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REGULAR ARTICLE

Limiting factors in the detection of tree roots using ground-penetrating radar

Yasuhiro Hirano · Masako Dannoura · Kenji Aono · Tetsurou Igarashi · Masahiro Ishii · Keitarou Yamase · Naoki Makita · Yoichi Kanazawa

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Abstract It has been reported that ground-penetrating radar (GPR) is a nondestructive tool that can be used to detect coarse roots in forest soils. However, successful GPR application for root detection has been site-specific and numerous factors can interfere with the resolution of the roots. We evaluated the effects of root diameter, root volumetric water content, and vertical and horizontal intervals between roots on the root detection of *Cryptomeria japonica* in sand using 900-MHz GPR. We found that roots greater than 19 mm in diameter were clearly detected. Roots having high volumetric water content were easily detected, but roots with less than 20% water content were not detected. Two roots that were located closely together were not individually distinguished. These results confirm that root diameter, root water content, and intervals between roots are important factors when using GPR for root detection and that these factors lead to an underestimation of root biomass.

Keywords Coarse roots · GPR · Nondestructive root methods · Root distribution · Water content

Abbreviations
GPR ground-penetrating radar

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Y. Hirano (✉)
Kansai Research Center,
Forestry and Forest Products Research Institute (FFPRI),
68 Nagai-Kyutaro, Momoyama, Fushimi,
Kyoto 612-0855, Japan
e-mail: yhirano@affrc.go.jp

M. Dannoura · N. Makita · Y. Kanazawa
Graduate School of Agricultural Science, Kobe University,
Kobe 657-8501, Japan

K. Aono · T. Igarashi · M. Ishii
The General Environmental Technos Co., Ltd.
(KANSO TECHNOS),
Osaka 541-0052, Japan

K. Yamase
Hyogo Prefectural Technology Center for Agriculture,
Forestry and Fisheries,
Shiso 671-2515, Japan

Present address:
M. Dannoura
Graduate School of Agricultural Science, Kyoto University,
Kyoto 606-8502, Japan

Introduction

According to the Kyoto Protocol, an international agreement intended to reduce greenhouse gases such as CO_2, root biomass of forest trees must be evaluated to determine carbon (C) storage in forest ecosystems (The Government of Japan 2008). Tree roots account for about 20–40% of global forest biomass, and coarse roots (i.e., those that are larger than 2–5 mm

in diameter) play an important role in C storage of forest trees (Brunner and Godbold 2007). Fine roots (less than 2 mm in diameter) are important in tree to soil C fluxes, and thus to C storage in the soil (Brunner and Godbold 2007; Strand et al. 2008). One method used to evaluate the biomass and distribution of coarse roots is the excavation of the whole root system. However, this method is labor-intensive, destructive, and limited by the manageability of the size and number of samples. In the Kyoto Protocol, root to shoot ratios have been used to estimate root biomass, although only a few studies have been performed on coarse root biomass. Few data are available on the root biomass of broad-leaved trees, and the same ratio (0.25) was applied to all species of broad-leaved trees (The Government of Japan 2008). Therefore, an urgent need exists to develop new sampling and measuring techniques to evaluate tree root biomass more accurately.

Recently, a nondestructive method using ground-penetrating radar (GPR) was used to map the coarse root systems (e.g., Hruska et al. 1999; Cermak et al. 2000; Butnor et al. 2001; Stover et al. 2007). GPR is a pulse radar system that can predict the depth, position, and size of matter buried in the soil using the time and characters of the reflected waves (for GPR details, see Butnor et al. 2001; Barton and Montagu 2004; Hagrey 2007). The pulses of electromagnetic energy from a transmitting antenna penetrate into the soil and reflect the boundary layer of objects with different physical values (Fig. 1). The reflected waves are intercepted by the receiving antenna and the waveforms are subsequently recorded on a portable computer. Generally, the reflection of the electromagnetic wave occurs at the boundary layers and its strength is determined by the reflection coefficient R (Milsom 2003; Hagrey 2007):

$$R = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}}.$$

In this formula, ε_1 and ε_2 are the relative dielectric permittivity of medium 1 and medium 2, respectively. The stronger the contrast between medium 1 and medium 2, the larger the value of R and the stronger the reflected wave at the boundary layer. GPR has been used for predicting gaps under roads, the position of buried pipes, water tables in compacted soil horizons, and archeological artifacts (Stokes et al. 2002; Miller et al. 2004).

