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Review

Ground penetrating radar for underground sensing in agriculture: a review**

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Abstract. Belowground properties strongly affect agricultural productivity. Traditional methods for quantifying belowground properties are destructive, labor-intensive and point-based. Ground penetrating radar can provide non-invasive, areal, and repeatable underground measurements. This article reviews the application of ground penetrating radar for soil and root measurements and discusses potential approaches to overcome challenges facing ground penetrating radar-based sensing in agriculture, especially for soil physical characteristics and crop root measurements. Though advanced data-analysis has been developed for ground penetrating radar-based sensing of soil moisture and soil clay content in civil engineering and geosciences, it has not been used widely in agricultural research. Also, past studies using ground penetrating radar in root research have been focused mainly on coarse root measurement. Currently, it is difficult to measure individual crop roots directly using ground penetrating radar, but it is possible to sense root cohorts within a soil volume grid as a functional constituent modifying bulk soil dielectric permittivity. Alternatively, ground penetrating radar-based sensing of soil water content, soil nutrition and texture can be utilized to inversely estimate root development by coupling soil water flow modeling with the seasonality of plant root growth patterns. Further benefits of ground penetrating radar applications in agriculture rely on the knowledge, discovery, and integration among differing disciplines adapted to research in agricultural management.

Keywords: ground penetrating radar, post-data analysis, crop roots, soil water content, soil texture

INTRODUCTION

The interactions and feedback between soil and plants affect the biogeochemical processes and biomass production in agriculture (Amundson *et al*., 2007). The ability of world food production to supply the increasing global population hinges on a steady increase in crop resource-use efficiency in the shallow subsurface of the earth (Morison *et al*., 2008). Plant roots take up essential water and nutrients from the soil, and the soil condition in turn affects plant root distribution and function (Hopmans and Bristow, 2002; Liu *et al*., 2015; Sharma *et al*., 2014; Zhang *et al*., 2009). New insights into belowground properties such as crop root distribution and soil water movements will benefit agricultural crop productivity.

Traditional methods to measure underground parts include excavation and sampling using soil cores or augers (Veihmeyer and Hendrickson, 1946; Frevert and Kirkham, 1949; Welbank and Williams, 1968). These standard methods sometimes can be the only way to measure soil characteristics with appropriate accuracy for a particular depth and point in space. But they are destructive, labor-consuming and expensive (Castro *et al*., 2015; Nanni and Demattê, 2006). Additionally, these methods usually do not allow long-term repeatable measurements (Danjon and Reubens, 2008). Other methods for belowground measurements include the use of soil moisture sensors (Baker and Allmaras, 1990; Dean *et al.*, 1987), soil conductivity meters (Rhoades and Corwin, 1981), soil compaction meters (Liu *et al*., 2015; 2016), the mini-rhizotron technique (Hansson and Andrén, 1987; Sharma *et al*., 2014; Upchurch and Ritchie, 1983) and digital root imaging (Clark *et al*., 2011). Though some applications combine traditional methods with new technologies to allow efficient data acquisition (Herrero *et al*., 2003; Wagner *et al*., 1999), most of these sensor measurements represent point information such as soil moisture measurements as reviewed by Robinson *et al.* (2008). In fact, due to the temporal and spatial variability of soil characteristics such as soil water in the field (Jackson

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and Le Vine, 1996; Ritsema and Dekker, 1998), it is difficult to extrapolate point measurement to the field scale. Satellite-based microwave remote sensing has good regional relevance but only captures soil characteristics at very shallow surface layer (Robinson *et al*., 2008; Wang and Qu, 2009). Geophysical techniques such as ground penetrating radar (GPR) and electrical resistance tomography are fast, nondestructive and on-site sensing tools that provide an excellent compromise between point-measurement and regional remote sensing (Daniels, 2004; Huisman *et al*., 2003; Ramirez *et al*., 1996).

