CHAPTER 6

SOILS, PEATLANDS, AND BIOMONITORING

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Contents

6.1. INTRODUCTION

Soils are three-dimensional (3D) natural bodies consisting of unconsolidated mineral and organic materials that form a continuous blanket over most of the earth's land surface. At all scales of measurements, soils are exceedingly complex and variable in biological, chemical, physical, mineralogical, and electromagnetic properties. These properties influence the propagation velocity, attenuation, and penetration depth of electromagnetic energy, and the effectiveness of ground penetrating radar (GPR). Knowledge of soils and soil properties is therefore useful, and often essential, both in the design and operation of GPR surveys. In this chapter, soil properties that influence the use of GPR are discussed. Ground penetrating radar soil suitability maps are introduced. These maps can aid GPR users who are unfamiliar with soils in assessing the likely penetration depth and relative effectiveness of GPR within project areas. This chapter cites studies that have used GPR to investigate soils. Also discussed are the uses of GPR to measure root biomass, distribution and architecture, and detect internal defects in trees.

6.2. Soils

6.2.1. Soil properties that affect the performance of ground penetrating radar

The resolution and penetration depth of GPR are determined by antenna frequency and the electrical properties of earthen materials (Olhoeft, 1998; Daniels, 2004). Because of high rates of signal attenuation, penetration depths are greatly reduced in soils that have high electrical conductivity. The electrical conductivity of soils increases with increasing water, soluble salt, and/or clay contents (McNeill, 1980). These soil properties determine electrical charge transport and storage (Olhoeft, 1998). In soils, the most significant conduction-based energy losses are due to ionic charge transport in the soil solution and electrochemical processes associated with cations on clay minerals (Neal, 2004). These losses can seriously impact the performance of GPR (Campbell, 1990; Olhoeft, 1998).

Electrical conductivity is directly related to the amount, distribution, chemistry, and phase (liquid, solid, or gas) of the soil water (McNeill, 1980). Electrical conductivity, dielectric permittivity, and energy dissipation increase with increasing soil water content (Campbell, 1990; Daniels, 2004). Water is a polar molecule. When an alternating electrical field is applied to the soil, water molecules experience a force that acts to align their permanent dipole moments parallel to the direction of the applied electrical field (Daniels, 2004). The small displacement of bound water molecules results in the loss of some energy as heat (Neal, 2004). Polarization processes result in the storage of some electrical field energy and dielectric relaxation losses. At frequencies above 500 MHz, the absorption of energy by water is the principal loss mechanism in soils (Daniels, 2004). Even under very dry conditions, capillary-retained water is sufficient to influence electrical conductivity and energy loss.

Electrical conductivity and energy loss are also affected by the amount of salts in the soil solution (Curtis, 2001). All soil solutions contain some salts, which increase the conductivity of the electrolyte. In general, soluble salts are leached to a greater degree from soils in humid than in semiarid and arid regions. In semiarid and arid regions, soluble salts of potassium and sodium, and less soluble carbonates of calcium and magnesium are more likely to accumulate in the upper part of soils. These salts increase the electrical conductivity of the soil solution and consequent attenuation of electromagnetic energy (Doolittle and Collins, 1995). Because of their high electrical conductivity, saline (electrical conductivity > 4 dS/m) and sodic (sodium absorption ratio ≥ 13) soils are considered unsuited to most GPR applications. In these soils, effective GPR penetration is usually restricted to the surface layers and depth of less than 25 cm.

Calcareous and gypsiferous soils mostly occur in base-rich, alkaline environments in semiarid and arid regions. These soils are characterized by layers with secondary accumulations of calcium carbonate and calcium sulfate, respectively. High concentrations of calcium carbonate and/or calcium sulfate imply less-intense leaching, prevalence of other soluble salts, greater quantities of inherited minerals from parent rock, and accumulations of specific mineral products of weathering (Jackson, 1959).

Typically, soils with higher calcium carbonate contents have higher dielectric permittivity (Lebron et al., 2004). Grant and Schultz (1994) observed a reduction in the depth of GPR penetration in soils that have high concentrations of calcium carbonate.

The electrical conductivity of soils is governed by the amount of clay particles (particles <0.002 mm in diameter) and the types of clay minerals present (McNeill, 1980). Clay particles have greater surface areas and can hold more water than the silt (particles 0.002–0.05 mm in diameter) and sand (particles 0.05–2.0 mm in diameter) fractions at moderate and high water tensions. Because of isomorphic substitution, clays minerals have a net negative charge. To maintain electrical neutrality, exchangeable cations occupy the surfaces of clay particles and contribute to energy losses (Saarenketo, 1998). These cations concentrate in the *diffuse double layer* that surrounds clay minerals and provide an alternative pathway for electrical conduction. Surface conduction is directly related to the amount of clay particles in the soil and the concentration and mobility of the adsorbed cations on the clay particles (Shainberg et al., 1980). In general, the contribution of clay particles and surface conduction to electrical conductivity and energy loss is more evident in soils that have low rather than high salt concentrations (Klein and Santamarina, 2003).

Because of their high adsorptive capacity for water and exchangeable cations, clays increase the dissipation of electromagnetic energy. As a consequence, the penetration depth of GPR is inversely related to clay content. Olhoeft (1986), using a 100-MHz antenna, observed a penetration depth of about 30 m in some clay-free sands. However, with the addition of only 5% clay (by weight), the penetration depth was reduced by a factor of 20 (Olhoeft, 1986). Doolittle and Collins (1998) noted that depending on antenna frequency and the specific conductance of the soil solution, penetration depths range from 5 to 30 m in dry, sandy (>70% sand and <15% clay) soils, but average only 50 cm in wet, clayey (>35% clay) soils.

Soils contain various proportions of different clay minerals (e.g., members of kaolin, mica, chlorite, vermiculite and smectite groups). The size, surface area, cation-exchange capacity (CEC), and water-holding capacity of clay minerals vary greatly. Variations in electrical conductivity are attributed to differences in CEC associated with different clay minerals (Saarenketo, 1998). Electrical conductivity and energy loss increase with increasing CEC (Saarenketo, 1998). Soils with clay fractions dominated by high CEC clays (e.g., smectitic and vermiculitic soil mineralogy classes) are more attenuating to GPR than soils with an equivalent percentage of low CEC clays (e.g., kaolinitic, gibbsitic, and halloysitic soil mineralogy classes). Soils classified as belonging to the kaolinitic, gibbsitic, and halloysitic mineralogy classes characteristically have low CEC and low base saturation. As a general rule, for soils with comparable clay and moisture contents, greater depths of penetration can be achieved in highly weathered soils of tropical and subtropical regions than in soils of temperate regions.

6.2.2. Soil suitability maps for ground penetrating radar

Increasingly, GPR is being used in agronomic, archaeological, engineering, environmental, crime scene, and soil investigations. A common concern of GPR users is whether or not the radar will be able to achieve the desired depth of penetration. Ground penetrating radar is highly suited to most applications in dry sands, where penetration depths can exceed 50 m with low-frequency antennas (Smith and Jol, 1995). However, a thin, conductive soil horizon or layer will cause high rates of signal attenuation, severely restricting penetration depths and limiting the suitability of GPR for a large number of applications. In saline and sodic soils, where penetration depths are typically less than 25 cm (Daniels, 2004), GPR is an inappropriate tool. In wet clays, where penetration depths are typically less than 1 m (Doolittle et al., 2002), GPR has a very low potential for many applications.