GPR was used to map coarse root systems and to estimate root biomass (Hruska et al. 1999; Butnor et al. 2001, 2003; Stokes et al. 2002; Barton and Montagu 2004; Cox et al. 2005; Stover et al. 2007). This technique can be a new tool because it is rapid and nondestructive. However, the successful application of GPR in root detection has been site-specific and numerous factors can interfere with the root resolution (Butnor et al. 2003). The method must still be rigorously tested. Therefore, before GPR can be effectively used to estimate root biomass under forest field conditions, various limiting factors should be evaluated to establish a reliable protocol. Butnor et al. (2001) evaluated the ability of GPR to delineate roots under a range of soil conditions and concluded that the resolution of roots is best in drained sandy soils and seriously degraded in soils with high water and clay contents. Barton and Montagu (2004) found that data analysis using waveform parameters provides a more accurate estimate of root diameters in the GPR profiles compared to previous analysis methods.

We recently reported that under optimal sandy soil conditions, the roots of *Cryptomeria japonica*, which is a major plantation tree species in Japan, were clearly detected using GPR (Dannoura et al. 2008). That is, significant relationships existed between the waveform parameters and root diameter. From tests using dowels of *C. japonica*, we also suggested that the difference in water content between the soil and buried objects may impact the ability to detect roots using GPR. However, no study has evaluated the effects of root water content on root detection using GPR.

The objectives of this study were to determine which tree root factors may affect root detection using GPR under optimal sandy soil conditions. Specifically, we evaluated the effects of root diameter, root volumetric water content, and vertical and horizontal intervals between roots on root detection using 900-MHz GPR.

Materials and methods

Root detection experiments

We created optimal testing conditions by creating a sand plot in the seedling nursery at Kansai Research

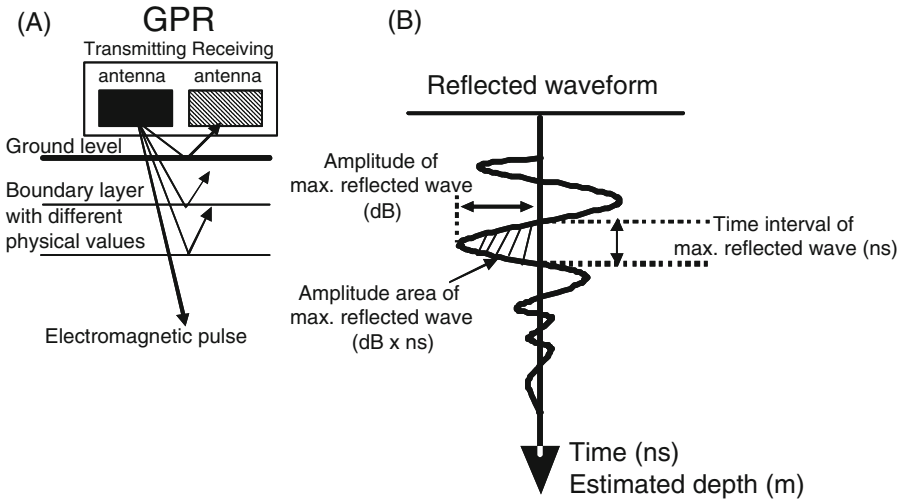

Fig. 1 **a** A schematic diagram of the GPR system. The electromagnetic pulse reflects off the boundary layers with different physical values. **b** A reflected waveform of GPR and the waveform parameters of amplitude (dB), time interval with zero crossing (ns), and amplitude area (dB × ns) of the maximum reflected wave

Center, Forestry and Forest Products Research Institute, Kyoto, Japan. We established a plot of 7×2×1.2 m. All soil in the plot was removed and the plot was filled with sand. We selected the sand with granite as parent material and the diameter was less than 5 mm. The bulk density of the sand was 1.4 g cm^{-3}. The plot was divided in half and two experiments were simultaneously undertaken.

The roots of 20-year-old *C. japonica* trees were excavated 1 day before the start of the experiment, and the root systems were cut into 1-m pieces. We selected 35 straight roots ranging in diameter from 10 mm to 78 mm (mean diameter = 39 mm). The ends of the cut roots were sealed with silicone to prevent water loss. We prepared one dowel from *C. japonica* wood that was 1 m long and 52 mm in diameter as a reference for detection with GPR. The dowel was soaked in tap water for 2 months so that it had a high volumetric water content (70%) that would be easily detected by GPR (Dannoura et al. 2008).