Ground penetrating radar is designed to locate buried objects (Daniels, 2004) and has been used widely in civil engineering (Goodman, 1994; Maierhofer, 2003; Salucci *et al*., 2014), archaeological research (Conyers, 2013), geophysical investigations (Carrière *et al*., 2013; Davis and Annan, 1989; Jol *et al*., 1996) and tree root detection (Hruska *et al*., 1999; Butnor *et al*., 2001; Guo *et al*., 2013a). GPR has been proven to produce a real, rapid, high-resolution and non-invasive measurement of underground features. However, despite its use in tree root sensing in the past 15 years, reports on agricultural crop root research using GPR have been limited (Thompson, 2014; Thompson *et al*., 2013). Most studies conducted in agriculture have focused on soil water measurement (Doolittle and Collins, 1995; Galagedara *et al*., 2005; Grote *et al*., 2003), owing to the rapid development in the knowledge of physical principles, methods of measurement, and post-data analysis tools in this research area (Robinson *et al*., 2008). Moreover, a frequency shift method in frequency domain analysis can analyze soil moisture and soil clay content easily based on GPR surveys (Benedetto, 2010; Benedetto and Tosti, 2013), but it is not yet to be used in agriculture. In crop physiology research, deep roots are generally considered beneficial for improved overall crop water use efficiency, yet more accurate information on root development is needed to design optimal root/shoot ratios in cropping systems (Amato and Ritchie, 2002; Blum, 2005; Wasson *et al*., 2012; Zaman-Allah *et al*., 2011). Accurate information on the spatial distribution of plant roots is critical for evaluating field management and new crop cultivars for improved water use efficiency.

The objectives of this review are twofold: 1) present the applications of GPR in underground measurements in soil-plant systems; 2) discuss the current challenges and possible solutions of using GPR in sensing fine roots for agricultural crop and water management.

INTRODUCTION TO GPR

As a geophysical technique, GPR uses electromagnetic radiation to locate objects or interfaces buried beneath the soil surface (Daniels, 2004). Generally, a GPR system has three components: transmitting and receiving antennas, a control unit with a computer and associated software, and a display unit (Conyers, 2013). The transmitting antenna generates radar pulses and propagates them into the ground. The objects buried in the ground absorb, reflect, or scatter the radar energy. After some travel time, a portion of emitted radiation returns to the receiving antenna, which is then analyzed using software. Digital signal processing techniques are routinely used to increase the signal/noise ratio so that the subsurface conditions are accurately conveyed and captured (Cassidy, 2009).

There is an abundance of literature on GPR theory and data processing (Annan, 1992; Daniels, 2004; Olhoeft, 2000). A particular focus of past studies can be found in civil engineering applications (Benedetto and Pajewski, 2015), geophysical detection (Rea and Knight, 1998), soil moisture measurements (Huisman *et al*., 2003; Qin *et al*., 2013; Van Dam, 2014), and plant coarse root detection (Guo *et al*., 2013a). Basic data processing steps may include: filtering, data/trace editing and 'rubber-band' interpolation, dewow filtering, time-zero correction, deconvolution, velocity analysis and depth conversion, elevation or topographic corrections, gain functions, migration, advanced imaging, attribute analysis, and numerical modeling (Cassidy, 2009).

APPLICATION OF GPR IN THE SENSING OF SOIL PHYSICAL CHARACTERISTICS AND ROOTS

As discussed earlier, some soil characteristics can be measured only by taking soil samples; here, we limit our discussion to the GPR sensing of physical soil properties such as soil clay content, soil moisture, and soil bulk density (Table 1). Most GPR root studies are on tree roots (coarse roots > 0.2 cm); here, we attempt to extrapolate using information from research on tree roots to assist in the detection of fine roots in crops (Table 2).

Sensing soils and roots

GPR systems were specifically designed to chart soil depth and extent of diagnostic subsurface horizons (Doolittle, 1987). Previous studies have used GPR to accurately estimate soil depth in rocky forest soils (Sucre *et al*., 2011), measure the depth to and thickness of several types of soil horizons (Johnson *et al*., 1982), determine thickness and characterize depths of organic soil materials (Collins *et al*., 1986; Shih and Doolittle, 1984; Winkelbauer *et al*., 2011) and bedrock (Novakova *et al*., 2013). GPR can also be used to identify subsurface flow pathways (Gish *et al*., 2005; Guo *et al*., 2014; Freeland *et al*., 2006), detect animal burrows (Chlaib *et al*., 2014), investigate the water table depth (Mahmoudzadeh *et al*., 2012) and identify offsite movement of agrochemicals (Yoder *et al*., 2001). In agriculture, soil quality is a key factor related to agricultural sustainability. There are some research conducted to study soil microvariability (Collins and Doolittle, 1987), investigate soil variability including soil water, soil bulk density and texture (Truman *et al*., 1988), evaluate soil clay content

Table 1. Studies on the application of GPR to determine soil physical characteristics

