected in the northern part of Canal Bed. These traverses are each 90 m long. The distance between each traverse is 24 m. Variations in the subsurface topography of the organic/mineral soil interface and the relative locations of the two kettles and channel are clearly shown in this figure. However, because of the comparatively large area covered by Figure 6, much detail has been lost.

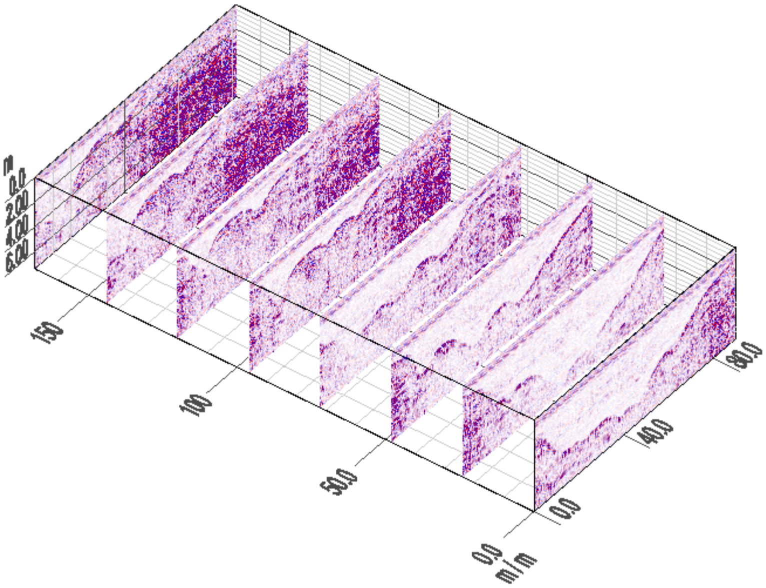

Figure 6. Fence diagram of Canal Bed showing the varied, underlying topography of the organic/mineral soil interface.

Figure 7 is a fence diagram of four parallel radar profiles that were collected in the southern part of Bergman Bed. Only a 60 m segment of each traverse has been shown. In Figure 7, the distances between traverses are 9, 9, and 7 m. Compared with Figure 6, the shallowness and smoother, more uniform slopes of this bed are clearly evident. In Figure 7, reverberated signals from an open drainage ditch are evident near the 20 m mark of each traverse. In the deeper portion of the depression located within the extreme southern part of the bed (lower left-hand corner of plot), two interfaces are apparent. Soil probing revealed the presence of a buried mineral layer that has been sandwiched between thicker layers of organic soil materials. The spatial distribution of this buried mineral soil layer is readily apparent in Figure 7 and can be easily assessed using the RADAN for Windows and 3D QuickDraw for RADAN NT software.

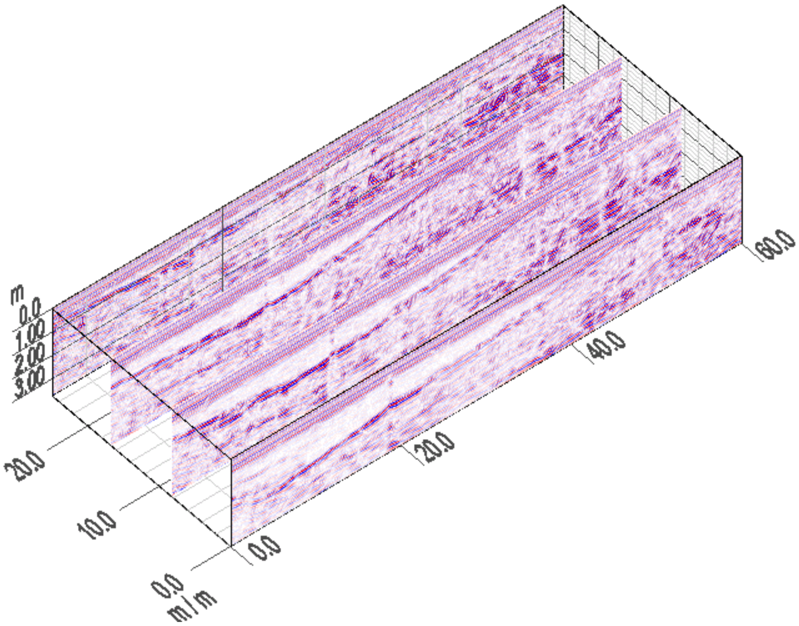

Figure 7. Fence diagram of Bergman Bed showing the more subdued, underlying topography of the organic/mineral soil interface