We conducted three root detection experiments with GPR using *C. japonica* roots and the dowel. In the first experiment, we examined how GPR detects small-diameter roots by burying six excavated roots having diameters of 10 mm, 19 mm, 31 mm, 37 mm, 50 mm, and 78 mm, along with the reference dowel, 30 cm deep and separated by 50 cm (Fig. 2a). In the second experiment, we examined how the root water content affects detection with GPR. Six root samples with different water contents were created by drying two roots at 80°C for 48 h, drying two roots at 80°C for 24 h, and not drying two roots at all. Six roots in total, having three different water contents were used. The six roots and the reference dowel were buried at the same positions as in the first experiment (Fig. 4a). The mean diameter of the six roots was 34 mm and ranged from 26 mm to 46 mm. Finally, in the third experiment, we tested the effects of vertical and horizontal intervals between roots on their detection with GPR. To test the effects of horizontal intervals, we buried all roots at a depth of 30 cm and placed two roots together at four different horizontal intervals: 0 cm, 10 cm, 20 cm, and 30 cm (Fig. 5a). To test the effects of vertical intervals on root detection, seven roots were buried at a depth of 30 cm and separated horizontally by 50 cm. Below each of the seven roots, other roots were placed at various intervals. Five roots were buried at vertical intervals of 0 cm, 10 cm, 20 cm, 30 cm, and 50 cm, and two roots were buried at vertical intervals of 50 cm and horizontal intervals of 5 cm and 10 cm (Fig. 6a). The mean diameter of the root samples was 36 mm. The reference dowel was included in the horizontal interval experiment, but not in the vertical experiment because of space limitation.

Data collection

A field-portable GPR system with a 900-MHz antenna (SIR SYSTEM 10H; Geophysical Survey

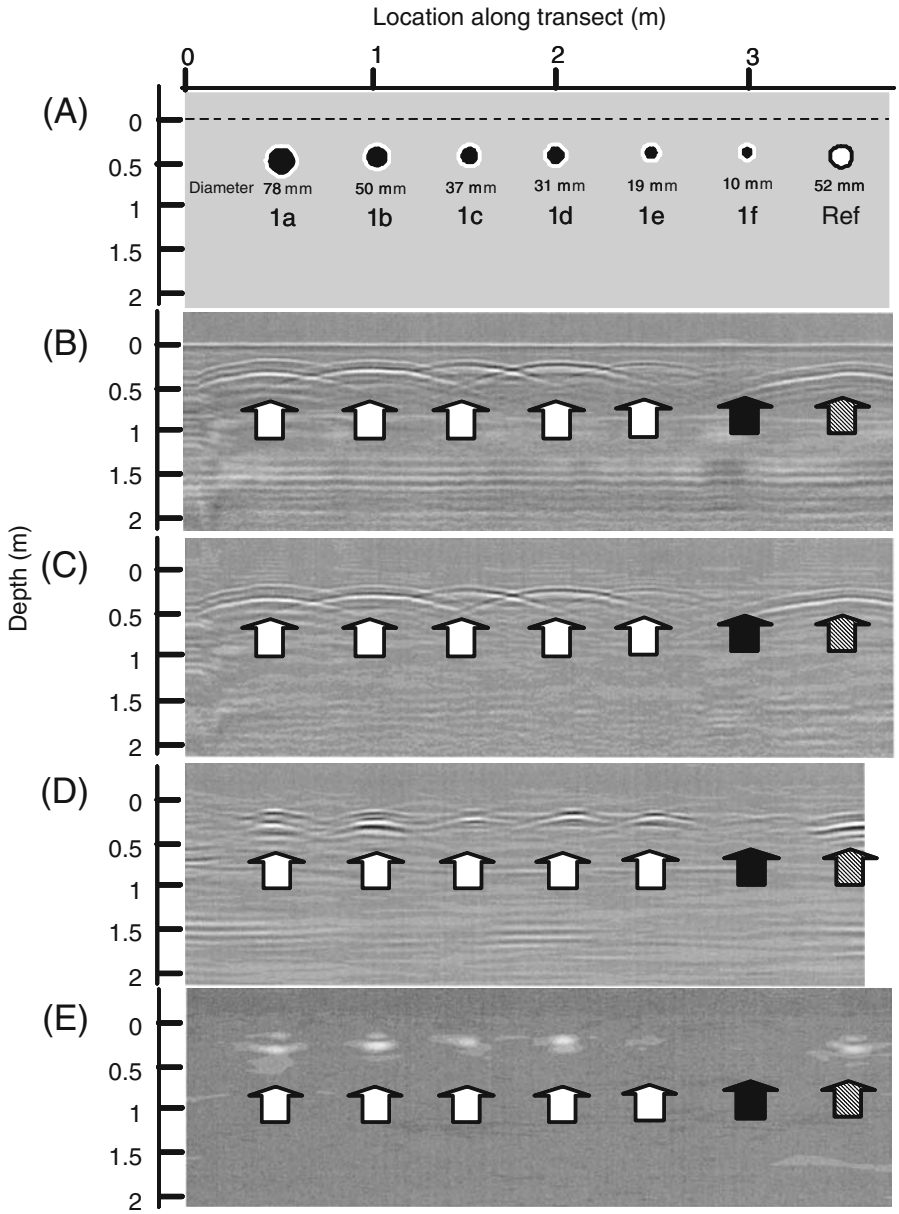

Fig. 2 **a** Positions of buried roots and dowels of *C. japonica*. **b** Representative radar profiles of buried roots before and **c** after background removal. **d** Representative radar profiles after the Kirchoff migration and **e** after the Hilbert transformation. *White arrows* indicate that the roots were visually detected and *black arrows* indicate that roots were not detected. The *oblique arrows* correspond to the reference dowels that were clearly detected