Knowledge of soils and soil properties is important for the effective use of GPR. Most radar users have limited knowledge of soils and are unable to foretell the relative suitability of soils for GPR within project areas. Soil survey reports and databases provide information on soil properties that affect GPR and are available for most areas of the United States. Hubbard et al. (1990) developed a GPR suitability map for the state of Georgia based on information contained in published soil survey reports. Collins (1992) used the US soil taxonomic classification system to create GPR suitability maps based on properties within the upper 2 m of soils. Doolittle et al. (2002, 2003, 2007) developed and later revised a thematic map, the *Ground Penetrating Radar Soil Suitability Map of the Conterminous United States* (GSSM-USA) (Figure 6.1), which shows the relative suitability of soils for GPR applications. The *GSSM-USA* is based on field observations made throughout the United States and soil attribute data contained in the USDA-Natural Resources Conservation Service (NRCS) State Soil Geographic (STATSGO) database. The STATSGO database was developed by the USDA-NRCS for broad land use planning encompassing state, multi-state, and regional areas (National Soil Survey Center, 1994). The STATSGO database consists of digital map data, attribute data, and Federal Geographic Data Committee compliant metadata. The database is linked to soil interpretation records that contain data on the physical and chemical properties of about 18,000 different soils.

The lack of adequate data on soil moisture and the high spatial and temporal variations in the degree of soil wetness precluded the use of moisture content in the preparation of this map. As a consequence, properties selected to prepare the *GSSM-USA* principally reflect variations in the clay and soluble salt contents of soils. Attribute data used to determine the suitability indices of soils include taxonomic criteria, clay content and mineralogy, electrical conductivity, sodium absorption ratio, and calcium carbonate and calcium sulfate contents. Each soil attribute was rated and assigned an index value ranging from 1 to 6. Lower attribute index values are associated with lower rates of signal attenuation, greater penetration depths, and soil properties that are characteristically more suited to GPR. For each soil attribute, the most limiting (maximum) index value within depths of 1.0 or 1.25 m was selected. These limiting soil attribute indices were summed for each soil. For each soil map unit, the relative proportions of soils with the same index values were summed. The dominant index value (value with the most extensive representative area in each map unit) is selected as the GPR suitability index for each soil map unit. The dominant suitability index for each soil map unit is joined to the map unit identifiers in the digital map for classification and visualization.

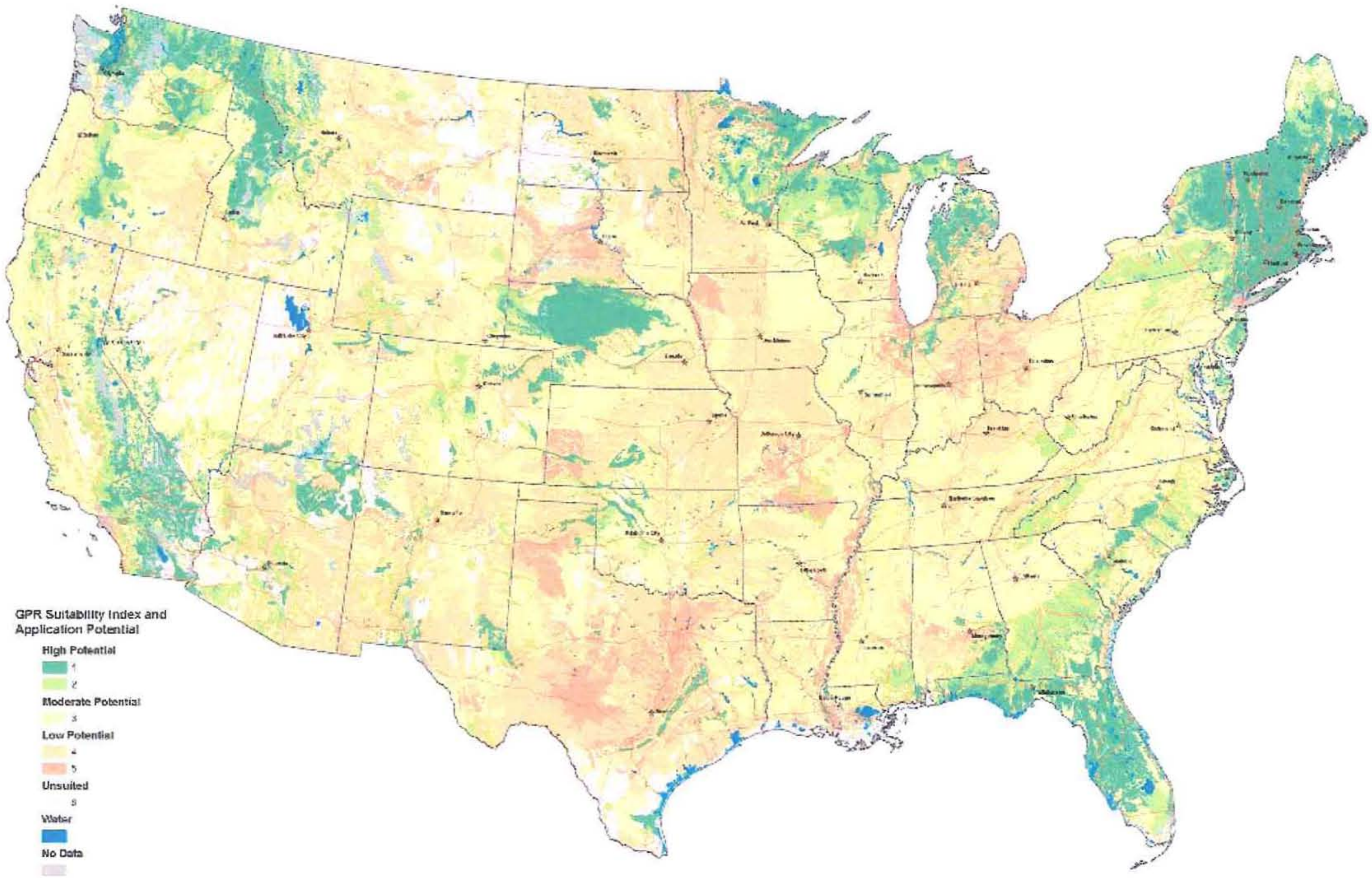

Figure 6.1 The *Ground Penetrating Radar Soil Suitability Map of the Conterminous United States* (GSSM-USA) is based on data contained in the state soil geographic (STATSGO) database.

Soil attribute index values and relative soil suitability indices are based on observed responses from antennas with center frequencies between 100 and 200 MHz. For mineral soils, the inferred suitability indices are based on unsaturated conditions and the absence of contrasting materials within depths of 1 m. Penetration depths and the relative suitability of mineral soils will be less under saturated conditions.

The *GSSM-USA* provides an indication of the relative suitability of soils to GPR within broadly defined soil and physiographic areas of the conterminous United States. Within any broadly defined area, the actual performance of GPR will depend on the local soil properties, the type of application, and the characteristics of the subsurface target. Because of the small compilation scale (1:250,000) of the *GSSM-USA*, the minimum polygon size is about 625 ha. As a consequence of this small map scale, field soil data have been generalized and much spatial information omitted.

Ground penetrating radar users would benefit from larger-scale, less-generalized maps, which show in greater detail the spatial distribution of soil properties that influence the penetration depth of GPR. Larger-scale GPR soil suitability maps have been prepared on a state basis using the Soil Survey Geographic (SSURGO) database (Doolittle et al., 2006). The SSURGO database contains the most detailed level of soil geographic data developed by the USDA-NRCS (1995). Base maps are USGS 7.5-min topographic quadrangles and 1:12,000 or 1:24,000 orthophotoquads. Soil maps in the SSURGO database duplicate the original soil survey maps, which were prepared at scales ranging from 1:12,000 to 1:63,360 (minimum delineation size ranging from about 0.6 to 16.2 ha, respectively) (Soil Survey Staff, 1993). The same soil properties attribute index values, and processing programs used to prepare the *GSSM-USA* are used with the SSURGO database to produce these larger-scale state maps.

