Geoderma Regional 34 (2023) e00659

Contents lists available at ScienceDirect

Geoderma Regional

journal homepage: www.elsevier.com/locate/geodrs

Unmasking adaption of tree root structure in agroforestry Systems in Switzerland using GPR

Johannes Hugenschmidt [a], Sonja Kay [b,*]

[a] Eastern Switzerland University of Applied Sciences, Rapperswil, Switzerland
[b] Agroscope, Agricultural Landscape and Biodiversity, Zurich, Switzerland

ARTICLE INFO

Keywords:
Ground penetrating radar (GPR)
Agroforestry systems
Tree root structure
Carbon storage
Cambisols

ABSTRACT

The interest in agroforestry systems has increased considerably in recent years. The systems are more resilient to climate change and offer advantages related to soil health and biodiversity. Although the aboveground impacts of agroforestry systems are well known, the knowledge concerning root growth of trees remains limited.

This study tested the applicability of a non-destructive investigation method, the ground penetrating radar (GPR), to detect tree roots. We mapped two 80-year-old pear trees in cropland and investigated the impact of tilled and no-tilled management on the root system architecture especially in deeper soils (>0.6 m).

The root mapping method was successful, we determined the main roots of the tree up to a depth of 0.75 m. In addition, we found tillage significantly impacted root distribution. Tillage removed tree roots almost completely to a depth of 0.4 m. The bulk of the roots was present at a depth of 0.6 to 0.75 m (83% of the roots) in the tilled section, while it was found at 0.3 to 0.55 m (74%) in the no-tilled section. Detected roots indicated an over-compensation by additional roots in the tilled section that were not formed without tillage.

Overall, we found agroforestry trees were rooting deeper, below the managed cropland and therefore colonise different soil layers. Thus, the potential volume of water and nutrient intake was enlarged, which might enhance the resilience of the combined production systems. In addition, our approach presents a method for future non-destructive and continuous monitoring of tree roots and their development.

1. Introduction

Agroforestry systems, i.e. the integration of trees and woody structures in agricultural cropland or pasture, store significant quantities of carbon in above- and below-ground biomass (Cardinael et al., 2017; Kay et al., 2019). They are, therefore, appreciated for their positive impact on climate mitigation and proposed as a carbon farming scheme in Europe (COWI, Directorate-General for Climate Action (European Commission), Ecologic Institute, IEEP, 2021). However, quantifying the amount of carbon stored remains challenging. Studies exist on above-ground biomass growth in various European agroforestry systems, e.g. olive trees in Italy (Spinelli and Picchi, 2010), poplar tree development in England (Burgess et al., 2005; Graves et al., 2010) or short rotation coppice in Germany (Graß et al., 2020). Limited information is available for belowground or soil organic carbon potential within agroforestry systems. A review described a broad range of results that varied based on tree species and age, as well as soil type and biogeographical region (Pellerin et al., 2020). Finally, little data exist on belowground root growth of crops and trees as well as the tree root system architecture in European agroforestry systems. A study investigating mature trees on dikes and small forest stands in France by Zanetti et al. (2015) revealed that environmental constraints in soil type and water availability had the strongest influence on root growth. The physical parameters even surpassed the tree species' individual rooting systems. If we expand these findings to agroforestry systems, several questions arise. How do tree roots adapt to external effects such as agricultural management? Do tree and crop roots grow in the same soil depth or do they exploit different soil compartments? Do tree roots respond to agricultural soil management strategies such as tillage?

This underground performance of trees and agricultural crops is crucial as they could either compete with or benefit from each other. However, a major limitation of studying root systems is (partly) destroying the roots when exploring soil horizons, e.g. by coring, trenching, profile walls (van Noordwijk et al., 2015) or root trenches (Upson and Burgess, 2013). Moreover, these sampling techniques only allow for a glimpse of insight in time and space, as the sampling area is

* Corresponding author at: Agroscope, Research Group Agricultural Landscape and Biodiversity, Reckenholzstrasse 191, 8046 Zürich, Switzerland.
E-mail address: sonja.kay@agroscope.admin.ch (S. Kay).

https://doi.org/10.1016/j.geodrs.2023.e00659
Received 12 January 2023; Received in revised form 2 June 2023; Accepted 6 June 2023
Available online 10 June 2023

small and replications addressing tree growth effects after several years are impossible.

The ground penetrating radar (GPR) approach can overcome these limitations. GPR is a non-destructive geophysical investigation method that allows the repeated mapping of crop and tree root horizons. Although the literature related to the application of GPR for imaging and monitoring tree roots is increasing, there are still few studies focused on agroforestry systems. Hruska et al. (1999) described the mapping of roots by acquiring data along lines in two orthogonal directions. Their results show root systems in great detail, suggesting an intuitive completion of the roots detected with GPR. Guo et al. (2013) reviewed coarse root detection and quantification studies highlighting that local soil conditions (best under dry conditions), root electromagnetic properties, and GPR antenna frequency (low-frequency GPR waves result in deeper detection, higher frequency GPR in higher resolution) are essential factors for high quality results. Liu et al. (2018) explored the applicability of GPR to detect the fine roots of agricultural crops using high-frequency antennas and were able to predict bulk root biomass and diameter. Almeida et al. (2018) focused on applying GPR to estimate subsurface biomass and optimise parameters for data acquisition. While Alani et al. (2018) aimed to optimise acquisition and processing parameters, including developing a root tracking algorithm. Based on the GPR outcomes, Cui et al. (2011) generated a method for estimating belowground biomass. Finally, Alani and Lantini (2020) provided a literature review of tree root assessment and monitoring using GPR and highlighted the need for further research.

In an attempt to merge the potential of GPR technologies with agroforestry land management, Borden et al. (2014, 2017) studied five tree species (*Quercus rubra* L., *Juglans nigra* L., *Populus deltoides* × *nigra* DN-177, *Picea abies* L. Karst, and *Thuja occidentalis* L.) among 25-year-old trees on sandy loam soils in Canada and found differences between the species' rooting depth and root system architecture. Using a high-frequency GPR, they detected roots to a depth of 0.6 m, deep coarse roots were barely detected. The GPR methodology has only been applied to a very limited number of tree species in agroforestry systems, the majority of which were juvenile trees. It is hypothesised that fully-established agroforestry systems colonise multiple above- and below-ground layers, with crop roots in the upper soil layer and tree roots in deeper soil horizons (van Noordwijk et al., 2015). It remains unclear how adult trees and their roots adapt to agricultural management (fertilization, tillage) in a managed agroforestry regime.

In this study, we therefore tested the applicability of the non-destructive investigation method GPR to detect (deeper) roots within arable land and aimed to investigate the root system architecture of adult fruit trees in agroforestry systems. Given the typical design of a modern agroforestry systems with lines of single trees within cropland, we addressed the following research questions: i) is the detection of tree roots possible in deeper soil layers (>0.6 m) using GPR techniques? and ii) whether and how does the root system architecture of adult fruit trees (>80 years) respond to the impact of soil management, especially tillage and no-tillage?

These findings aim to gain basic understanding of how crop and tree roots inhabit soils in agroforestry systems. Do they compete for water and nutrients (i.e., exhibit competition) or do trees exploit deeper soil compartments (below arable cropping), benefit from the nutrient and water surplus of the arable production and serve as a 'nutrient pump' and 'safety net' for crops (i.e., exhibit complementarity)?

2. Material and methods

2.1. Case study location

We investigated two pear trees near the villages of Watt and Rümlang, both in the Canton of Zürich in Switzerland. The surrounding fields were continuously used for arable production, with crop rotations that included wheat, maize, ley, and rapeseed. Additionally, regular tillage was carried out.

Pear tree 1 (P1) is located at 47°27′01.8"N and 8°28'53.0"E in Watt, at approximately 482.1 m above sea level. The soil type is a lime brown earth consisting of sandy loam, where plants can grow to a depth of up to 0.7–1 m. A second pear tree (P2) exists at this site. According to the owner and aerial images, the area between the two trees was never tilled as it was always maintained as a shady picnic area. This enabled us to inspect two areas, one with tillage (A1) and one without tillage (A2).