Systems Inc., North Salem, NH, USA) was used in all experiments. Eleven transects of GPR scanning were conducted 10 cm apart and perpendicular to the long axis of the roots. Radar profiles were collected along these transects. Only data from the five middle transects were used in the analysis because we confirmed that the radar passed directly over the roots in these transects. After GPR scanning, soil cores of 100 cm^3 were taken on the middle transect at the middle points of the buried roots to measure the volumetric water content within the soils for all experiments. All root and dowel samples were excavated and the positions of the buried samples were traced. The volumetric water content of each root sample was also measured.

Data processing

Radar profile normalization, filtration, and migration routines were performed with RADAN for Windows (Geophysical Survey Systems Inc.). The application of a background removal filter eliminated the parallel

bands observed in the scans resulting from plane reflectors such as the ground surface, soil horizons, and bands of low- frequency noise (Butnor et al. 2003; Fig. 2b,c). The Kirchoff migration was used to correct the positions of the objects and collapse hyperbolic diffractions based on signal geometry (Butnor et al. 2003; Fig. 2d). Root detection was determined visually according to where hyperbolas and higher amplitudes of reflected waves were observed compared to the surrounding area in the radar profiles. The waveform parameters of amplitude (dB; Dannoura et al. 2008), time interval between zero crossing (ns; Barton and Montagu 2004), and high amplitude area (dB × ns; Butnor et al. 2001) of the maximum reflected wave were extracted at the points of root detection in the radar profiles (Fig. 1). We also calculated the number of pixels within the threshold range after Hilbert transformation (Fig. 2 e; Butnor et al. 2003; Dannoura et al. 2008). This calculation was only done with the root samples from the first experiment testing the effects of root diameter. The Pearson correlation coefficient (r) was also determined in the first experiment to assess the relationships between root diameter and waveform parameters. Statistical analyses were performed in STATISTICA (StatSoft Ver. 06J, Tokyo, Japan).

Results

In the first experiment on root diameter, five roots having diameters greater than 19 mm were clearly detected using the radar profiles (Fig. 2b–e). The hyperbolas of these roots were visible and the amplitude of reflected waves decreased with decreasing root diameter (Fig. 2b). The smallest root (diameter = 10 mm) was not detected with a hyperbola and the same trend was observed with the profiles after filtering and migration (Fig. 2c,d). The volumetric water contents of the roots and soil ranged from 46% to 60% and from 11% to 18%, respectively (Table 1). Roots with larger diameters had higher amplitudes and amplitude areas of the maximum reflected waves. The reflected wave and root diameter were sign significantly correlated (Fig. 3a,c). However, the mean value of parameters of 78 mm diameter roots was less than that of 50 mm diameter roots, and the same trend was observed for 37 mm and 31 mm diameter roots (Table 1). The variation in the amplitude of the roots was greater in 50 mm diameter roots than in roots with smaller diameters (Fig. 3a). The waveform parameter of time interval was not significantly correlated with root diameter (n=30, r= 0.314, P>0.05; Fig. 3b). After the Hilbert transformation, the image areas of the root profiles were calculated (Fig. 2e). A significant positive relationship was observed between the pixels within the threshold range and root diameter (Fig. 3d).

The root volumetric water contents of the roots after drying (Table 1: root samples 2a–d) were different from the roots that did not undergo drying (Table 1: root samples 2e,f), whereas the water contents of the soils were similar and within the range of 13–14% for all root positions (Table 1). Hyperbolas in the radar profiles of the dried roots were not detected, but were seen in the roots without drying (Fig. 4). The amplitude and the amplitude area corresponded to the hyperbolas, and the values for roots after drying (root samples 2a–d) were smaller than those without drying (Table 1: root samples 2e, f). The time interval did not change with root volumetric water content (Table 1).

The radar profiles after Kirchoff migration were best at delineating roots that were closely located (Figs. 5, 6). Roots with intervals of 20 cm were individually determined using radar profiles (Figs. 5, 6). However, the smaller the interval between roots, the fainter the signals were after migration, especially within the vertical interval of 20 cm (Figs 5, 6). The waveform parameters were not individually determined for the roots having intervals of 20 cm (Table 2: root samples 3a and 3a', 3b and 3b', 4a and 4a', 4b and 4b') because the values of the parameters at the buried position could not be distinguished from those of the background. The amplitude and the area at undistinguished positions 3a and 3a' did not have values two times higher than two individual roots, such as 3c and 3c'.