Target	Antenna center frequency (MHz)	Soil type	Scan method	Other equipment	Data analysis method	Index/model
Soil clay content	500	2-25% clay	linear	no	time and frequency domain	frequency spectra peaks
	600	7-30% clay	linear	no	frequency domain	frequency peak
Hard pan	500	sandy loam and clay loam	–	no	–	–
Soil bulk density/ soil moisture	400	sandy loam	linear	no	frequency domain	power spectrum
Soil resistance/ soil water	400	silty loam	linear	EMI	time domain	no/Topp equation
Soil moisture	1000	sand	linear	no	time domain	Topp equation
	400	sand	linear	TDR	time domain	mixing model
	2000	sand	–	no	time and frequency domain	mixing model/ full-wave inversion
	200-800	silt clay	linear	FDR	time domain	full wave model, mixing model and Debye equation
	600 and 1600	sandy soil, subgrade soil, 5% clay and 20% clay	linear	no	frequency domain	peak of the frequency
	600 and 1600	sandy loam	linear	ERI	time and frequency domain	Topp equation, peak of the frequency

EMI – electromagnetic induction, TDR – time-domain reflectometry, FDR – frequency domain reflectometry, ERI – electrical resistivity imaging.

(West *et al*., 2003; Tosti *et al*., 2013), sense hard pan in the field (Raper *et al*., 1990), reveal biogenic gas accumulation (Comas *et al*., 2005), assess the inorganic pollutant contamination in groundwater (Wijewardana *et al*., 2015), and study soil salinity (Hagrey, 2000). The electromagnetic method can also be used for identifying the dynamic changes in available soil nitrate, as affected by animal manure and nitrate fertilizer treatments, during the corn-growing season (Eigenberg *et al*., 2002). Doolittle and Brevik (2014) summarized additional uses of electromagnetic induction techniques in soil studies. Generally, GPR can be used to monitor subsurface features that have contrasting dielectric constants (Truman *et al*., 1988). In particular, GPR has been used for soil water content estimation including measuring soil water content profile (Lambot *et al*., 2004), estimating soil water variation under irrigation conditions (Galagedara *et al*., 2005), identifying specific soil water depth and monitoring spatial and temporal variation of soil water content (Pan *et al*., 2012), mapping the spatial variation of soil water content at the field scale (Weihermüller *et*

Table 2. Recent studies on the application of GPR to detect root characteristics (scan method – linear, data analysis method – time domain)

Target	Antenna center frequency (MHz)	Soil type	Other equipment	Index
Root diameter and root biomass	500 and 800	brown forest soil	TDR	pixels within threshold range, high amplitude area, time interval, magnitude width
Root diameter	900	sandy clay soil	no	sum of amplitude areas and amplitude area for the maximum reflection waveform
Root biomass and root architecture	1 000	silt loam	TDR	reflection intensity
Root diameter	1 500	sandy soil	no	amplitude of reflected wave, time interval, amplitude area of reflected wave, threshold area
Root biomass	1 000	sandy loam	no	pixel intensity
	500, 900 and 2 000	sandy soil	no	pixels within the threshold range and high amplitude area
Root diameter and root depth	900	granitic soil	ThetaProbe	maximum amplitude, time interval and magnitude area
Root detection	900	sand	no	amplitude area and time interval
Root biomass	1 500	sand, sandy loam and sandy clay	no	intensity threshold
Root number	900	sandy loam	no	patterns in the radargrams

Explanation as in Table 1.

al., 2007), and comparing the tillage effects on soil water content (Jonard *et al.*, 2013). Compared to time domain reflectometry, GPR is better suited for mapping large-scale features (>5 m) in soil water content (Huisman *et al.*, 2002). The precision of GPR used to measure soil water content can vary from 0.0026 $cm^3 cm^{-3}$ (Stoffregen *et al.*, 2002) to 0.115 $cm^3 cm^{-3}$ (Weihermüller *et al.*, 2007) depending on soil conditions and GPR antenna configuration. Using a 100 MHz GPR, for example, Schmelzbach *et al.* (2012) obtained soil water information down to 7 m with decimeter resolution.