Pear tree 3 (P3) is located at 47°26′05.0"N and 8°30'15.1"E in Rümlang, at approximately 446.3 m above sea level. The soil type is a Parabrown earth. The topsoil is sandy loam up to 0.5–0.7 m and the subsoil transitions into loam or loamy silt. This tree was used for validation only.

The exact planting date of either tree is unknown. However, P1, P2, and P3 feature on aerial images from 1946 and 1932, respectively (swisstopo, 2021). Therefore, we concluded that all trees were older than 80 years.

We measured tilled areas (in yellow, hereafter A1 and B1, Fig. 1a and b) and a no-tilled area (in blue, hereafter A2, Fig. 1a). Using the trees P1 or P3 as centre point, we measured 5.5 m in three directions, resulting in a datacube of 11 m × 5.5 m, as shown in Fig. 1c. For the no-till area A2, tree P1 was used as centre point. It should be noted that tree P2 was located at the top border of the measured area (Fig. 1a). Areas in close proximity to the trees (~2 m) were covered by grassland and not tilled. We therefore divided the tilled areas into i. close to the trees with grassland (A1_i, B1_i) and ii. tilled cropland (A1_ii, B1_ii).

2.2. Ground penetrating radar

Ground penetrating radar (GPR) (Carrick, 2017; Daniels, 2004; Hugenschmidt, 2010, 2012) is a geophysical method that uses high-frequency electromagnetic waves to identify changes in the subsurface. It is based on the emission, reflection, and reception of electromagnetic waves (Fig. 2a). An electromagnetic impulse is emitted via a transmitter antenna. When changes in the subsurface are encountered, e.g., a layer interface, part of the energy is reflected and can be recorded via the receiver antenna. A time series (trace) containing information on the subsurface can be obtained from a single measurement. As the method is rapid (i.e., hundreds of measurements registered per second), vast amounts of data can be recorded and processed using sophisticated algorithms. GPR inspections are usually carried out in 2D along lines (radargram; Fig. 2b) or 3D by scanning whole areas (datacube; Fig. 2c). This method is used frequently in geology (i.e., KurjaŃski et al., 2021), non-destructive testing (i.e., Bianchini Ciampoli et al., 2021) and archaeology (i.e., Gallegos-Poch et al., 2023).

A dataset containing information on the subsurface beneath the antenna along a line is called a radargram or 2D dataset. The antenna is moved along a line, recording traces at fixed intervals of, for example, 0.25 cm. If data are recorded along several parallel lines, information on the subsurface beneath an area can be obtained, forming a dataset known as a datacube or 3D dataset. Subsets, e.g., containing data from a certain depth (time slice) or single radargrams, can be extracted from this type of dataset. The velocity of the radar signal in the subsurface has to be known to convert the original time scale to depth. In the present study, a signal velocity of 0.08 m/ns was used. This velocity was obtained during migration, a processing step aimed at collapsing diffraction hyperbolae.

Fig. 2 shows the geometry to acquire data for mapping tree roots. The antenna was moved along parallel lines over the surface. A survey wheel measured the distance, allowing traces to be recorded at fixed intervals. In this survey, the distance between single traces was 0.25 cm and each trace consisted 1024 samples (values). The antenna was connected to the central unit. Based on pre-survey tests (Hugenschmidt and Kay, 2022), we opted to use an antenna with a nominal centre frequency of 400 MHz. In general, it can be stated that high frequency antennas provide high resolution at the expense of a limited inspection depth,

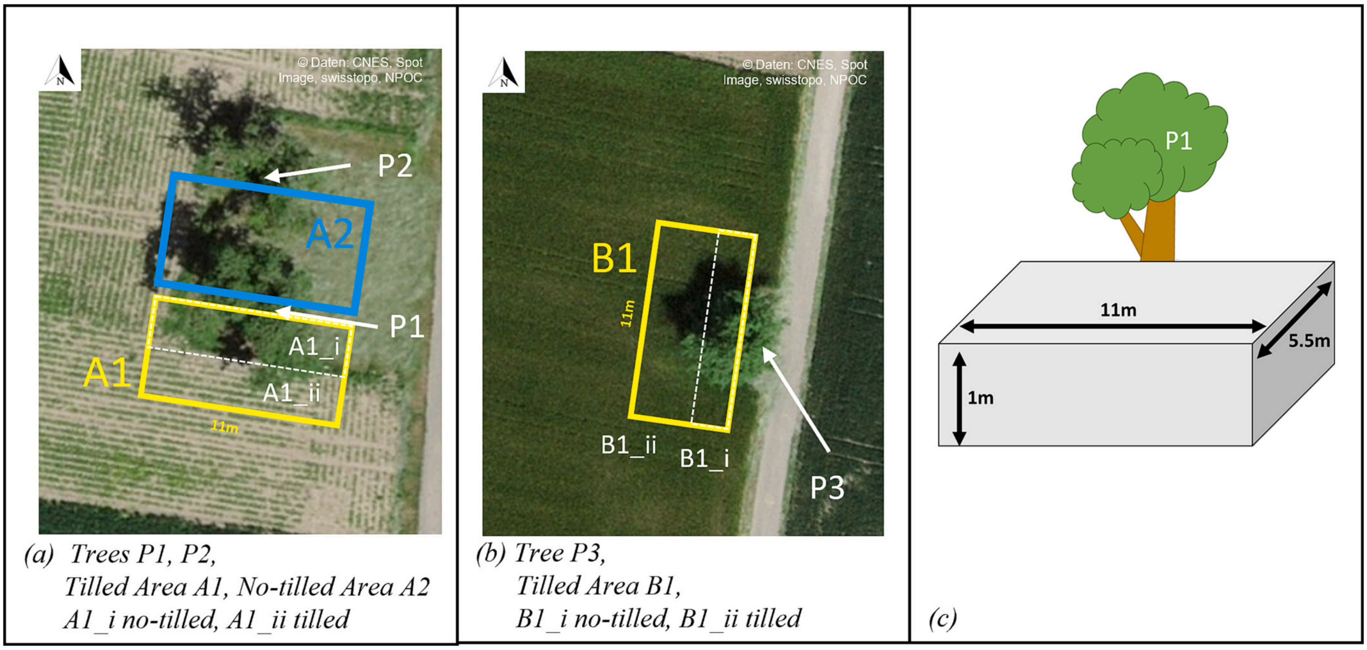

Fig. 1. (a) Aerial image of pear tree 1 (P1) and tree 2 (P2) with the tilled area (yellow, A1, 11 m × 5.5 m) and no-tilled area (blue, A2, 11 m × 6 m), A1 is further divided into the no-tilled A1_i and the tilled A1_ii; (b) aerial image of pear tree 3 (P3) with the tilled area (yellow, B1, 11 m × 5.5 m) divided into no-tilled B1_i and tilled B1_ii; (c) example of an acquisition geometry of GPR measure.

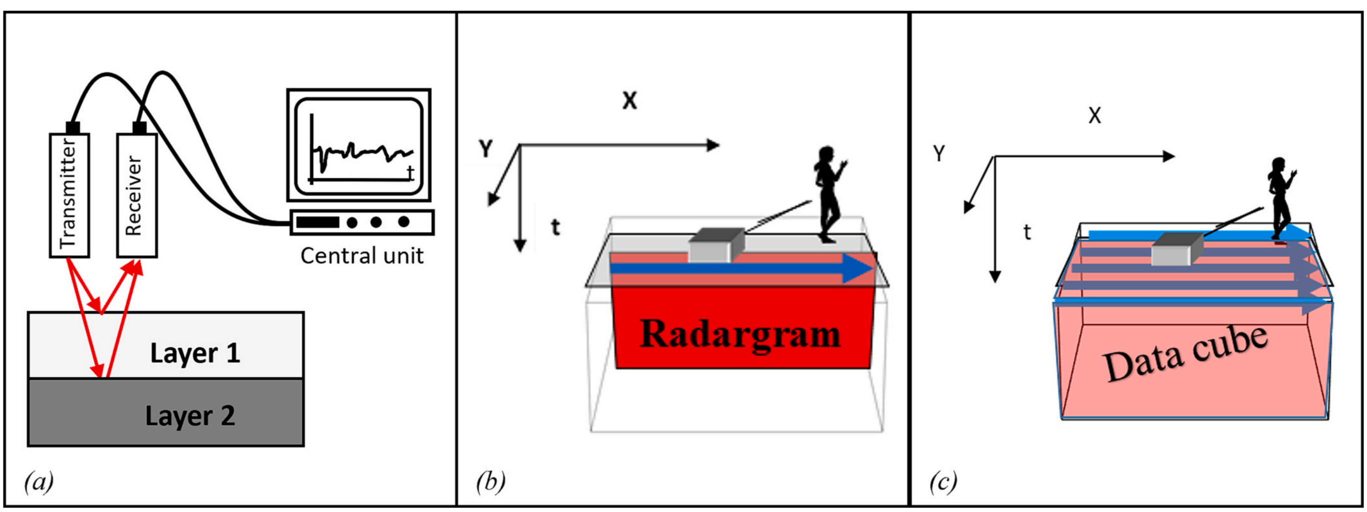

Fig. 2. (a) Principles of GPR with emitted and reflected signal (red arrows); (b) acquisition of a 2D dataset (radargram); (c) acquisition of a 3D datacube.