Discussion

The major findings of our study were that the intervals and volumetric water contents of buried roots affected root detection with GPR: the narrower the intervals between roots, the more the reflected waveforms were overlapped and difficult to differentiate. To our knowledge, this is the first study on the

Table 1 Mean root diameter, water content of root and soil, waveform parameters, and visible root detection using ground-penetrating radar in the experiments on the effects of root diameter and root volumetric water content

Root sample no.	Diameter[a]	Water content[b]		Waveform parameter[a]				Visible root detection[d]
		Root	Soil	Amplitude of reflected wave	Time interval	Amplitude area	Pixels within the threshold range	
	(mm)	(%)	(%)	(dB)	(ns)	(dB x ns)	(pixels)	
Experiment on root diameter								
1a	78±2	48	18	60±11	1.4±0.2	49±5	115±23	○
1b	50±2	60	14	82±8	1.0±0.1	50±4	112±14	○
1c	37±2	57	11	51±3	1.1±0.1	37±6	74±18	○
1d	31±3	46	13	53±5	1.1±0.1	37±6	73±18	○
1e	19±2	60	14	34±3	0.9±0.1	20±4	40±10	○
1f	10±0	51	14	19±3	1.2±0.1	15±1	2±1	×
Experiment on root volumetric water content								
2a	46±4	5	14	15±2	0.9±0.1	8±1	N.D.[d]	×
2b	27±2	5	14	18±4	0.8±0.0	9±2	N.D.	×
2c	26±2	10	14	10±1	1.0±0.2	6±1	N.D.	×
2d	28±3	21	13	10±2	1.0±0.1	6±1	N.D.	×
2e	39±3	48	14	61±8	0.8±0.0	30±4	N.D.	○
2f	35±2	56	14	59±6	1.0±0.1	36±2	N.D.	○

[a] Means ± S.E. of five samples, [b] Volumetric water content, [c] Root detections were visibly determined using five radar profiles, [d] Not determined

effects of intervals on the accurate detection of tree roots with GPR. Our results suggest that individual roots that have intervals greater than 20 cm, both horizontally and vertically, can be accurately identified using 900-MHz GPR, while roots with intervals less than 20 cm cannot be individually distinguished and are often recognized as one root. For example, the amplitude of the reflected wave of two overlapping roots, such as roots 3a and 3a', was 59. This value was the same as that for root 3c', which occurred

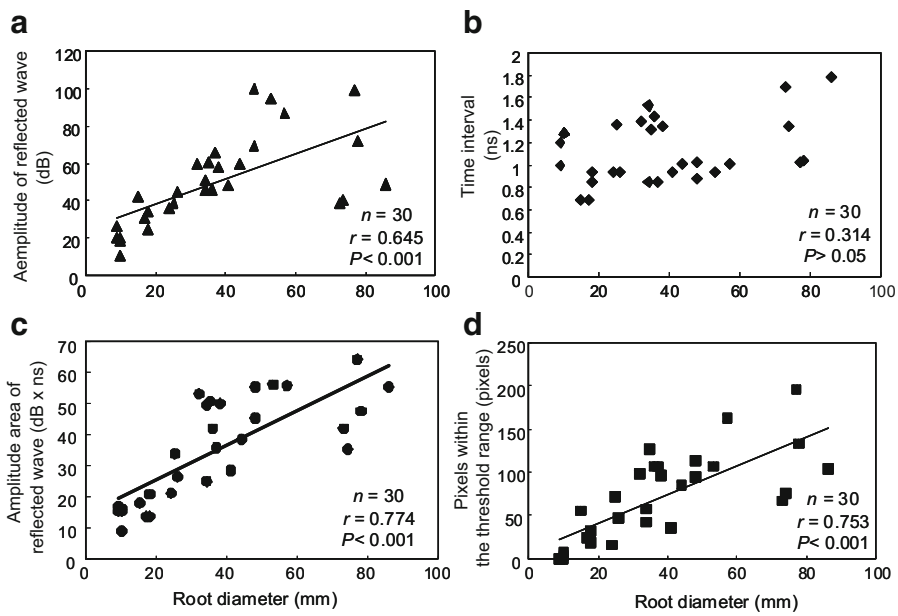

Fig. 3 Relationships between root diameter of *C. japonica* and **a** amplitude, **b** time interval with zero crossing, **c** amplitude area of maximum reflected waveform, and **d** pixels within the threshold range from the experiment on the effects of root diameter. The *lines* in **a**, **c**, and **d** indicate significant linear regression relationships ($P<0.001$)