An example of a state GPR soil suitability map, the *Ground Penetrating Radar Soil Suitability Map of Wisconsin* (*GSSM-WI*), is shown in Figure 6.2. The *GSSM-WI* was prepared at a display scale of 1:700,000. Compared with the *GSSM-USA* (see Figure 6.1), information contained on the *GSSM-WI* (see Figure 6.2) is less generalized, soil patterns are more intricate, and soil polygons are shown in greater detail. Broad spatial patterns, which correspond to major soil and physiographic units within Wisconsin, are evident on both thematic maps (see Figures 6.1 and 6.2). However, the *GSSM-WI* provides a more detailed overview of the spatial distribution of soil properties that influence the depth of penetration and effectiveness of GPR. As soil delineations are not homogenous and contain dissimilar inclusions, on-site investigations are needed to confirm the suitability of each soil polygon for different GPR applications. The spatial information contained on GPR soil suitability maps can aid investigators who are unfamiliar with soils in assessing the likely penetration depth and relative effectiveness of GPR within project areas. In addition, these maps can help radar users evaluate the relative appropriateness of using GPR, select the most suitable antennas and survey procedures, and assess the need and level of data processing. Ground penetrating radar soil suitability maps are available for most states and can be accessed at http://soils.usda.gov/survey/geography/maps/GPR/index.html. These maps are periodically updated as additional areas are surveyed and soil information is collected and certified.

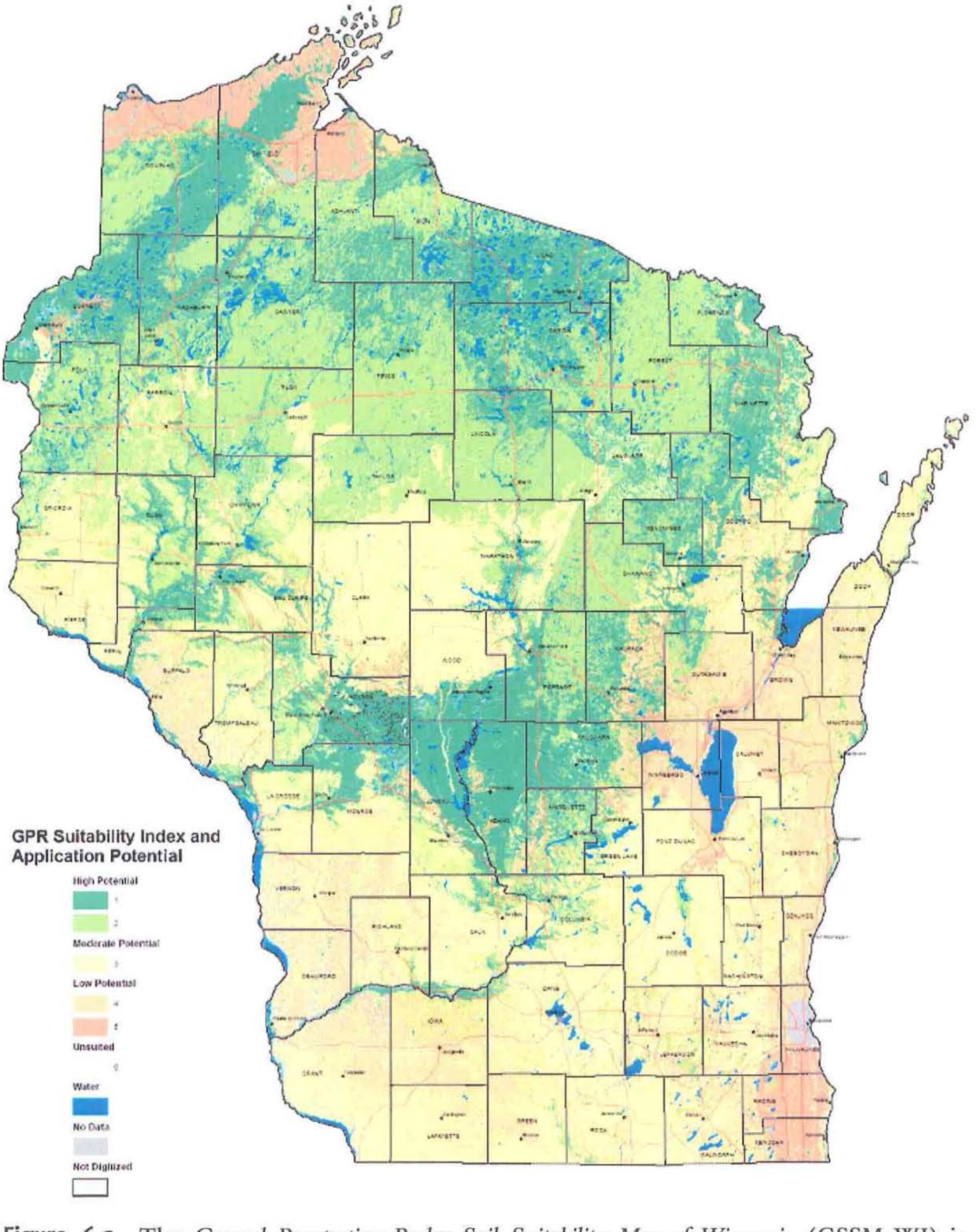

Figure 6.2 The *Ground Penetrating Radar Soil Suitability Map of Wisconsin* (GSSM-WI) is based on data contained in the Soil Survey Geographic (SSURGO) database.

6.2.3. Ground penetrating data and soil surveys

Soil surveys are the "systematic examination, description, classification, and mapping of soils" (Soil Science Society of America, 2001). The nature, composition, and boundaries of soil polygons that appear on soil maps were inferred by soil scientists from a limited number of point observations made with augers, probes, and shovels. Soil mapping is a slow and labor-intensive process. As a consequence, observations are generally sparse and a very large portion of the soil continuum below the surface is not observed. Constrained by limited exposures and burdened by partial or detached information, inferences on the nature and properties of soils must be extended across the more expansive areas between observation points. Because of these limitations, alternative methods are being explored to complement traditional soil survey techniques, provide more comprehensive coverage, and improve the assessment of soil properties. To be effective, these methods must be relatively fast, accurate, and inexpensive. Different geophysical tools are being used to characterize soil properties and variability at different scales and level of resolutions. Ground penetrating radar has been used to help characterize the soil continuum and support soil survey investigations.

Since the late 1970s, GPR has been used as a quality control tool for soil surveys in the United States. In 1979, the use of GPR for soil surveys was successfully demonstrated in Florida (Benson and Glaccum, 1979; Johnson et al., 1979). Because of the ubiquity of sandy soils with favorable characteristics and contrasting soil horizons, GPR has been extensively used to update soil surveys in Florida (Schellentrager et al., 1988).

In the United States, mineral soils are typically observed, described, and classified to a depth of 2 m or to bedrock (if within depths of 2 m) (Soil Survey Staff, 1999). Ground penetrating radar is principally used by soil scientists as a quality control tool to verify the taxonomic composition of soil map units, document the presence and depth to diagnostic soil horizons and features, and assess spatial and temporal variations in soil properties.