whereas low frequency antennas provide an increased inspection depth at the expense of a limited resolution. We opt for the 400 MHz, which resulted in an increased inspection depth and focused on root structure.

Moreover, we estimated the minimal detection diameter to be approximately 1.0 cm based on a pre-survey test which included an excavation of roots (Hugenschmidt and Kay, 2022). This estimation is based on a comparison of root points obtained with a GPR survey and roots found in an excavation along a line with a length of several meters and a depth of about 0.4 m. All roots with a diameter of 1.0 cm and above were identified as root points in the GPR survey. Most roots with a diameter of <1.0 cm remained unidentified in the GPR survey.

An example of an acquisition geometry is shown in Fig. 1c. Parallel lines with a distance of 5 cm between single lines were recorded across an area measuring 11 m × 5.5 m. The time required to record a dataset for one tree was approximately 5 h. A summary of the acquisition parameters is presented in Appendix A.

2.3. Data processing and interpretation

Data processing was carried out using the REFEXW software (Version 7.2.3, Sandmeier Scientific Software, 2020) and included bandpass filtering, static correction, stacking, gain control, background removal and 3D Kirchhoff migration. A summary of the processing parameters is presented in Appendix B. The interpretation was performed manually by marking the positions of roots in the 3D datasets. A datapoint was marked as a root if it appeared as a linear structure in several consecutive position and could thus be distinguished from stones or other obstacles.

The position of marked root points could be output as x, y, and depth coordinates (root points) for further analysis. The resulting GPR datasets allowed us to distinguish between roots and other objects, e.g., drainpipes, based on their specific shape. Data were recorded and processed in 3D. We verified the GPR outcomes by a soil map (Peyer et al., 1998), a drainage map (Amt für Landschaft und Natur, 2019) and farmers knowledge.

3. Results

In line with our research questions, we divided the results section in two parts. First focussing on the methodological approach and its applicability to detect deep roots and second, looking into the specifications of agroforestry systems and the tree root system architecture related to different soil management options.

3.1. Applicability of GPR method for deep root detection

The time slices shown in Figs. 3 and 4 show the existence and location of the roots from several depths.

The non-tilled area A2 with trees P1 (at x: 0 m, y: 6.5 m) and P2 (at x: 6 m, y: 8.5 m) is presented in Fig. 3. Approximately 1300 root points were detected in the no-tilled area. These visible roots, depicted as root points, range from 0.11 m to 0.63 m soil depth (see Fig. 3g). In addition, we noted a drainage pipe at 0.8 m and mainly noise at 1.0 m. Verifying the GPR outcomes by a soil map (Peyer et al., 1998), a drainage map (Amt für Landschaft und Natur, 2019) and farmers knowledge, we found the drainage pipe mapped at the expected location (see Fig. 3e).

The time slices generated at different depths of the tilled area A1 with tree P1 can be seen in Fig. 4 (x: 0 m, y: 4.5 m). The depth distribution of all detected roots was between 0.11 m and 0.73 m (Fig. 4d). At a depth of 1 m, the GPR showed only noise. A top view of the root points from all depths is presented in Fig. 4e.

Although the mapping process was successful even in deeper soil horizons (up to approximately 0.75 m), it should be noted that only roots with a minimal diameter could be mapped because of the physical limitations of the method used.

3.2. Specifications of the tree root system architecture in agroforestry systems

To address our second research question, we compared tree root distribution with and without tillage using pear tree P1 as an example.

3.2.1. Comparison of the tree root system architecture with (A1) and without tillage (A2) for tree P1

Fig. 5 gives an overview of tree root points in A1 (tilled) and A2 (no-tilled) at a depth of <0.4 m. No tree root points were found at a depth of <0.4 m in the tilled area (in A1_ii, Fig. 5a). In the no-tilled area (A2, Fig. 5b), the majority of the tree root points were found in the vicinity of the trees; however, no sharp boundary was detected.

The percentage of tree root points and the total number of root points per square meter are presented in Table 1. For <0.3 m, we detect 40% root points in the no-till A2, but only 13% in the tilled A1. An opposite effect was found in deeper soils. While in the tilled area only 19% root points were found in deeper soils (>0.5 m), around 31% root points were found in the tilled area. This shift from depths <0.3 m towards greater depths was only found in the tilled area A1. The number of root points per square metre was considerably lower in tilled soil suggesting that additional roots at greater depths may compensate for the missing roots at shallow depths. Accordingly, these findings suggest an overcompensation for the roots removed by tillage.

3.2.2. Comparison of the tree root system architecture with (A1_ii) and without tillage (A1_i) for P1

In the year 2020 and 2021, the tilled field within the investigated area A1 (A1_ii) started 2.5 m from the tree (Fig. 1a). These 2.5 m around the tree are covered by grass. As the grass area (A1_i) may have varied previously, the analysis above included all root points in the investigated area A1, even if they occurred outside the tilled section in the grass around the tree.

Hence to evaluate the impact of the tillage, we divided the area A1 into a tilled (A1_ii) and a no-tilled subsection (A1_i) and examined them separately. The percentage of root points in the tilled subsection A1_ii was only 15% of the total number of root points suggesting that compensation occurred mainly in the no-till subsection. The graph showing the percentage versus depth ranges in the tilled subsection (Fig. 6b) shows that most of the root points (83%) were within depths of 0.6 m and 0.75 m. <5% of the root points were found beyond a depth of 0.75 m. The corresponding result for the no-till subsection is presented in Fig. 6a. Most of the root points (75%) were within a depth interval between 0.3 m and 0.55 m.

3.2.3. Validation of results using data from the tree P3

Results obtained for P3 were mostly consistent with those obtained for P1. Fig. 7a shows the 1851 root points obtained for P3. In 2020, the tilled section within the investigated area (B1_ii, Fig. 1b) started 2 m from the tree.

Most of the root points (76%) for P3 in B2 occurred within depths of 0.3 m and 0.45 m (Fig. 7a). <10% of the root points were detected beyond a depth of 0.55 m. Moreover, nearly all of the P3 roots were removed to a depth of 0.3 m. This suggests that tillage might be shallower for P3 than for P1. Thus, the effect of tillage was limited to a depth of approximately 0.3 m for P3, while it was to 0.4 m for P1.

4. Discussion

4.1. Limitations of the study

4.1.1. Technical limitations of GPR

GPR provides several advantages for the mapping of tree roots. It is a non-destructive method and allows for fast and repeated mapping in comparison to conventional soil sampling techniques (Xie et al., 2020).

Nevertheless, GPR also presents several limitations. In this study, our GPR mapping process could only map roots with a minimal diameter of 1 cm. A similar approach was used by Xie et al. (2020), who investigated water infiltration by urban trees and focused on coarse roots with a diameter >1 cm. But there are also other approaches, e.g., Aboudourib et al. (2019) investigated the correlation between water content and root diameter, allowing them to estimate root diameters <1 cm. And also, Zhang et al. (2019) determined root diameter in citrus trees >6 mm. According to de Aguiar et al. (2021), the accuracy of estimating root diameters strongly depends on the roots' moisture content.