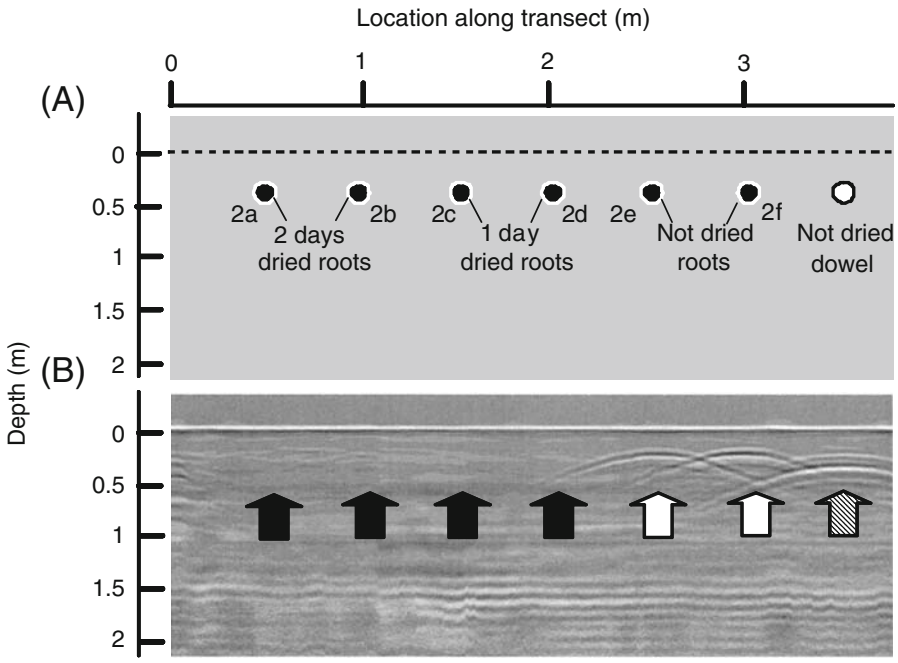

Fig. 4 **a** Positions of buried roots and **b** representative radar profiles for the buried roots before background removal in the experiment on the volumetric water contents of roots. *White arrows* indicate that the roots were visually detected and *black arrows* indicate that the roots were not detected. The *oblique arrow* corresponds to the reference dowel that was clearly detected

alone and had a value of 60 (Table 2). These results suggest that overlapping roots that cannot be identified using GPR lead to an underestimation in the distribution and biomass of coarse roots. In the field, this may be a limiting factor in root detection using GPR because it is common that roots of *Cryptomeria japonica* are less than 20 cm apart from each other (Karizumi 1976). Furthermore, Stokes et al. (2002) revealed that two roots crossing over each other could not be individually identified using 450-MHz GPR.

Our study also showed that roots larger than 19 mm in diameter at a depth of 30 cm and roots having a 26 mm diameter at a depth of 80 cm could be identified using 900-MHz GPR (Tables 1 and 2).

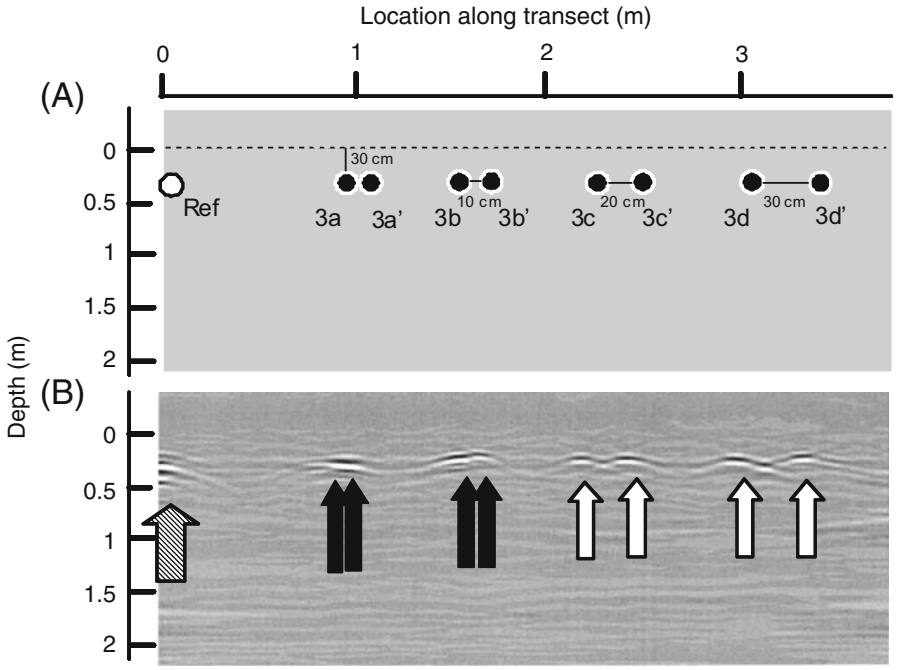

Fig. 5 **a** Positions of buried roots and **b** representative radar profiles of buried roots after the Kirchoff migration in the experiment on horizontal intervals. *White arrows* indicate that the roots were individually differentiated and *black arrows* indicate that the roots were not differentiated. The *oblique arrow* corresponds to the reference dowel that was clearly detected