Some of recently published papers on root detection are summarized in Table 2. Recent applications of GPR for plant root detection have focused on coarse roots (>0.2 cm) (Guo *et al.*, 2013a). Previous studies have shown that GPR can be used to estimate root diameter (Barton and Montagu, 2004; Cui *et al.*, 2011), root biomass (Butnor *et al.*, 2003; Guo *et al.*, 2013c; Zhu *et al.*, 2014), root zone area (Lorenzo *et al.*, 2010) and root mapping (Hruska *et al.*, 1999). In particular, Guo *et al.* (2013a) conducted a thorough review of the application of GPR for coarse root detection and quantification. They summarized the state of knowledge of coarse root measurement using GPR and discussed the potentials, constraints, and possible solutions to improve coarse root estimations.

GPR equipment

The judicial selection of the antenna is important because the size of a target detectable with a GPR depends on the center frequency of the antenna. There is a trade-off between radar resolution and penetration depth. Generally, a high-frequency antenna will get a high resolution of information on the objects within a shallow depth. A low-frequency antenna will get a low resolution of information but can propagate deeper into soil layers. A wide range of antenna frequencies are used because they focus on different objects (Tables 1 and 2).

GPR measuring environment

Soil suitability maps for GPR application was developed in the United States based on data of soil electrical conductivity which is influenced by soil clay content, electrical conductivity, sodium absorption ratio, and calcium carbonate content (Doolittle *et al.*, 2002, 2007). This map can provide a quick overview of soil properties that affect the application of GPR in a broad area. However, it does not mean GPR cannot be used in the unsuited area. The actual performance and effectiveness of GPR application will depend on local site conditions (Goodman *et al.*, 2006), characteristics of subsurface target (Doolittle *et al*., 2002; Weaver, 2006), the strategy of setting up survey grids (Pomfret, 2006), as well as data processing technique (Benedetto and Pajewski, 2015). Soil dielectric permittivity and electrical conductivity are the two key factors affecting the GPR signal (Daniels, 2004). A large contrast between the soil and buried objects helps GPR to capture the target information. Generally, GPR is most useful in low electrical-loss materials because a large portion of the transmitted electromagnetic radiation is reflected and captured by the receiving antenna, making the buried objects more detectable (Jol, 2008). Therefore, most studies on plant roots have been conducted in sandy loam soil and dry conditions (Borden *et al*., 2014; Butnor *et al*., 2003; Barton and Montagu, 2004; Hirano *et al*., 2009). Some studies show that soil water measurements are more feasible in sandy soils as compared to loamy sand and silty clay soil (Stoffregen *et al*., 2002). In a field with soil containing high silt and clay, GPR cannot provide adequate spatial information on soil water content (Weihermüller *et al*., 2007). Soils with high water, clay and soluble salt contents have high dielectric permittivity and electrical conductivity, which could decrease the electromagnetic gradient between soil and buried objects (Butnor *et al*., 2001, 2005; Hagrey, 2000). Actually, the very nature of water, clay and soluble salts can be utilized to characterize significant changes in root zone features based on contrasts in dielectric permittivity (Topp *et al*., 1980) and the Rayleigh scattering phenomenon (Benedetto, 2010; Benedetto and Tosti, 2013).

Post-data analysis

GPR data analysis can be conducted in time domain or frequency domain (Benedetto and Pajewski, 2015) to get a useful index reflecting the buried objects. Generally, two main groups of indexes can be extracted from the radargrams for coarse root estimation: (a) the reflection strength indexes, such as areas within threshold range, pixels within threshold and mean pixel; (b) the reflection waveform indexes from reflected signals such as amplitude of reflected wave, high amplitude areas and time interval between zero crossing (Guo *et al*., 2013a). Also pattern of radargrams can be used to detect root number (Table 2). Values of dielectric permittivity can be obtained by computing the delay time of reflections once the value for the velocity propagation of the wave in the soil is determined (Benedetto and Benedetto, 2002) and soil water content can be estimated using Topp petrophysical equation, a dielectric mixing model, or a full wave model (Table 1). These models for the estimation of soil physical characteristics are based on permittivity measurements.

Another more efficient and accurate approach to measuring soil water and clay content used in civil engineering is the frequency shift method (Benedetto, 2010; Benedetto and Tosti, 2013). This method does not need calibration to estimate soil moisture and clay content. As soil water or clay content increases, the frequency spectrum will shift from high to low frequency (Benedetto, 2010; Benedetto and Tosti, 2013; Tosti *et al*., 2013) (Table 1).