In addition, vertical roots are difficult to detect using GPR due to their orientation perpendicular to the soil surface. This creates a small cross-sectional area for radar signals to interact with and limits the detectability of these roots. This limitation was studied in more detail by Wang et al. (2020). They investigated GPR signals from coarse roots by testing different orientations in situ and found that vertical roots did either not reflect or were difficult to detect, mainly due to geometrical reasons. It may, therefore, be desirable to combine this method with a model approach to overcome these limitations.

Stokes et al. (2002) found limited similarities of the root system architecture reconstruction to the actual observation obtained in the field by excavation, especially in vertical views. These similarities are to be expected where vertical roots are concerned. However, as shown in this study, the overall quality of a GPR survey can be improved significantly using full three-dimensional data acquisition and processing. The limitations related to noise and the difficulties encountered during data interpretation (Lorenzo et al., 2010) could be minimized to a large extent by using a lower frequency antenna and full 3D data acquisition and processing. Implementing these techniques would potentially increase the data quality considerably, thus facilitating the interpretation of data at the expense of more time required for data acquisition and processing.

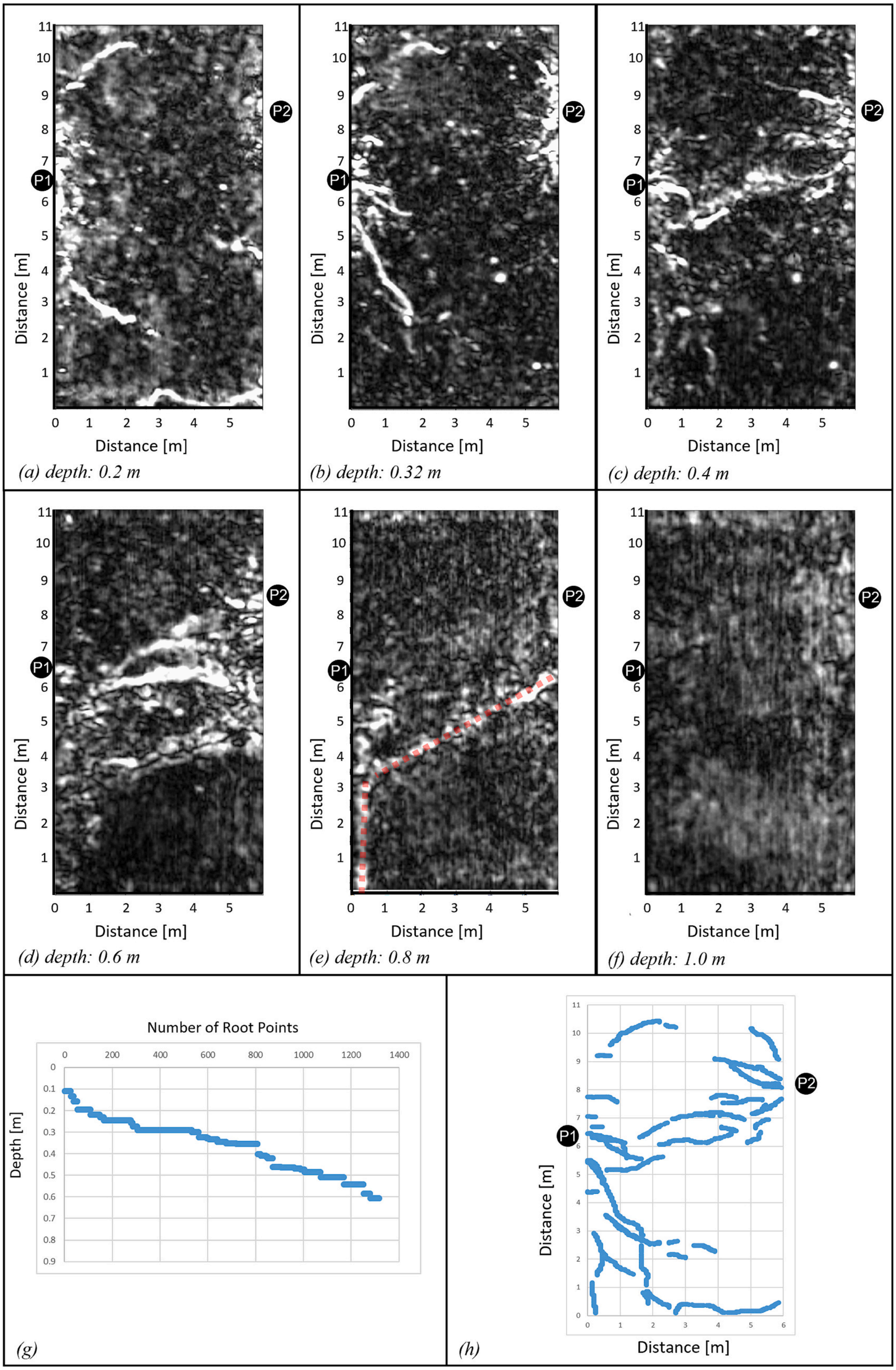

Fig. 3. No-tilled area A2 with locations of the trees (P1, P2) marked by black circles. Time slices from depths of (a) 0.2 m, (b) 0.32 m, (c) 0.4 m, (d) 0.6 m, (e) 0.8 m (drainage pipe marked with dashed red line), (f) 1.0 m without tillage; (g) depth distribution of roots; (h) result of interpretation [map of detected roots].