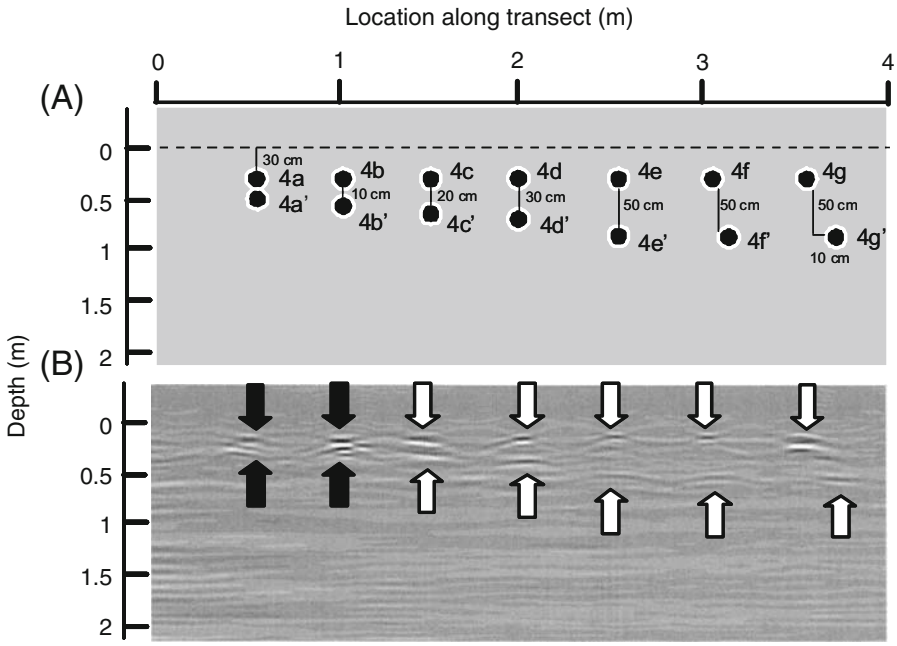

Fig. 6 **a** Positions of buried roots and **b** representative radar profiles of buried roots after the Kirchoff migration in the experiment of vertical intervals. The *white arrows* indicate that the roots were individually differentiated and the *black arrows* indicate that the roots were not differentiated

The effects of root diameter and depth using GPR have been investigated (Table 3), and in general, the frequency of GPR is correlated with the depth of penetration and resolution (Barton and Montagu 2004). High-frequency systems (e.g., 100 MHz) provide information to a depth of 30 m, whereas a 2-GHz system is unlikely to provide useful information beyond approximately 0.2 m (Barton and Montagu 2004). A 450- or 500-MHz system can identify roots having 30 mm diameters at depths of 2 m (Hruska et al. 1999; Stokes et al. 2002; Barton and Montagu 2004), while roots as small as 5 mm up to 50 cm were detected using a 1.5-GHz system (Butnor et al. 2001). Using a combination of GPR with frequencies ranging from 400 MHz to 1.5 GHz may more accurately detect tree roots greater than 5 mm. However, fine roots less than 2 mm, which are good indicators of environmental stress (Hirano et al. 2007), cannot be detected using GPR (Stover et al. 2007).

We confirmed that the volumetric water content of roots is a crucial factor in tree root detection using GPR. GPR wave propagation through a medium is mainly controlled by the dielectric permittivity, and the contrast is shown by the reflection coefficient *R* (see Introduction). Generally, water content is the most dominating factor among the dielectric properties in soils because water contents relate well with the dielectric properties (Hagrey 2007). Therefore, the larger the difference in water content between the roots and soil, the higher the value of *R*. The dielectric permittivity of soil has been shown to range between 4 and 30 in geophysics studies and in studies on soil (Hagrey 2007). In contrast, few studies have been done on the dielectric permittivity of roots. Hagrey (2007) showed that the electric permittivity of wood cellulose ranges between 4.5 and 22. However, it is the contrast in dielectric permittivity, or the contrast in water content between roots and soil that creates the reflection pattern in GPR. Therefore, we need to investigate the dielectric permittivity and water content of tree roots. Until now, few studies have focused on the volumetric water content of roots using GPR, while soil conditions have received greater attention (Butnor et al. 2001). Our previous study using dowels of *C. japonica* (Dannoura et al. 2008) suggested that differences in volumetric water contents between soils and buried samples affect root detection using GPR. In this study, we studied *C. japonica* roots having different volumetric water contents. We found that dried roots with a volumetric water content of less than 20% could not be detected, whereas roots with contents of approximately 50% were clearly identified. This result suggests that coarse woody debris, residual root fragments, and