Figure 8 is an X-Y fence diagram of two intersecting lines that were simulated from radar data collected in the southern part of Bergman Bed. Radar surveys were conducted in directions that paralleled the X-axis. As a consequence, the imagery is more detailed and less generalized than the data that was synthesized in the Y-axis direction.

Figure 9 consists of three solid cubes generated from the same radar data collected at Bergman Bed. All cubes have the same orientation. The lower cube, cube “c” is a solid cube. Cubes “B” and “A” are cutout cubes, each sliced at a depth of 2.6 m. Cubes “B” and “A” have different sub-blocks removed from the cube along different X and Y axes coordinates. The 3D software allows the viewing of data from any angle and the analysis of reflector continuity through cutouts of the cube.

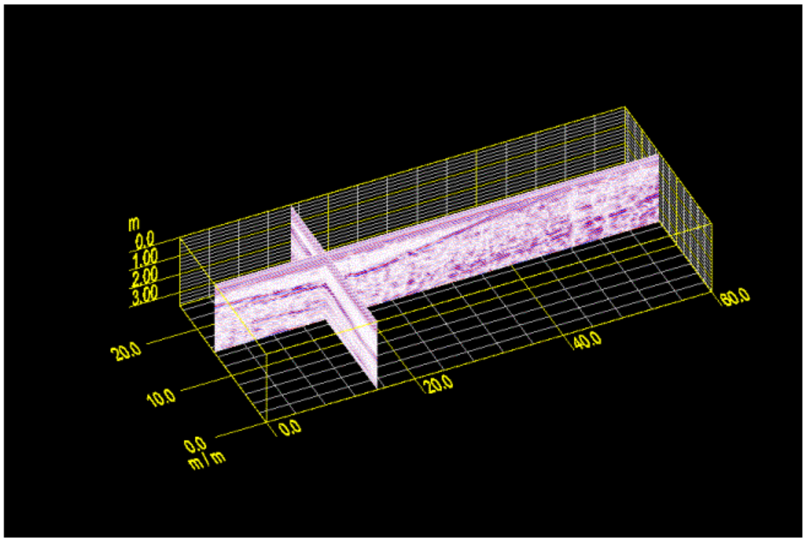

Figure 8. X-Y fence diagram of Bergman Bed showing the subdued, underlying topography of the organic/mineral soil interface along two axes.

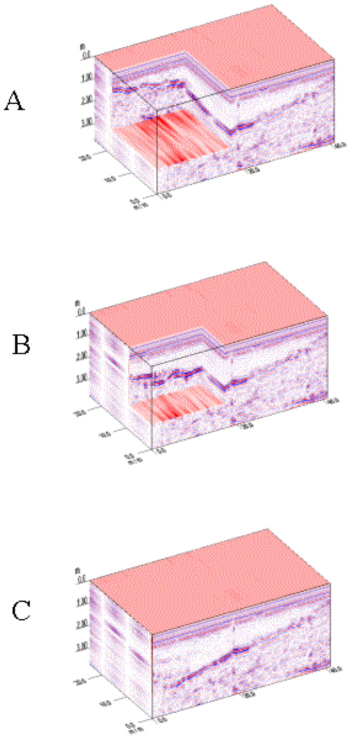

Figure 9. 3D cubes of Bergman Bed showing progressive cube cutouts (C to A) and the underlying form of the organic/mineral soil interface and a buried mineral layer (see B).

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