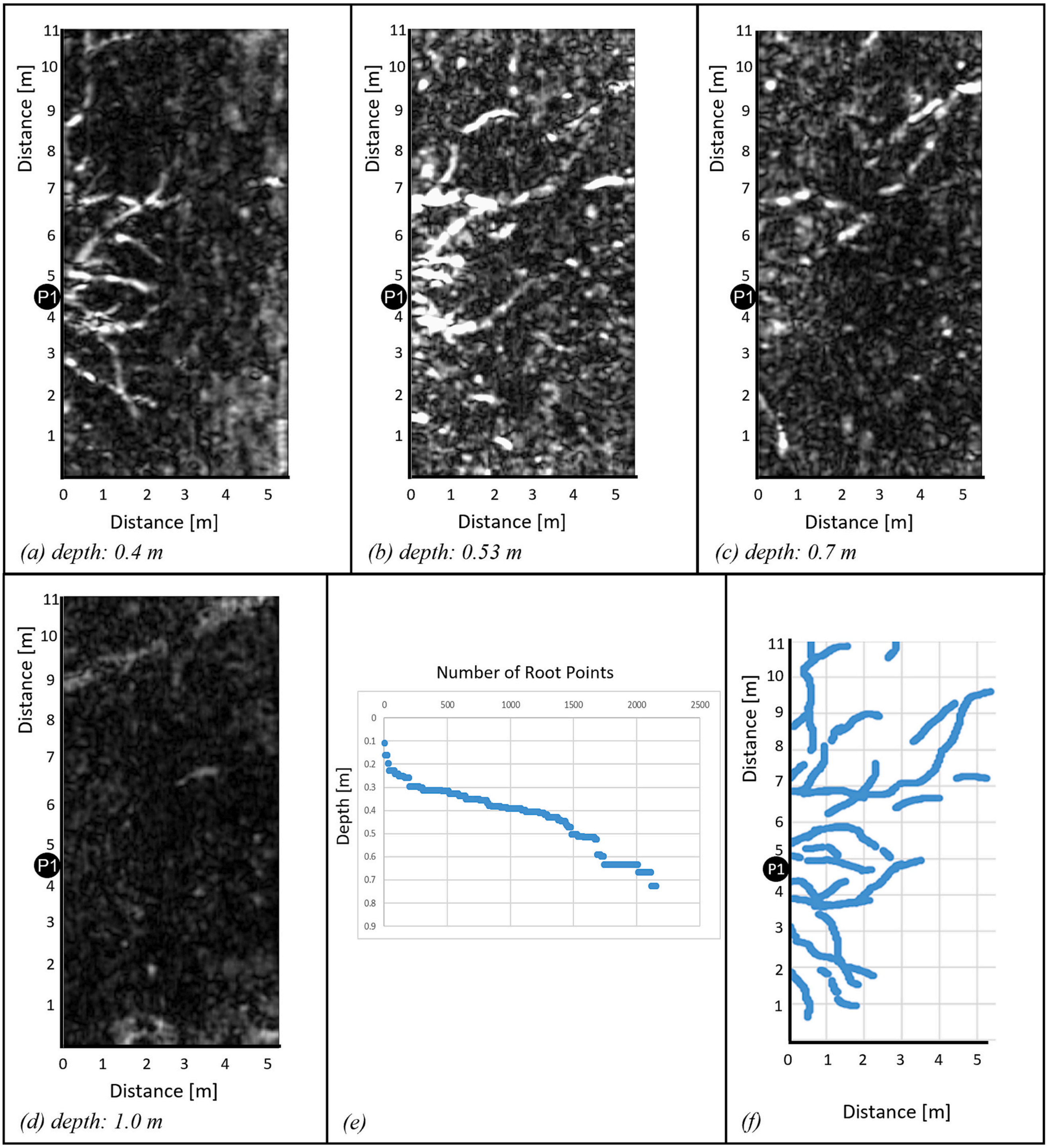

Fig. 4. Tilled area A1 with location of tree P1 marked by a black circle. Time slice from a depth of (a) 0.4 m, (b) 0.53 m, (c) 0.7 m; (d) depth distribution of roots; (e) result of interpretation [map of all detected roots].

4.1.2. Limitations of the sampling size

We are aware that the study of two trees presents a minimal sampling size. This comes with several shortcomings. First, we only focus on two individual trees at two different sites with similar environmental conditions. But even in Switzerland a great variety of different soil and climatic conditions prevail between sites with a huge impact on tree roots. Zanetti et al. (2015) pointed out that especially environmental constraints in soil and water availability are the main factors affecting root growth. In addition, the individual tree, its management and its physical condition have huge effects on the presented result. Tree P3, for example, had green leaves only on one side of the crown, the other half was dead. Consequently, only one half of the root system was still active.

Moreover, we focus only on a single tree species, the pear tree. However, Xie et al. (2020) found different tree species associated to different root characteristics and root systems. For example, they divided between three types, deep, medium, and shallow root distributions. These species-specific rooting systems are also true for fruit trees. In addition, the management and pruning of the tree as well as the soil management play an important role.

Although we are aware of all these above-mentioned limitations, we

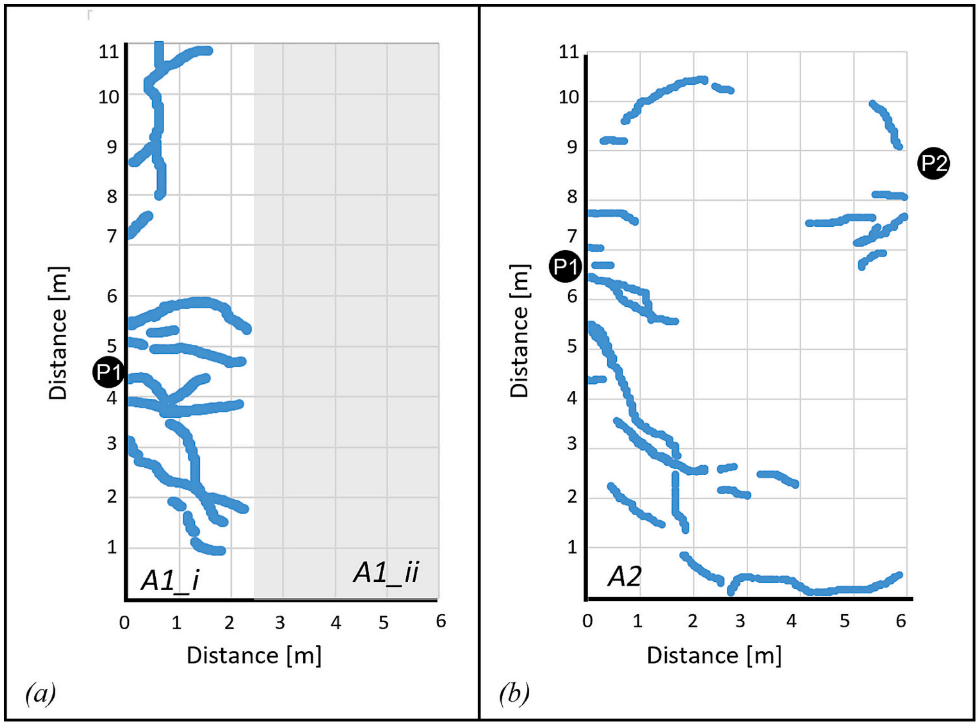

Fig. 5. Root points at a depth of <0.4 m (a) in the tilled area A1, divided into no-tilled A1-i and the tilled A1-ii (grey) area and (b) in the no-tilled area A2.

Table 1
Percentages of tree root points and number of root points per m^2 at different depths for P1 in A1 (tilled) and A2 (no-tilled).

Depth	A1, tilled		A2, no-tilled	
	%	Root points / m^2	%	Root points / m^2
All		36		20
< 0.3 m	13%	5	40%	8
< 0.4 m	52%	19	61%	12
< 0.5 m	69%	25	81%	16
> 0.5 m	31%	11	19%	4

have chosen this method mainly for two reasons. Firstly, we specifically aimed to study the growths of fruit tree roots. While forest tree species were measured by Borden et al. (2014, 2017) for example, we could not find any data on fruit trees in literature. Although, fruit tree systems are the most important modern agroforestry systems in Switzerland (Kay et al., 2020), and traditional orchards still exist on 1.5% of Swiss farmland (Herzog et al., 2018). Secondly, we focused our research on old trees (>80 years) to evaluate the synergies of or problems within the systems over a longer period. Although several studies were carried out in agroforestry systems aged <40 years (Cardinael et al., 2015), systems with old trees are underrepresented in the literature. Here, we selected two trees that were older than 80 years. As these specific settings (i.e., older-aged fruits trees on cropland) are scarce, we had to reduce the study to only two locations.

4.2. Impact of tillage on tree root system architecture

Several studies have examined tree root architecture (Borden et al., 2014, 2017), tree rooting depth (Cardinael et al., 2015), and soil organic carbon content (Cardinael et al., 2017) in agroforestry systems where the age of the trees ranged from 6 to 41 years. They state divergent results. Using a GPR approach, Borden et al. (2017) located the main tree roots in topsoil layers (<0.4 m) within an intercropping system with no-till cultivation. Cardinael et al. (2015) reported different results in an intercropping system with regular soil tillage. Using a trench wall mapping approach, they found that walnut tree roots grew significantly deeper (>0.5 m). The latter method is a pit system dug into the field that partly changes root growth in terms of their depth and direction. In our non-destructive study, tree roots were also affected by tillage. Firstly, the tilled horizon contained almost no tree roots (see Figs. 6b and 7b), and, secondly, tree roots continued to grow below the tilled area (<0.3 m). Consequently, the tree roots exhibited plasticity and adapted their root system architecture to the soil management practices. They opened up deeper soil horizons for their water and nutrient uptake.

Moreover, over study indicated an overcompensation by additional roots in the tilled area that were not formed without tillage. This compensation effect is well-known for above ground biomass management, where thinning and pruning of trees results in increased individual tree average stem, crown, and total biomass (Forrester et al., 2012, 2017; Muñoz et al., 2008). Also for below-ground root biomass production this effect was seen within a modelling approach by Boutchakdjian et al. (2022). After pruning of walnut tree roots in an agroforestry system, the tree roots recolonised very fast and increased in biomass.

4.3. Potential to inhabit new soil horizons

Our findings revealed that the tree rooting systems of the old (fruit) trees provided a 'safety net' for nutrients and water below the cropping area. Both, the crop and the tree, benefited from the nutrient surplus of the arable production and reduced nutrient leaching into groundwater. These findings are in line with those obtained by Bergeron et al. (2011), who observed a positive effect on nutrient uptake within poplar agroforestry systems aged 5–8 years. Wolz et al. (2018) found similar effects in a field study comparing maize-soybean rotation with fruit and nut alley cropping systems.