Table 2 Mean root diameter, root intervals, water content of root and soil, waveform parameters, and visible root separation using ground-penetrating radar in the experiments on horizontal and vertical intervals

Root sample no.	Diameter[a]	Horizontal and vertical interval[b]	Water content[c]		Waveform parameter[a]			Visible root separation[d]
			Root	Soil	Amplitude of reflected wave	Time interval	Amplitude area	
	(mm)	(cm, cm)	(%)	(%)	(dB)	(ns)	(dB x ns)	
Experiment on horizontal interval								
3a	60±9	0, 0	52	12	59±12	1.0±0.2	36±7	×
3a'	31±6		48	12				
3b	49±7	10, 0	59	13	78±17	0.8±0.1	38±8	×
3b'	30±4		50	7				
3c	30±2	20, 0	48	13	71±9	0.7±0.0	34±6	○
3c'	28±4		67	13	60±9	0.9±0.1	33±6	
3d	26±3	30, 0	53	13	67±9	0.9±0.0	40±6	○
3d'	32±4		50	13	59±8	0.9±0.0	33±5	
Experiment on vertical interval								
4a	47±3	0, 0	61	13	38±4	0.9±0.1	22±2	×
4a'	32±4		50	13				
4b	41±2	0, 10	52	14	67±10	0.8±0.0	32±5	×
4b'	28±4		48	14				
4c	41±2	0, 20	55	13	40±10	0.9±0.1	22±5	○
4c'	32±4		47	13	32±5	1.0±0.0	20±3	
4d	28±4	0, 30	55	14	45±3	0.8±0.0	22±2	○
4d'	30±2		67	14	45±6	0.9±0.1	25±3	
4e	31±1	0, 50	50	13	50±3	0.8±0.1	24±2	○
4e'	36±2		48	13	41±7	0.9±0.0	23±3	
4f	26±3	5, 50	53	13	49±3	0.8±0.0	25±2	○
4f'	31±3		59	13	35±3	0.9±0.1	20±3	
4g	45±3	10, 50	51	14	40±6	0.9±0.1	23±3	○
4g'	33±1		56	14	46±8	1.1±0.1	32±6	

[a] Means ± S.E. of five samples, [b] Horizontal and vertical intervals between two adjacent samples, [c] Volumetric water content, [d] Root separations were visibly determined using five radar profiles

Table 3 A comparison among studies using various frequencies in ground-penetrating radar on the detection of diameter and depth in tree roots

Radar frequency	Tree species	Soil	Detected root diameter		Detected root depth		Reference
			min	max	min	max	
(MHz)			(cm)		(cm)		
400	*Pinus taeda*	Gergeville soil	3.7	10	-	130	Butnor et al. (2001)
450	*Quercus petraea*	Luvisoil	3–4	-	-	200	Hruska et al. (1999)
500, 800	*Eucalyptus* sp.	River sand	1	10	15	155	Barton and Montagu (2004)
900	*Prunus persica*	Faceville fine sandy loam	2.5	8.2	11	114	Cox et al. (2005)
900	*Cryptomeria japonica*	Sandy granite soil	1.1	5.2	-	-	Dannoura et al. (2008)
900	*Cryptomeria japonica*	Sandy granite soil	1.9	7.8	30	80	This study
1,500	*Populus deltoides*	Lakeland soil	0.6	-	-	45	Butnor et al. (2001)
1,500	*Pinus taeda*	Wakulla soil	0.5	-	-	50	Butnor et al. (2001)

dead roots that have lower water contents in the soil will not be detected using GPR, leading to an underestimation of carbon stocks in forest soils. However, our results support those of previous studies suggesting that GPR can be a useful tool in tree health diagnostics by quantifying internal root water content (Hruska et al. 1999; Stokes et al. 2002). Further clarification is necessary with regard to the relationships among volumetric water content, root detection, and soils using various frequencies of GPR.

In conclusion, we evaluated the effects of root diameter, root volumetric water content, and vertical and horizontal intervals between roots on root detection using 900-MHz GPR under optimal sandy soil conditions. We found that roots of *C. japonica* that have diameters greater than 19 mm, volumetric water contents greater than 20%, and depths less than 80 cm with intervals more than 20 cm, could be detected. Intervals less than 20 cm between neighboring roots and low volumetric water contents will result in underestimating the biomass of coarse roots. These results suggest that accurate root biomass cannot be estimated using single frequency of GPR, such as 900 MHz frequency used in this study, because root size and interval are limiting factors, even under our controlled conditions. The utility of combining two or three frequencies with GPR for estimating root biomass should be investigated and evaluated. Although various factors affect detection of roots using GPR, such as root position and the conditions surrounding roots, for example, the volumetric water content and the existence of small stones, GPR also warrants further study because it is a nondestructive method with the potential to be a useful tool in detecting coarse roots.

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