For most GPR soil investigations, a transect line or a small grid is established across a representative soil area. Typically, reference points are located at uniform intervals along transect or grid lines. The interval between reference points varies with the purpose of the survey and the anticipated variability of soil features under investigation but typically ranges from 0.5 to 15 m. A suitable radar antenna is towed or dragged along these lines. After reviewing the radar record in the field, soils are observed and described at selected reference points to verify GPR depth measurements and interpretations. Based on these observations, diagnostic subsurface horizons, contrasting layers, and/or soil features are identified and traced laterally across the radar record. The presence and depth to diagnostic subsurface horizons or soil features is used to determine the taxonomic classification and name of the soil at each reference point.

The most commonly used antennas for soil investigations have center frequencies between 100 and 500 MHz. Higher-frequency (400–500 MHz) antennas often provide more satisfactory results in relatively dry, electrically resistive soils. In highly attenuating soils, where the depth of penetration is very limited, these higher-frequency antennas often provide comparable depths and greater resolution than lower-frequency antennas. Antennas with frequencies of 900 MHz–1.5 GHz have been used for some shallow investigations in sandy soils. For organic soils, where greater depths of penetration are often needed, lower-frequency (70–200 MHz) antennas are commonly used.

Ground penetrating radar has been effectively used to provide data on the presence, depth, lateral extent, and variability of diagnostic subsurface horizons that are used to classify soils (Collins et al., 1986; Doolittle, 1987; Schellentrager et al., 1988; Puckett et al., 1990). Provided soil conditions are suitable, GPR is used to determine the depth to contrasting master (B, C, and R) subsurface horizons. Other soil horizons and layers (e.g., buried genetic horizons, dense root-restricting layers, frozen soil layers, illuvial accumulations of organic matter, and cemented or indurated horizons) have also been identified with GPR. Ground penetrating radar does not image subtle changes in soil properties (e.g., color, mottles, structure, porosity, and slight changes in texture), transitional horizons (e.g., AB, AC, BC), or vertical divisions in master horizons.

Radar interpretations provide fairly accurate measurements of the depth and thickness of some soil horizons. Johnson et al. (1979), working in sandy soils with well-expressed horizons, observed that radar-interpreted depths were within $\pm$2.5–5.0 cm of the measured depths. Asmussen et al. (1986) observed an average difference of 19.2 cm between the interpreted and measured depths to argillic (Bt) horizons, which ranged in depth from approximately 20 to 450 cm. Rebertus et al. (1989) observed that the difference between the interpreted and measured depths to a discontinuity, which ranged in depth from 0 to about 230 cm, was less than 15 cm in 94% of the observations. Collins et al. (1989) observed an average difference of 6 cm between the interpreted and measured depths to bedrock, which ranged in depth from about 80 to 240 cm.

Typically, strong radar reflections (high-amplitude reflections) are produced by soil interfaces that have abrupt boundaries and separate contrasting soil materials. These interfaces often correspond to boundaries that separate soil horizons. Contrast between soil horizons is often associated with differences in moisture contents, physical (texture and bulk density), and/or chemical (organic carbon, calcium carbonate, and sesquioxides) properties. Ground penetrating radar has been used to estimate the depth to argillic (Asmussen et al., 1986; Collins and Doolittle, 1987; Doolittle, 1987; Truman et al., 1988; Doolittle and Asmussen, 1992), spodic (Collins and Doolittle, 1987; Doolittle, 1987; Burgoa et al., 1991), and placic (Lapen et al., 1996) horizons. These horizons generally have well-defined upper boundaries that display abrupt increases in bulk density and illuviated silicate clays (argillic horizon), humus and free sesquioxides (spodic horizon), or cemented Fe, Mn, or Fe–humus complexes (placic horizon). Ground penetrating radar has also been used to determine the thickness of albic horizons and chart the depth, lateral extent, and continuity of duripans, petrocalcic, and petroferric horizons (Doolittle et al., 2005), fragipans (Olson and Doolittle, 1985; Lyons et al., 1988; Doolittle et al., 2000), ortstein (Mokma et al., 1990a), and traffic pans (Raper et al., 1990). Duripans, petrocalcic, and petroferric horizons are indurated (primarily cemented with secondary SiO_2, $CaCO_3$, and, Fe_2O_3, respectively). Fragipans and traffic pans have higher bulk densities and are less permeable than overlying or underlying horizons. Ortstein is a cemented spodic horizon. Ground penetrating radar has been used to infer distinct changes in soil color associated with abrupt and contrasting changes in organic carbon contents (Collins and Doolittle, 1987). Ground penetrating radar has also been used to infer the concentration of lamellae (Farrish

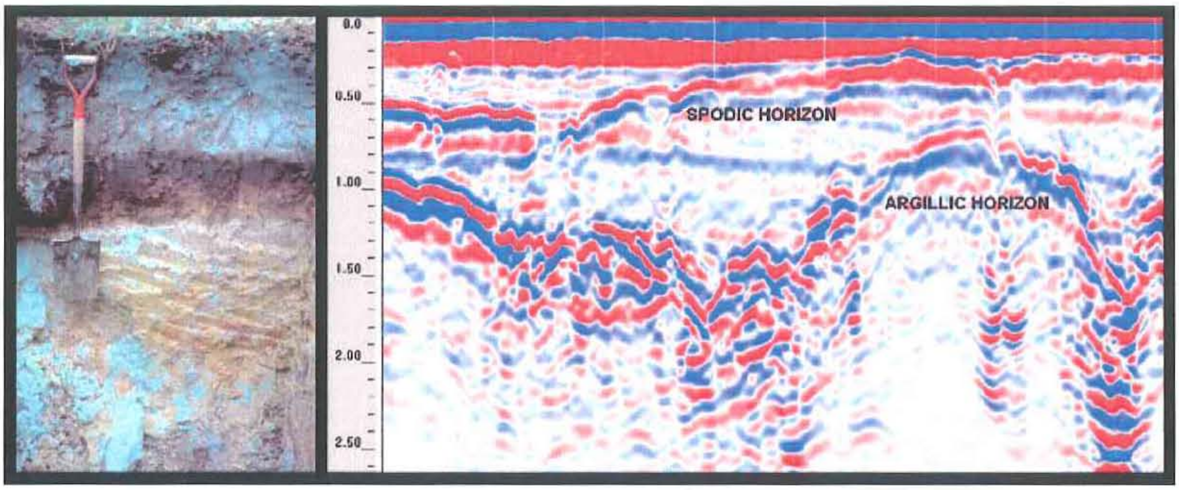

Figure 6.3 The spodic and argillic horizons of Pomona soil are well expressed in this picture and radar record from north-central Florida. (Picture of soil profile is courtesy of Dr. Mary Collins, University of Florida.)

et al., 1990; Mokma et al., 1990b; Tomer et al., 1996) and plinthite (Doolittle et al., 2005) in soils. In areas of permafrost, GPR has been used to estimate the thickness of active layers (Doolittle et al., 1990b).

Figure 6.3 shows a soil profile and radar record from an area of Pomona soil (sandy, siliceous, hyperthermic Ultic Alaquods) in north-central Florida. The Pomona soil formed in sandy overlying loamy (10 to 27 percent clay) marine sediments on the Lower Coastal Plain. The shovel in the picture of the soil profile (left) is about 90 cm in length. The depth scale on the radar record (right) is in meters. The white vertical lines at the top of the radar record represent equally spaced (3 m) reference points. The upper boundaries of the spodic and argillic horizons are abrupt and separate contrasting soil materials and therefore produce high-amplitude reflections. The spodic horizon is the dark subsurface horizon in the upper part of the soil profile (midway along the shovel handle). Spodic horizons are illuvial layers of active amorphous materials composed of organic matter and aluminum, sometimes with iron (Soil Survey Staff, 1999). Because of differences in their bulk density and water retention capacity, spodic horizons are detectable with GPR. On the radar record, the spodic horizon provides a continuous reflection that varies in depth from about 20 to 60 cm.