In addition to nutrient uptake, also the water balance benefits from inhabiting deeper soil horizon. On the one hand, the deeper tree roots can reach for other water sources such as ground water and therefore do not need to compete with arable crops for rainwater. On the other hand, intensive tree root systems support water infiltration rates. According to Xie et al. (2020) water infiltration was higher when trees had a deep root

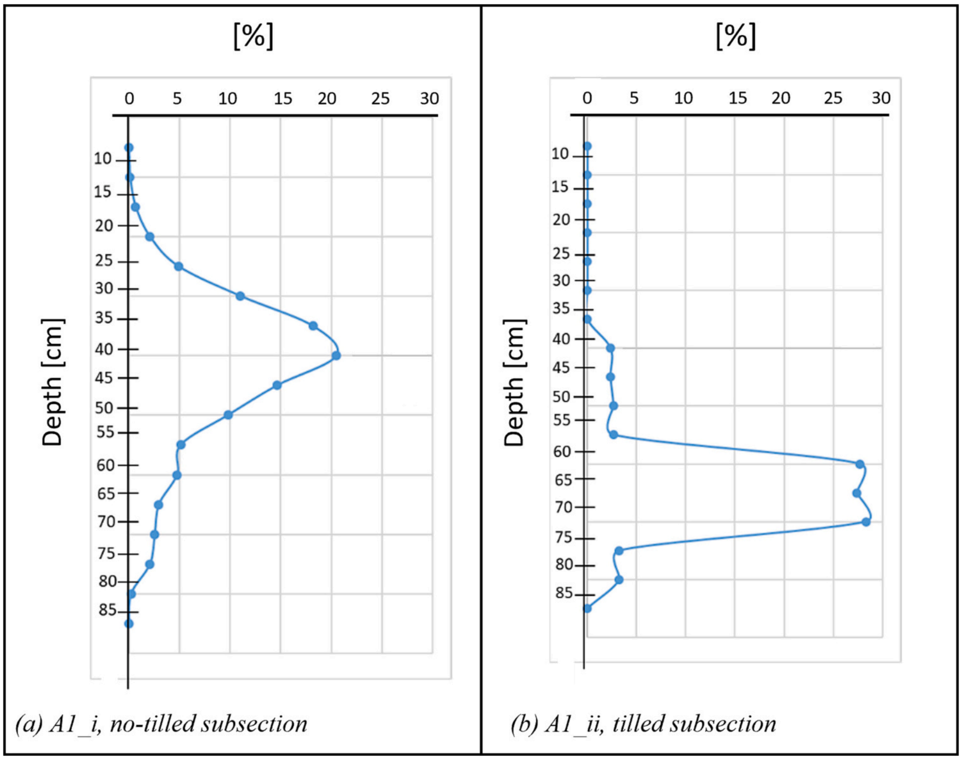

Fig. 6. (a) Percentage of roots along soil depth in the no-tilled subsection A1_i and (b) in the tilled subsection A1_ii.

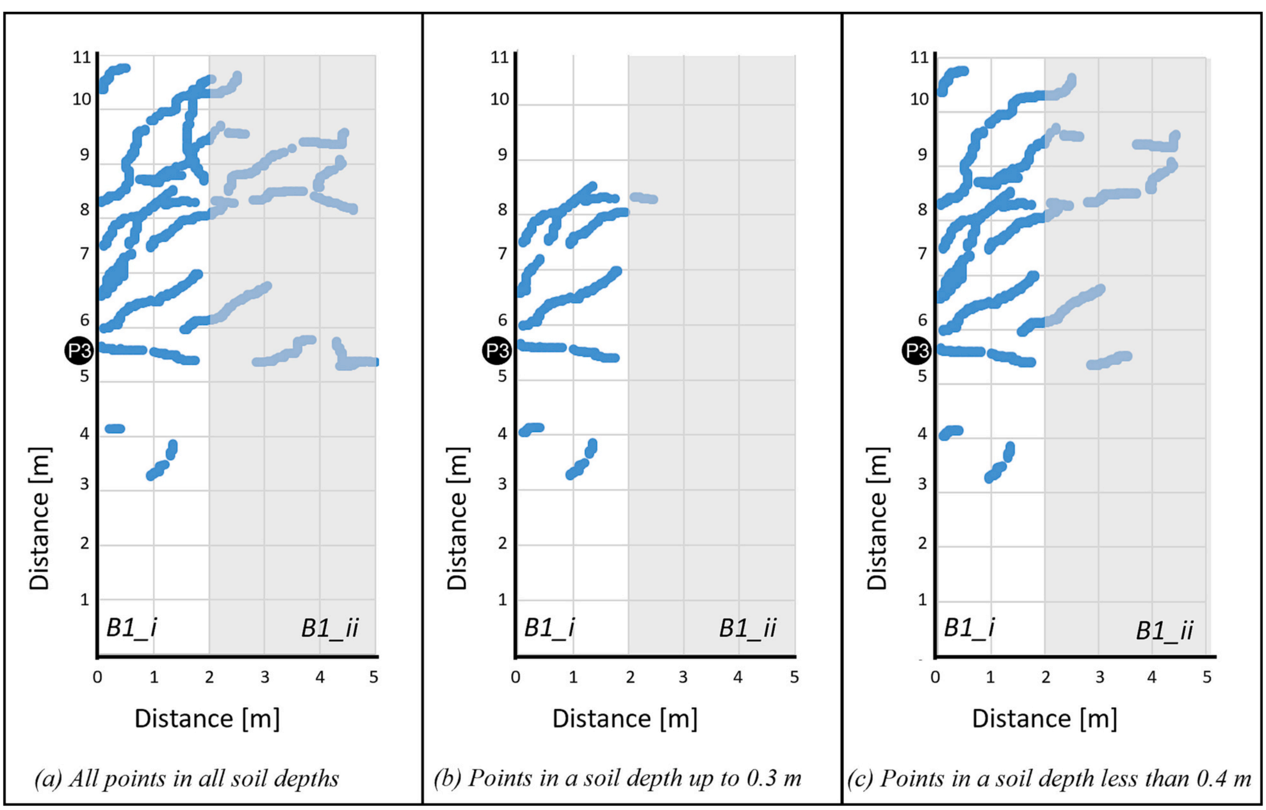

Fig. 7. (a) All root points of tree P3 in B1, divided into no-tilled B1-i and the tilled B1-ii (grey) area, (b) points in a soil depth up to 0.3 m, (c) points in a soil depth <0.4 m.

distribution. They recommended mixed planting of species to optimise infiltration effects by ensuring that root systems develop at different soil depths. Applying these findings to our study shows tremendous potential for optimising the nutrient and hydrologic cycles through agroforestry systems.

5. Conclusions

We mapped the tree root system architecture with and without tillage of two 80-year-old pear trees in the context of intercropping systems using GPR.

Our approach for a non-destructive investigation of tree roots using a 400 MHz antenna and full 3D data acquisition and processing was successful up to 0.75 m. This estimate was based on the mapping of drainage pipes existing at this depth. Several limitations mentioned by other authors, such as noise or limited interpretability, were minimized by our approach. In future studies it may be desirable to include a larger number of trees and other types of plants to enable estimates of the subsurface biomass. Nonetheless, the described method allows for repetitive measurements of the tree root system. This opens up the possibility of observing root development over a longer period of time and monitoring the root stock in the long term.

Furthermore, our results highlight a significant impact of agricultural management or tillage on tree root systems. Comparing the root system with and without tillage showed that all tree roots within a certain depth range were removed by tillage. There were (nearly) no roots at depths of <0.4 m for tree P1 and <0.3 m for P3. No such effect was observed on tree roots in no-tilled areas. Our findings suggest that the removed roots are 'overcompensated' by additional roots in tilled soil; this phenomenon did not occur in no-till soil. Regarding the depth range, the bulk of the roots was shifted from 0.3 to 0.55 m in the no-till section to 0.6 to 0.75 m in the tilled section. However, the limited data set (only two trees, same tree species, same environment) might limit the transferability of the results obtained.