CHALLENGES AND POTENTIAL SOLUTIONS OF USING GPR IN AGRICULTURE

Despite progress made in GPR applications in engineering and forestry in past 20 years, the use of GPR technology to assist agricultural crop production has been very limited. There are challenges, such as the inability of GPR to detect individual fine roots of most agricultural crops as well as detecting roots buried deep in the soil profile, but ample opportunities exist to integrate current research methodologies from soil science, forestry and engineering to agricultural applications.

Developing more advanced GPR methods for belowground measurements in agriculture

Soil and root features interested in agricultural research mostly locate within top 2 meter of soil. Combined use of antennas of high (such as 1-2 GHz) and low (400-600 MHz) frequencies should be useful in exploring the interested soil depth, constrained by the afore-mentioned resolution vs. penetrating depth trade-off and local soil condition. Almost all of the previous studies used linear measurements because the current radar system is designed only for linear data analysis (Tables 1 and 2). Sometimes this method cannot fully capture the characteristics of buried roots if their orientation is parallel to the downward direction of the GPR wave propagation (Guo *et al*., 2013a). While some scientists have tried to use circular scanning to better detect the buried objects (Zenone *et al*., 2008), more effective software tools are still needed to extract root information (Guo *et al*., 2013a).

In an agricultural field, the interactions underground can be very complex. For example, soil water, soil texture and soil compaction all may affect plant root distribution. As the original GPR transmitted electromagnetic pulses are modified at multiple frequencies, the returned signals carry influences from various sources (Cui *et al*., 2015). Wavelet multiresolution analysis, a mathematical technique whereby natural signals are systematically partitioned into different frequency components with varying window sizes appropriate for different scales, has been shown to be useful for GPR signal de-noising and physical information extraction in engineering (Baili *et al*., 2009; Oskooi *et al*., 2014; Walker, 2008). At the same time, as data processing using various wavelet thresholding algorithms tend to remove the high-frequency components from the original signal (Dong *et al*., 2008; Oskooi *et al*., 2014), the efficacy may be limited for uncovering subtle features of objects. To get around this influence, alternative signal partitioning methods, such as wavelet packet decomposition (Walker, 2008), may be used to preserve portions of the high-frequency signals that might otherwise be removed as part of the signal noises in traditional dyadic wavelet decomposition procedures. Also, algorithms for the systematic sampling of the returned GPR spectrum are needed to correlate more effectively the GPR frequency bands with the target objects.

Forward simulation is another useful method to capture the response of GPR signal to interested underground part. By forward simulation, radar responses to specific soil characters can be modeled, making possible the differentiation of unexpected signals (Guo *et al*., 2013b). Though not new in GPR data analysis (Giannopoulos, 2005; Goodman, 1994), more investigations are still needed to build forward simulation algorithms to address different research objectives.

Sensing fine roots: a paradigm change from detecting single roots to capturing root cohorts and xylem-hydro-coherence

Plant root research using GPR is focused currently on coarse roots because the minimum detectable root size is 0.25-0.5 cm for high frequency antenna (1 500-2 000 MHz) (Cui *et al*., 2011; Wielopolski *et al*., 2000). For most agricultural field crops, however, fine roots are more important than coarse roots in terms of water and nutrient uptake. For example, most root diameter sizes of wheat, corn and soybean are less than 0.033, 0.50, 0.125 cm, respectively (Seversike *et al*., 2014; Wang *et al*., 2014, 2015). Even though many studies have used GPR successfully to measure coarse roots as discussed above, the physical principle behind the effect of roots on soil dielectric permittivity is presently unclear (Guo *et al*., 2013a). This limitation was also reported on tree roots smaller than 0.1 cm (Hirano *et al*., 2009). Therefore, GPR may not detect individual fine crop roots directly. However, for root phenotyping, parameters describing root cohorts, such as root biomass, root length, density or root distribution patterns, are equally important as those describing the architecture of an individual root, such as root angle and root diameter.

The embedment of fine roots in the soil matrix profoundly changes soil physical properties. Fine roots increase the macropore spaces due to the creation of air spaces between root micro-tunnels and the bulk soil structure. Thompson (2014) used GPR to successfully differentiate wheat root mass from soil under field conditions. Another important feature that fine roots bring to the soil system is the water-filled xylem hydro-coherence structure, especially for crops under normal management in which the xylem water potential is maintained within a hydraulic safety threshold (Holloway-Phillips and Brodribb, 2011). Because water has a significantly higher dielectric permittivity than many soil-borne materials such as bio-cellulose (McDonald *et al*., 2002; Stoops, 1934) or soil minerals (Davis and Annan, 1989), the influence of the fine root xylem network to the soil dielectric permittivity should be captured by GPR at a bulk soil volume scale, instead of the individual root scale. However, the physical theory governing the interaction between the fine root xylem network and GPR-generated electromagnetic wave is unknown (Andrea Benedetto, personal communication). This calls for controlled experiments to provide firsthand empirical data in support of GPR-based fine root sensing.