On the soil profile (see Figure 6.3), the argillic horizon appears as a grayish colored, subsurface horizon with an irregular upper boundary near the base of the shovel blade. Argillic horizons are illuvial layers that contain significant accumulations of silicate clay (Soil Survey Staff, 1999). Because of abrupt and substantial increases in clay content and bulk density, the upper boundary of argillic horizons is usually detectable with GPR. On the radar record (see Figure 6.3), the upper boundary of the argillic horizon is highly irregular and varies in depth from about 60 to 160 cm. Generally, argillic horizons provide smooth, continuous reflectors that occur at more uniform depths. The irregularly upper boundary of the argillic horizon is attributed to underlying dissolution features that are associated with karst.

Figure 6.4 contains a soil profile and radar record from an area of Enfield soil (coarse–silty over sandy or sandy-skeletal, mixed, active, mesic Typic Dystrudepts)

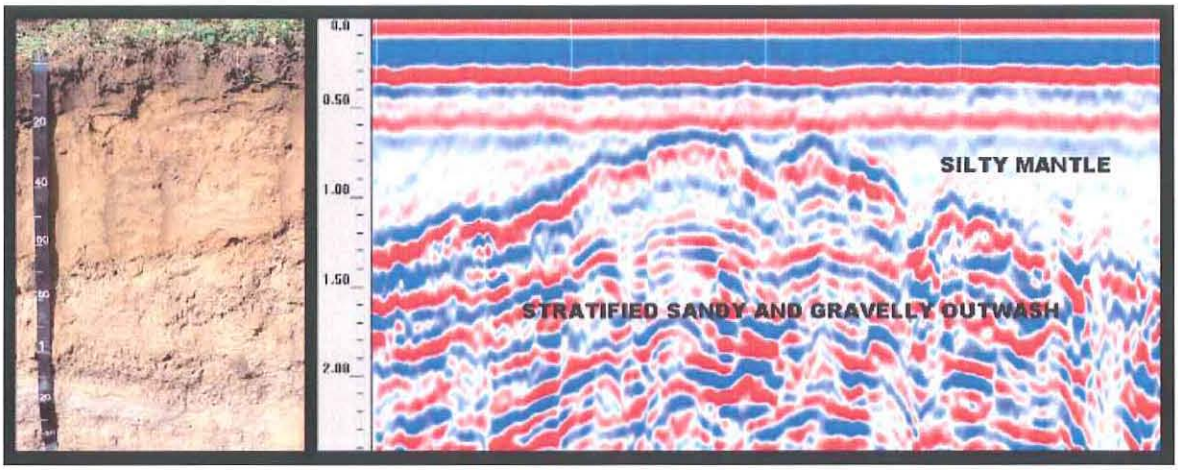

Figure 6.4 A discontinuity separating a loamy eolian mantle from sandy glacial outwash is evident in this picture and radar record from southern Rhode Island. (Picture of soil profile is courtesy of Jim Turenne USDA-NRCS.)

in southern Rhode Island. The depth scales are in centimeters on the soil profile (left) and meters on the radar record (right). The white vertical lines at the top of the radar record represent equally spaced (3 m) reference points. In both the soil profile and the radar record, an abrupt and contrasting *discontinuity* separates the loamy eolian mantle from the underlying sandy outwash. Discontinuities represent contrasting soil materials. Soil materials on both sides of this discontinuity differ substantially in particle size distribution, bulk density, pore size distribution, and mineralogy. On the radar record shown in Figure 6.4, the discontinuity affords an easily identified, high-amplitude reflector that ranges in depth from about 70 to 140 cm. Linear reflectors in the materials underlying the discontinuity helped to confirm that the substratum consists of glacial outwash rather than till. Tills represent unsorted and unstratified materials deposited by glacial ice. Typically, on radar records, tills display chaotic graphic signatures characterized by an abundance of point reflectors from cobbles and boulders and the absence of linear reflectors, which would suggest layering and the flow of water. Other than parallel bands of reverberated signals, the eolian mantle is relatively free of reflectors.

In many upland areas, it is difficult to excavate and examine soil profiles and determine the depths to bedrock. Rock fragments and irregular or weathered bedrock surfaces limit the effectiveness of conventional probing techniques. Ground penetrating radar has been used extensively to chart the depths to bedrock (Collins et al., 1989; Davis and Annan, 1989), changes in rock type (Davis and Annan, 1989), characterize internal bedding, cleavage and fracture planes (Holloway and Mugford, 1990; Stevens et al., 1995; Toshioka et al., 1995; Lane et al., 2000; Grasmueck et al., 2004; Nascimento da Silva et al., 2004; Porsani et al., 2005), and cavities, sinkholes, and fractures in limestone (Barr, 1993; Pipan et al., 2000; Al-fares et al., 2002).

In many upland soils, GPR is more reliable and effective than traditional soil-surveying tools for determining the depth to bedrock and the composition of soil map units based on soil depth criteria (Collins et al., 1989; Schellentrager and

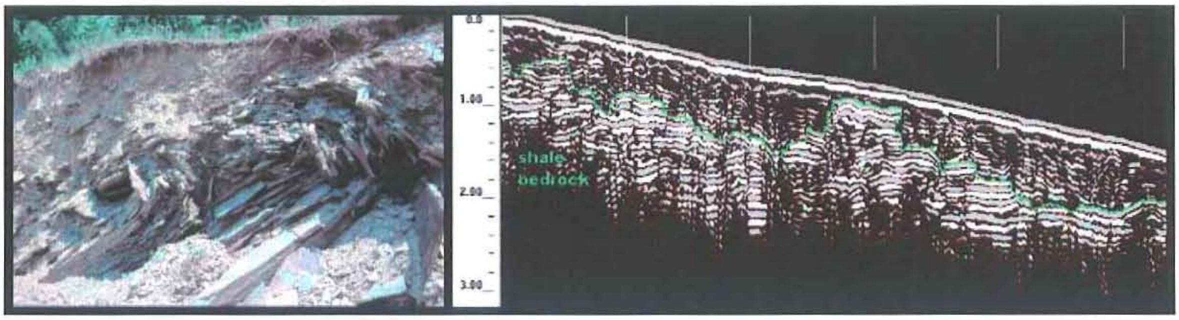

Figure 6.5 The irregular topography of the soil/bedrock interface can be traced laterally on this picture and radar record from an area of Berks and Weikert soils in central Pennsylvania.

Doolittle, 1991). The soil/bedrock interface often provides an abrupt and well-expressed, easily identifiable reflector on radar records. Often, this interface provides smooth, continuous, and high-amplitude reflections. However, the soil/bedrock interface is not always easy to identify on radar records. Coarse fragments in the overlying soil, irregular bedrock surfaces, fracturing, and the presence of saprolite make the identification of the soil/bedrock interface more ambiguous on some radar records.

Figure 6.5 shows a soil profile and a radar record from an area of Weikert and Berks soils (loamy-skeletal, mixed, active, mesic Lithic and Typic Dystrudepts, respectively) in central Pennsylvania. The depth scales is about 3 m. The white vertical lines at the top of the radar record represent equally spaced (3 m) reference points. Weikert and Berks soils are shallow (0–50 cm) and moderately deep (50–100 cm) to shale bedrock, respectively. On the picture of the soil exposure, the shale bedrock appears highly fractured with noticeably inclined, twisted, and convoluted bedding and fracture planes. On the radar record, a green-colored line has been used to identify the interpreted soil/bedrock interface. This interface is highly irregular and segmented. Because of the lack of a single, well-expressed, continuous, high-amplitude reflection, the picking of the soil/bedrock interface is unclear on this radar record, and the accuracy of interpreted soil depth measurements is lessened.