Overall, we found that intercropping (e.g., an agroforestry system) allows crop and tree roots to colonise different soil horizons when managed by root pruning using tillage. The trees, especially, open up deeper soils as if grown in monocultures. This occurrence opens up a larger source of water and nutrients, as well as enables the system to better respond to the impacts of climate mitigation and adaption. Consequently, the resilience of the combined production systems is enhanced. In addition, studying the belowground structures of roots provide useful information on carbon balances and the impacts of climate mitigation. Future studies can utilize and develop the application of the proposed method for quantitative long-term monitoring of biomass carbon storage in the soil.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This project was funded by OST-Eastern Switzerland University of Applied Sciences and the European Union's Horizon 2020 research and innovation programme under grant agreement No 862696 (EJP SOIL). Special thanks to Kilian Meier and Stefanie Meier for the permission to perform the data acquisition on their land and their support. Special thanks to Mauro Demont and Etienne Blaser for their support during fieldwork. The authors acknowledge the support of Klaus Jarosch for his constructive review.

Appendix. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geodrs.2023.e00659.

References

Aboudourib, A., Serhir, M., Lesselier, D., 2019. Impact of root diameter and water content on tree roots detection using ground penetrating radar. In: 13th European Conference on Antennas and Propagation, 2019. EuCAP.

Alani, A.M., Lantini, L., 2020. Recent advances in tree root mapping and assessment using non-destructive testing methods: a focus on ground penetrating radar. Surv. Geophys. https://doi.org/10.1007/s10712-019-09548-6.

Alani, A.M., Ciampoli, L.B., Lantini, L., Tosti, F., Benedetto, A., 2018. Mapping the root system of matured trees using ground penetrating radar. In: 2018 17th International Conference on Ground Penetrating Radar, 2018. GPR. https://doi.org/10.1109/icgpr.2018.8441535.

Almeida, E.R., Porsani, J.L., Booth, A., Brunello, A.T., Säkinen, T., 2018. Analysis of GPR field parameters for root mapping in Brazil's caatinga environment. In: 2018 17th International Conference on Ground Penetrating Radar, 2018. GPR. https://doi.org/10.1109/icgpr.2018.8441547.

Amt für Landschaft und Natur, 2019. Meliorationskataster [WWW Document]. Übersicht über alle mit Staatl. Unterstützung ausgeführten Unternehm. der Landwirtsch. Strukt. (generalisierte Darstellung). URL. https://maps.zh.ch/?offlayers=bezirkslabels&scale=320000&srid=2056&topic=ALAwwwZH&x=2692500&y=1252500.

Bergeron, M., Lacombe, S., Bradley, R.L., Whalen, J., Cogliastro, A., Jutras, M.F., Arp, P., 2011. Reduced soil nutrient leaching following the establishment of tree-based intercropping systems in eastern Canada. Agrofor. Syst. 83, 321–330. https://doi.org/10.1007/s10457-011-9402-7.

Bianchini Ciampoli, L., Calvi, A., Di Benedetto, A., Fiani, M., Gagliardi, V., 2021. Ground Penetrating Radar (GPR) and Mobile Laser Scanner (MLS) Technologies for Non-destructive Analysis of Transport Infrastructures. https://doi.org/10.1117/12.2599283.

Borden, K.A., Isaac, M.E., Thevathasan, N.V., Gordon, A.M., Thomas, S.C., 2014. Estimating coarse root biomass with ground penetrating radar in a tree-based intercropping system. Agrofor. Syst. 88, 657–669. https://doi.org/10.1007/s10457-014-9722-5.

Borden, K.A., Thomas, S.C., Isaac, M.E., 2017. Interspecific variation of tree root architecture in a temperate agroforestry system characterized using ground-penetrating radar. Plant Soil 410, 323–334. https://doi.org/10.1007/s11104-016-3015-x.

Boutchakdjian, L., Dupraz, C., Lecomte, I., Gosme, M., Reyes, F., 2022. Tree root pruning in maize alley-cropping: would it have saved the maize? The Hi- sAFe model answers. Will you believe it?. In: 6th Agroforestry Conference, Book of Abstracts, pp. 79–80.

Burgess, P.J., Incoll, L.D., Corry, D.T., Beaton, A., Hart, B.J., 2005. Poplar (Populus spp) growth and crop yields in a silvoarable experiment at three lowland sites in England. Agrofor. Syst. 63, 157–169. https://doi.org/10.1007/s10457-004-7169-9.

Cardinael, R., Mao, Z., Prieto, I., Stokes, A., Dupraz, C., Kim, J.H., Jourdan, C., 2015. Competition with winter crops induces deeper rooting of walnut trees in a Mediterranean alley cropping agroforestry system. Plant Soil 391, 219–235. https://doi.org/10.1007/s11104-015-2422-8.

Cardinael, R., Chevallier, T., Cambou, A., Béral, C., Barthès, B.G., Dupraz, C., Durand, C., Kouakoua, E., Chenu, C., 2017. Increased soil organic carbon stocks under agroforestry: a survey of six different sites in France. Agric. Ecosyst. Environ. 236, 243–255. https://doi.org/10.1016/j.agee.2016.12.011.

Carrick, U.E., 2017. Ground Penetrating Radar – Theory and Practice, 1. edition. Butterworth-Heinemann.

COWI, Directorate-General for Climate Action (European Commission), Ecologic Institute, IEEP, 2021. Operationalising an EU Carbon Farming Initiative - Executive Summary. https://doi.org/10.2834/594818.

Cui, X.H., Chen, J., Shen, J.S., Cao, X., Chen, X.H., Zhu, X.L., 2011. Modeling tree root diameter and biomass by ground-penetrating radar. Sci. China Earth Sci. 54, 711–719. https://doi.org/10.1007/s11430-010-4103-z.

Daniels, D.G., 2004. Ground Penetrating Radar, Iee Radar, Sonar, Navigation and Avionics Series.

de Aguiar, G.Z., Lins, L., de Paulo, M.F., Maciel, S.T.R., Rocha, A.A., 2021. Dielectric permittivity effects in the detection of tree roots using ground-penetrating radar. J. Appl. Geophys. 193 https://doi.org/10.1016/j.jappgeo.2021.104435.

Forrester, D.I., Collopy, J.J., Beadle, C.L., Baker, T.G., 2012. Interactive effects of simultaneously applied thinning, pruning and fertiliser application treatments on growth, biomass production and crown architecture in a young *Eucalyptus nitens* plantation. For. Ecol. Manag. 267, 104–116. https://doi.org/10.1016/j.foreco.2011.11.039.

Forrester, D.I., Tachauer, I.H.H., Annighoefer, P., Barbeito, I., Pretzsch, H., Ruiz-Peinado, R., Stark, H., Vacchiano, G., Zlatanov, T., Chakraborty, T., Saha, S., Sileshi, G.W., 2017. Generalized biomass and leaf area allometric equations for European tree species incorporating stand structure, tree age and climate. For. Ecol. Manag. 396 https://doi.org/10.1016/j.foreco.2017.04.011.

Gallegos-Poch, F., Viguier, B., Menanno, G., Mandakovic, V., Yáñez, G., Gutiérrez, S., Lizarde, C., Vargas Araya, J., López-Contreras, C., Mendez-Quiros, P., Maldonado, A., Uribe, M., 2023. Integration of near-surface complementary geophysical techniques for the study of ancient archaeological areas in the Atacama desert (Pampa Iluga, Northern Chile). Surv. Geophys. https://doi.org/10.1007/s10712-022-09750-z.

Graß, R., Malec, S., Wachendorf, M., 2020. Biomass performance and competition effects in an established temperate agroforestry system of willow and grassland—results of the 2nd rotation. Agronomy 10, 1819. https://doi.org/10.3390/agronomy10111819.

Graves, A., Burgess, P.J., Palma, J., Keesman, K.J., van der Werf, W., Dupraz, C., van Keulen, H., Herzog, F., Mayus, M., 2010. Implementation and calibration of the parameter-sparse yield-SAFE model to predict production and land equivalent ratio in mixed tree and crop systems under two contrasting production situations in Europe. Ecol. Model. 221, 1744–1756. https://doi.org/10.1016/j.ecolmodel.2010.03.008.