In the field of agricultural crop improvement, characterizing root growth and distribution of newly developed genotypes and cultivars under field conditions, particularly for drought-prone environments, is important. Root distribution can help evaluate soil water status (Zhang *et al*., 2015); conversely, soil water distribution will help explain root characters if we know how much soil water is used by the crop. Soil nutrition, soil bulk density and texture also influence root development (Wang *et al*., 2013; Zhang *et al*., 2012; Liu *et al*., 2015). The capability of GPR to capture soil characteristics, particularly soil water content and soil nutrition as main determinants of crop growth, provides new opportunities to improve fine root estimation with a hydrology-based inverse modeling approach. For decades, one effective way of estimating fine root development has been to use a macroscopic root uptake model in conjunction with soil water flow modeling (Feddes *et al*., 1978; Yadav and Mathur, 2008). In order to estimate root growth patterns along with unknown soil physical properties, various optimization approaches have been utilized based on measured soil water content data (Dong *et al*., 2010). The fact that most applications rely on point-measured soil water and physical properties makes it time-consuming and even difficult to reliably determine unknown parameters including root growth. In addition to non-invasiveness, GPR-based soil sensing also provides a good spatial averaging of soil features (as effectively illustrated in Figs 1-2 of Davis and Annan, 1989), which would be ideal for enhancing root growth estimation by macroscopic root uptake modeling. Finally, other geophysical sensing tools – electromagnetic induction, time-domain reflectometry, frequency domain reflectometry, and electrical resistivity imaging – can be used in combination with GPR to provide a more robust measurement of soil features (Tables 1 and 2).

Knowledge integration for new GPR applications and development in agriculture

The literature survey of this review highlights the contrast between the extensive use of the GPR sensing tools in engineering sciences and the meager data in agriculture (except for forest root surveys). Those applications in engineering sciences in which experimental methods were employed to calibrate the currently available GPR tools for detecting new features of soil and environment are especially of valuable for agricultural research. While experimental approach has been the strongest pillers supporting the advancement of agricultural and biological sciences, it seems that the recent trends of agricultural methodology are tinged with statistical considerations more than physical/biophysical ones. Manipulative experiments focused on physical considerations, such as that done in Benedetto and Tosti (2013), would allow agricultural researchers effectively establish the relations between GPR signal frequency bands and interested soil and plant features. Considering the near-term trend that GPR application and data interpretation in agriculture would remain less 'straightforward', GPR training courses should emphasis experimental approaches for assisting GPR signal interpretation, in addition to the routine topics of GPR operating principles. Without doubt, the new development in GPR hardware and software requires close collaborations between scientists working in geoscience or engineering and those in agriculture. For example, Dirk Hays (Texas A&M University and AgriLife Research) is leading a U.S. Department of Energy project 'Ground-Penetrating Radar (GPR) for Enhanced Root and Soil Organic Carbon Imaging', (http://aglifesciences.tamu.edu/blog/2016/02/02/agrilife-research-to-take-ground-penetrating-research-to-new-crops/). Breeders, agronomists, rangeland ecologists, geoscientists, agricultural engineers and GPR equipment and software developers are working together in this project. This kind of cooperation is expected to enhance the application of GPR in agriculture, especially crop root measurements.

SUMMARY

Traditional methods for underground feature measurements are destructive, time-consuming and expensive. GPR is a non-invasive, on-site measurement technique with which we can get more accurate and complete underground information. Though GPR has been widely used in civil engineering, geosciences, and forestry, some of the advanced methods have not been adopted by agricultural soil research nor focused on root sensing. This review summarizes the application of GPR for soil/root detection and discusses the current challenges of using GPR in agriculture. Advanced data analysis methods for soil physical measurements are needed in the agricultural field. GPR sensing can be adapted and applied to further explore crop root characteristics and xylem-hydro-coherence. Finally, new development in GPR applications in agriculture will rely on successful collaboration between biological and engineering sciences.

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