Ground penetrating radar has also been used by soil scientists and geomorphologists to improve soil–landscape models and soil map unit design on glacial-scoured uplands (Doolittle et al., 1988), wetland catena (Lapen et al., 1996), and coastal plain sediments (Rebertus et al., 1989; Puckett et al., 1990). Recent advancements in processing technologies have facilitated the manipulation of large datasets and the creation of 3D radar images. These displays can provide unique perspectives into the subsurface but have been infrequently used in soil–landscape investigations.

6.2.4. Uses of ground penetrating radar in organic soils and peatlands

Peatlands occupy an estimated area of $3.46 \times 10^6\,km^2$ and comprise more than 50% of the global wetlands (Bridgham et al., 2001). Within the United States, peatlands cover an estimated area of $231{,}781\,km^2$ (Bridgham et al., 2001). Globally, peatlands represent a significant soil carbon reserve and methane reservoir. Once avoided or overlooked, today many peatlands are managed to meet increasing agricultural, mining, and urban needs (Johnson and Worley, 1985). A prerequisite for the effective use and management of these peatlands is knowledge of the thickness, distribution, and volume of peat. Ground penetrating radar has been used to inventory and map peatlands. Compared to traditional surveying methods, GPR is faster and requires significantly less time and effort to obtain similar information on the thickness, volume, and geometry of peatlands (Jol and Smith, 1995).

Ground penetrating radar can provide information on the depth and geometry of organic deposits at a level of detail and accuracy that is comparable to information obtained with manual methods (Ulriksen, 1980). In a comparative study with traditional methods, Ulriksen (1982) found GPR to be a more efficient tool for estimating the thickness and characterizing the subsurface topography of organic deposits. Ground penetrating radar has been used to estimate the thickness and volume of organic deposits (Ulriksen, 1982; Shih and Doolittle, 1984; Tolonen et al., 1984; Collins et al., 1986; Worsfold et al., 1986; Welsby, 1988; Doolittle et al., 1990a; Pelletier et al., 1991; Hanninen, 1992; Turenne et al., 2006), to distinguish layers having differences in degree of humification and volumetric water content (Ulriksen, 1982; Tolonen et al., 1984; Worsfold et al., 1986; Chernetsov et al., 1988; Theimer et al., 1994; Lapen et al., 1996), and to classify organic soils (Collins et al., 1986). Lowe (1985) used GPR to assess the amount of logs and stumps buried in peatlands. Holden et al. (2002) used GPR to locate subsurface piping in organic deposits. Ground penetrating radar has also been used to provide information for the placement of roads, pipelines, and dikes on peatlands (Ulriksen, 1982; Saarenketo et al., 1992; Jol and Smith, 1995). Moorman et al. (2003) discussed GPR surveys of peatlands located in areas of permafrost. Ground penetrating radar has also been used in peatlands to characterize subsurface deposits and look for communalities in substrate formations and sequences, which may be used for their hydrologic classification.

Although profiling depths as great as 8–10 m have been reported in some peatlands (Ulriksen, 1980; Worsfold et al., 1986), GPR does not provide similar results on all organic soils. In organic soils, the penetration depth and resolution of subsurface features is limited by the specific conductivity and the concentration of solutes in the pore water (Theimer et al., 1994). In general, penetration depths are greater in ombrogenous bogs than in minerogenous fens (Malterer and Doolittle, 1984). Ombrogenous bogs receive inputs only from precipitation and therefore have lower pH and basic cation (Ca, Mg, Na, and K) contents. Minerogenous fens receive significant inputs from groundwater and/or overland runoff, which contain varying amounts of soluble salts. As a consequence, the groundwater in minerogenous fens often has higher ionic conductivity and pH than the groundwater in ombrogenous bogs (Bridgham et al., 2001). Ground penetrating radar is more effective in acidic, low-nutrient peatlands than in alkaline, high-nutrient peatlands. However, because of variations in the specific conductivity of the groundwater, wide ranges in minerotrophy exist (Bridgham et al., 2001).

Organic soils that are classified as *sulfidic* or *halic* are unsuited to GPR. Typically, these organic soils form in coastal marshes that are inundated by brackish waters and are either enriched with acid sulfates (*sulfidic*) or salt (*halic*) (Soil Survey Staff, 1999).

The high salinities and ionic solute levels in these fens rapidly absorb the radar's electromagnetic energy and restrict observation depths to less than 0.5 m.

Organic deposits often display considerable anisotropy in moisture content and bulk density. Differences in moisture contents have allowed some to distinguish organic layers that are different in degree of humification, bulk density, and dielectric permittivity (Tolonen et al., 1982; Chernetsov et al., 1988; Hanninen, 1992; Nobes and Warner, 1992; Theimer et al., 1994). Some peatlands consist of organic layers that are interstratified with mineral soil layers. These mineral layers may have high clay contents that rapidly attenuate the radar's energy and limit penetration depths.

Lower-frequency (<200 MHz) antennas are typically used to profile peatlands. Survey procedures vary with site conditions and survey objectives. In higher latitudes, peatlands are often surveyed during winter months when the upper organic soil layers are frozen and the surface is snow covered. Under these conditions, the use of snowmobiles or tracked vehicles facilitates GPR surveys. In lower latitudes, grass and reed-covered peatlands have been successfully surveyed in all seasons with airboats. Pelletier et al. (1991) described the use of helicopters to survey extensive peatlands in remote areas of Ontario.

Figure 6.6 shows a soil profile and a radar record from an area of Freetown soil (dysic, mesic Typic Haplosaprists) in southeastern Massachusetts. In Figure 6.6, the depth scales are in meters: 0–2 m on the soil profile and 0–7.2 m on the radar record. The white vertical lines at the top of the radar record represent equally spaced (10 m) reference points. Abrupt and strongly contrasting differences in water content makes the organic/mineral interface distinguishable on radar records. In Figure 6.6, this interface forms a conspicuous reflector that varies in depth from about 1.0 to 5.1 m. Weak planar reflectors are evident and suggest layering within the organic materials. The layering within the organic materials represents differences in degree of decomposition and associated water contents. On the soil profile shown in Figure 6.6, layers of lighter-colored, less-decomposed organic soil materials (fibric materials) alternate with darker-colored layers of more decomposed organic soil materials (sapric materials). No variations in signal attenuation,

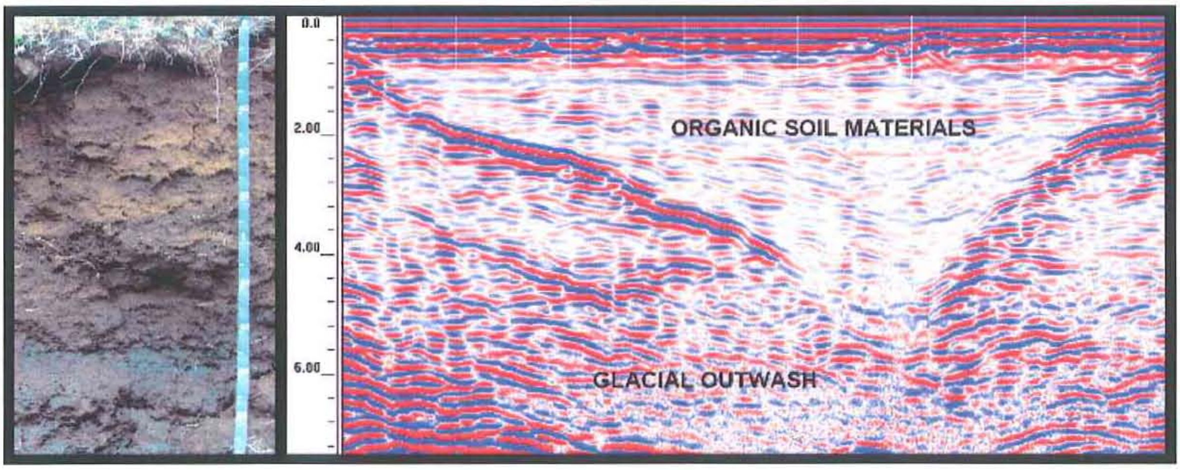

Figure 6.6 The organic/mineral soil material provides a high-amplitude reflector that can be traced laterally across a peatland formed in a kettle in southeastern Massachusetts.

penetration depths, or the effectiveness of GPR have been associated with differences in the degree of organic matter decomposition (e.g., fibric, hemic, and sapric organic materials).