Guo, L., Chen, J., Cui, X., Fan, B., Lin, H., 2013. Application of ground penetrating radar for coarse root detection and quantification: a review. Plant Soil 362, 1–23. https://doi.org/10.1007/s11104-012-1455-5.

Herzog, F., Szerencsits, E., Kay, S., Roces-Díaz, J.V., Jäger, M., 2018. Agroforestry in Switzerland – a non-CAP European Country. In: Agroforestry as Sustainable Land Use., 4th European Agroforestry Conference, Nijmegen, pp. 74–78, 28.-30.05.2018.

Hruska, J., Cermák, J., Sustek, S., 1999. Mapping tree root systems with ground-penetrating radar. Tree Physiol. 19 https://doi.org/10.1093/treephys/19.2.125.

Hugenschmidt, J., 2010. Ground penetrating radar for the evaluation of reinforced concrete structures. In: Non-Destructive Evaluation of Reinforced Concrete Structures: Non-Destructive Testing Methods. https://doi.org/10.1533/9781845699604.2.317.

Hugenschmidt, J., 2012. Ground-penetrating radar. In: Breysse, D. (Ed.), Non-Destructive Assessment of Concrete Structures: Reliability and Limits of Single and Combined Techniques: State-of-the-Art Report of the RILEM Technical Committee 207-INR.

Hugenschmidt, J., Kay, S., 2022. GPR for the inspection of root structures in agroforestry systems. In: 19th International Conference on Ground Penetrating Radar. Golden, Colorado, p. 60.

Kay, S., Rega, C., Moreno, G., den Herder, M., Palma, J.H.N., Borek, R., Crous-Duran, J., Freese, D., Giannitsopoulos, M., Graves, A., Jäger, M., Lamersdorf, N., Memedemin, D., Mosquera-Losada, R., Pantera, A., Paracchini, M.L., Paris, P., Roces-Díaz, J.V., Rolo, V., Rosati, A., Sandor, M., Smith, J., Szerencsits, E., Varga, A., Viaud, V., Wawer, R., Burgess, P.J., Herzog, F., 2019. Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe. Land Use Policy 83, 581–593. https://doi.org/10.1016/j.landusepol.2019.02.025.

Kay, S., Jäger, M., Herzog, F., 2020. Moderne Agroforstsysteme in der Schweiz - Partizipative Entwicklung und künftige Herausforderungen. Berichte über Landwirtschaft. Zeitschrift für Agrar und Landwirtschaft 98, 22. https://doi.org/10.12767/buel.v98i2.299.

KurjaŃski, B., Rea, B.R., Spagnolo, M., Cornwell, D.G., Howell, J., Comte, J.C., GonzÁlez QuirÓs, A., Palmu, J.P., Oien, R.P., Gibbard, P.L., 2021. Cool deltas: sedimentological, geomorphological and geophysical characterization of ice-contact deltas and implications for their reservoir properties (Salpausselkä, Finland). Sedimentology 68. https://doi.org/10.1111/sed.12884.

Liu, X., Dong, X., Xue, Q., Leskovar, D.I., Jifon, J., Butnor, J.R., Marek, T., 2018. Ground penetrating radar (GPR) detects fine roots of agricultural crops in the field. Plant Soil 423. https://doi.org/10.1007/s11104-017-3531-3.

Lorenzo, H., Pérez-Gracia, V., Novo, A., Armesto, J., 2010. Forestry applications of ground-penetrating radar. For. Syst. 19, 5–17. https://doi.org/10.5424/fs/2010191-01163.

Muñoz, F., Rubilar, R., Espinosa, M., Cancino, J., Toro, J., Herrera, M., 2008. The effect of pruning and thinning on above ground aerial biomass of *Eucalyptus nitens* (Deane & Maiden) Maiden. For. Ecol. Manag. 255, 365–373. https://doi.org/10.1016/j.foreco.2007.09.063.

Pellerin, S., Bamière, L., Launay, C., Martin, R., Schiavo, M., Angers, D., Augusto, L., Balesdent, J., Basile-Doelsch, I., Bellassen, V., Cardinael, R., Cécillon, L., Ceschia, E., Chenu, C., Constantin, J., Darroussin, J., Delacote, P., Delame, N., Gastal, F., Gilbert, D., Graux, A.-I., Guenet, B., Houot, S., Klumpp, K., Letort, E., Litrico, I., Martin, M., Menasseri, S., Mézière, D., Morvan, T., Mosnier, C., Roger-Estrade, J., Saint-André, L., Sierra, J., Thérond, O., Viaud, V., Grateau, R., Le Perchec, S., Savini, I., Réchauchère, O., 2020. Stocker du carbone dans les sols français, Quel potentiel au regard de l'objectif 4 pour 1000 et à quel coût ? Rapport scientifique de l'étude. INRA (France) 540, 540.

Peyer, K., Videtic, J., Petrasek, M., Hanic, R., 1998. Bodenkarte der Landwirtschaftsflächen [WWW Document]. Grundlagenbericht zur Bodenkartierung des Kantons Zürich. URL. https://maps.zh.ch/?offlayers=bezirkslabels&scale=320000&srid=2056&topic=ALAwwwZH&x=2692500&y=1252500.

Sandmeier Scientific Software, 2020. REFEXW, Version 7.2.3.

Spinelli, R., Picchi, G., 2010. Industrial harvesting of olive tree pruning residue for energy biomass. Bioresour. Technol. 101, 730–735. https://doi.org/10.1016/j.biortech.2009.08.039.

Stokes, A., Fourcaud, T., Hruska, J., Cermak, J., Nadyezdhina, N., Nadyezhdin, V., Praus, L., 2002. An evaluation of different methods to investigate root system architecture of urban trees in situ: I. ground-penetrating radar. J. Arboric. 28.

swisstopo, 2021. SWISSIMAGE HIST 1946: Das Orthophotomosaik der Schweiz von 1946 [WWW Document]. URL. https://map.geo.admin.ch/?lang=de&topic=ech&bgLayer=ch.swisstopo.pixelkarte-farbe&layers=ch.swisstopo.swissimage-productch.swisstopo.swissimage-product_1946,ch.swisstopo.lubis-luftbilder_schwarzweiss&layers_timestamp=current,1946,99991231&E=2678508.94&N.

Upson, M.A., Burgess, P.J., 2013. Soil organic carbon and root distribution in a temperate arable agroforestry system. Plant Soil 373, 43–58. https://doi.org/10.1007/s11104-013-1733-x.

van Noordwijk, M., Lawson, G., Hairiah, K., Wilson, J., 2015. Root distribution of trees and crops: competition and/or complementarity. In: Tree-Crop Interactions: Agroforestry in a Changing Climate, pp. 221–257. https://doi.org/10.1079/9781780645117.0221.

Wang, M., Wen, J., Li, W., 2020. Qualitative research: the impact of root orientation on coarse roots detection using ground-penetrating radar (GPR). BioResources 15, 2237–2257.

Wolz, K.J., Branham, B.E., DeLucia, E.H., 2018. Reduced nitrogen losses after conversion of row crop agriculture to alley cropping with mixed fruit and nut trees. Agric. Ecosyst. Environ. 258, 172–181. https://doi.org/10.1016/j.agee.2018.02.024.

Xie, C., Cai, S., Yu, B., Yan, L., Liang, A., Che, S., 2020. The effects of tree root density on water infiltration in urban soil based on a ground penetrating radar in Shanghai, China. Urban For. Urban Green. 50 https://doi.org/10.1016/j.ufug.2020.126648.

Zanetti, C., Vennetier, M., Mériaux, P., Provansal, M., 2015. Plasticity of tree root system structure in contrasting soil materials and environmental conditions. Plant Soil 387, 21–35. https://doi.org/10.1007/s11104-014-2253-z.

Zhang, X., Derival, M., Albrecht, U., Ampatzidis, Y., 2019. Evaluation of a ground penetrating radar to map the root architecture of HLB-infected citrus trees. Agronomy 9. https://doi.org/10.3390/agronomy9070354.