6.3. Biomonitoring

Ground penetrating radar can be used to detect and monitor below-ground biological structures, provided there is sufficient electromagnetic contrast with the surrounding soil matrix. Forest researchers are interested in measuring root biomass, distribution, and architecture to evaluate forest productivity and health. Tree root systems are commonly evaluated via labor-intensive, destructive, time-consuming excavations. Ground penetrating radar has been used to resolve roots and buried organic debris, assess root size, map root distribution, and estimate root biomass (Butnor et al., 2001). Being noninvasive and nondestructive, GPR allows repeated measurements that facilitate the study of root system development. Root biomass studies provide insight into the effectiveness of varying water and fertilizer treatments and are an indicator of tree health. Although live tree roots are the most common targets for biomonitoring studies, GPR can be used to detect internal tree defects (Miller and Doolittle, 1990; Schad et al., 1996).

Hruska et al. (1999) first used GPR to nondestructively map the distribution of coarse (>3 cm diameter) root systems. In this study, a 450-MHz antenna and an image analysis system were used to produce 3D graphics showing the distribution of roots of several oak trees (*Quercus petraea*) within a 6 × 6 m plot. Woody roots often present very complex reflective surfaces, which require some degree of verification. This may be accomplished with root excavations (Stokes et al., 2002) or soil core samples (Butnor et al., 2003) to confirm that root distribution maps are accurate for a particular site. When data collected with a 450-MHz antenna were compared to excavations, large roots were accurately profiled, while smaller structures (<2 cm) were not detectable (Stokes et al., 2002). Surface-based GPR systems can provide useful information on lateral roots; however, the distribution of large roots extending vertically or near-vertically in the soil is not possible (Stokes et al., 2002).

Roots, as small as 0.5 cm in diameter, have been detected at depths of less than 30 cm with a 1.5-GHz antenna in well-drained, sandy soils (Butnor et al., 2001). However, without detailed, methodical scanning of small grids, it is not possible to separate roots by size class or depth under field conditions (Wielopolski et al., 2000; Butnor et al., 2001). Under optimal conditions in a sand test bed, enhanced migration filtering methods have allowed accurate determination of root diameter (Barton and Montagu, 2004). This work represents an important advance in postcollection processing of root data, but the ideal conditions (widely spaced, nonoverlapping roots, scanned at 90°) are quite different from the orientation and geometry of root reflective surfaces found in a forest. More work is needed to parameterize this type of analysis for real-world conditions. Since forests and tree plantations are often found on soils that are marginal for agriculture, there are many surface and textural conditions, which can confound interpretation. Root detection is ineffective in soils with high clay or water contents, having large number of coarse fragments, or in most unimproved, forested terrains where presence of herbaceous vegetation, fallen trees limbs, and irregular soil surfaces impede the travel of the antenna (Butnor et al., 2001).

The estimation of root mass and root distribution in forests has been successful on sites amenable to radar investigations. Butnor et al. (2003) correlated GPR-based estimates of root biomass within the upper 30 cm of soil profiles with harvested root samples. With advanced image processing, high-amplitude areas and reflector tally were directly proportional to the actual root biomass. A highly significant ($r = 0.86$, $p < 0.0001$) relationship was observed between actual biomass in cores and GPR estimates in a loblolly pine (*Pinus taeda* L.) plantation. Transect-based root biomass surveys combined with small destructive samples (soil cores) are the most widely adopted application of biomonitoring with GPR. The USDA Forest Service, Southern Research Station has partnered with universities to include GPR root biomass surveys in forest productivity studies in North Carolina, South Carolina, Georgia, Florida, and Ontario. Other practical applications of this methodology include monitoring residual root materials that harbor root disease fungi (*Armillaria* spp.) following the clearing of an old peach orchards (Cox et al., 2005) and evaluating the mass of coarse roots, burls, and lignotubers in a scrub-oak ecosystem that had been exposed to elevated carbon dioxide at the Kennedy Space Center (Stover et al., 2007).

Postcollection processing is necessary to reduce clutter on radar records containing root data. Tree roots typically appear as hyperbolic reflections on radar records (Figure 6.7a), unless the root follows the same path as the antenna. Background removal filters are required to eliminate parallel echoes from plane reflectors such as the ground surface or soil horizons (Oppenheim and Schafer, 1975). Background removal is helpful to distinguish roots near the soil surface from the surface reflection generated at the soil–air interface (see Figure 6.7b). Reflected GPR data may not be representative of the actual size and shape of the buried anomaly. Migration techniques are essential for developing a 3D representation of roots. Kirchoff migration is a filter technique (see Figure 6.7c) that uses the geometry of a hyperbolic reflection to guide decomposition to a representative size (Oppenheim and Schafer, 1975; Barton and Montagu, 2004). However, Kirchoff migration may be confused by the variable orientations of roots. An alternative approach is the Hilbert transformation (see Figure 6.7d), which uses the magnitude of the return signal to decompose multiple hyperbolic reflections into a more compact and representative form (Oppenheim and Schafer, 1975; Berkhout, 1981; Daniels, 2004). Both techniques can be very valuable for assessing tree roots (Butnor et al., 2003; Stover et al., 2007). The Hilbert transform is useful when the orientations of the roots are unknown, but may be affected by moisture content in poorly drained sites.

There has been considerable interest in mapping tree root systems to understand root architecture and soil volume utilization (Hruska et al., 1999; Cermak et al., 2000; Stokes et al., 2002). Compared with simple transects for biomass analysis, 3D datasets are tedious to collect and process for interpretation. As long as the grid line spacing is kept small (2–5 cm between scans), larger roots that are continuous across several two-dimensional (2D) radar records are distinguishable. Reconstructing

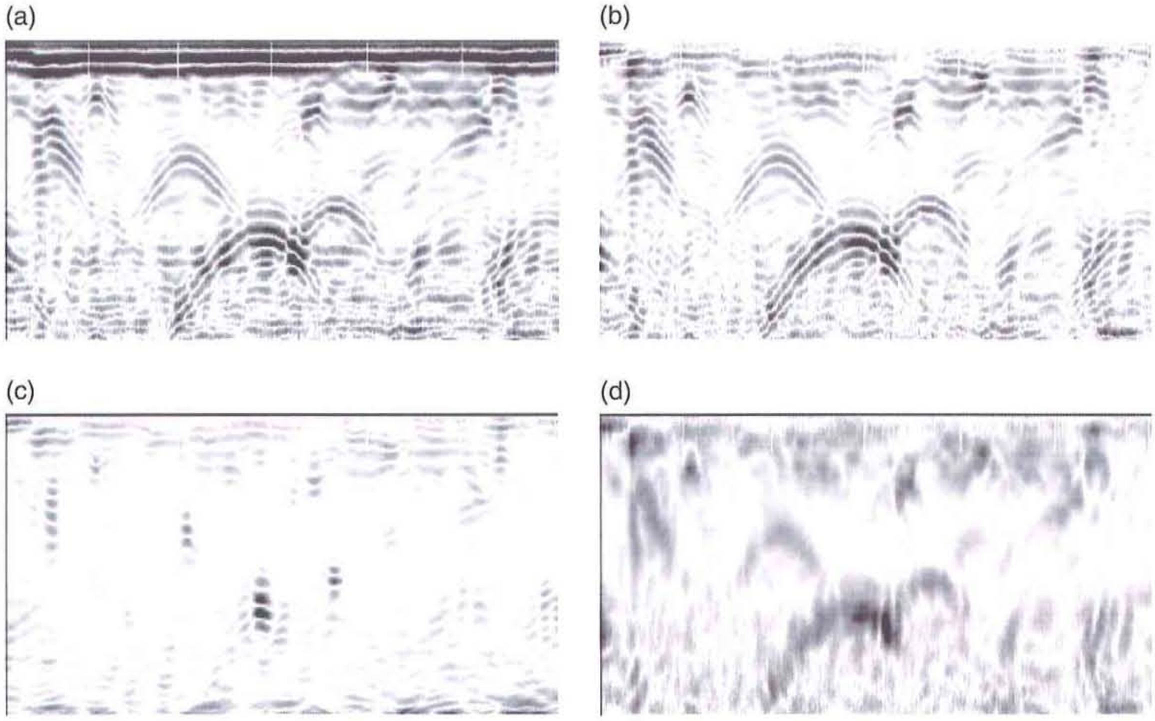

Figure 6.7 Radar profiles collected with a 1500-MHz antenna in the North Carolina Sand Hills ($Z = 0$–0.6 m, $X = 3$ m). In this well-drained, sandy soil, there is sufficient contrast to resolve tree roots. Interpretation may be enhanced by digital signal processing: (a) raw data, (b) background removal, (c) background removal and migration, and (d) background removal and Hilbert transform.

the location of roots is straightforward, but successfully modeling size, shape and root volume is not. Examples of mapping loblolly pine (*P. taeda* L.) roots are shown in Figure 6.8, where a series of *Z* slices (*X* and *Y* coordinates projected at specific *Z* depth) illustrate the location of several tree roots located between two rows of trees. For most forest survey projects, root biomass transects yield-sufficient information. Three-dimensional root mapping is useful when detailed root location information is required for a small area, provided there is sufficient time to collect and process the data.

Surface-based GPR can provide excellent records of lateral roots. However, some forest trees have a significant allocation to large, vertical tap roots (i.e. loblolly pine, *P. taeda* L., longleaf pine, *Pinus palustris* Mill.), which cannot be accurately assessed by surface measures (Butnor et al., 2003). A collaborative project between the USDA Forest Service, Southern Research Station (Research Triangle Park, NC), Radarteam AB (Boden, Sweden), and the SLU, Vindeln Experimental Forest System (Vindeln, Sweden) was undertaken in 2003 to assess the potential of high-frequency borehole radar to detect vertical near-surface reflectors (0–2 m). Cross-hole tomography provided excellent information on the depth of electromagnetic anomalies but was less useful for imaging near-surface features. Borehole to surface data provided the best information on the near surface, where the bulk of roots are found (0–0.3 m). Cross-hole and borehole to surface data may be combined to further define vertical root systems.

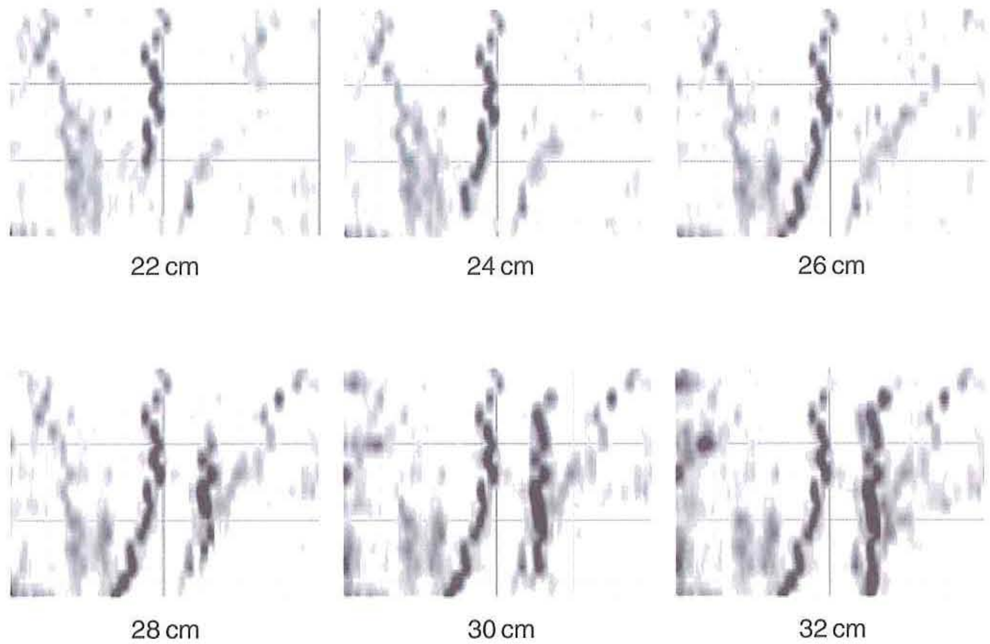

Figure 6.8 A series of parallel radar scans (2 cm interval) were combined using RADAN 4.0 to map loblolly pine roots. Each Z slice presented above is reconstructed from the raw data and centered ($\pm$1 cm) at the specified depth. The x-axis is 3 m and the y-axis is 2 m.

Ground penetrating radar has been used to detect internal defects in forest and urban trees (Miller and Doolittle, 1990; Detection Sciences, Inc., 1994; Nicolotti et al., 2003). Internal decay, which results in changes in moisture content or wood density, can provide a detectable target for electromagnetic techniques (Nicolotti et al., 2003). Miller and Doolittle (1990) were able to detect hollow areas, decayed wood, and brown rot in several species of forest trees. Using a 500-MHz antenna in bistatic mode, healthy trees were generally void of internal reflections, with the exception of weak parallel bands attributed to variations in moisture and wood density near the heartwood/sapwood interface. Miller and Doolittle (1990) found that areas of hollowness and decay were correlated with cluttered reflections and discontinuities on radar records. Four trees were destructively ground-truthed and found to have a high degree of accuracy with the GPR assessment. High-frequency radar (1.5 GHz) has been employed to identify areas of decay in a plane tree (*Platanus hybrida* Brot.) in an urban setting (Nicolotti et al., 2003). By advancing the antenna around the circumference of the tree, researchers were able to acquire data in single reflection mode from a bistatic antenna. The linear, 2D data were transformed into polar coordinates for ready comparison to tree sections. There was good agreement between radar assessment of decay and destructive sampling via physical means; areas of decay exhibited increased dielectric properties. The greatest difficulty with using GPR to evaluate defects is the difficulty in coupling the antenna to the curved bark surface of the tree and interpretation of complex data (Schad et al., 1996; Nicolotti et al., 2003). Differences between tree species, stem diameters, moisture gradients related to heartwood development, and environmental conditions may make interpretation between trees complicated. This area of research is rapidly advancing, and applications of GPR designed specifically for trunk evaluations are now commercially available.

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