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Effect of tree density on root distribution in *Fagus sylvatica* stands: a semi-automatic digitising device approach to trench wall method

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Abstract Knowledge of root profiles is essential for measuring and predicting ecosystem dynamics and function. In the present study, the effects of management practices on root ($0.5 \leq ø < 20$ mm) spatial distribution were examined in a 40-year-old coppice stand (CpS 1968) and other two stands converted from coppice to thinned high forest in 1994 (CvS 1994) and 2004 (CvS 2004), respectively. The use of a semi-automatic digitising device approach was compared with a conventional root mapping method in order to estimate the time per person required from fieldwork to the final digital map. In July 2009, six trench walls per stand were established according to tree density, i.e. as equidistant as possible from all surrounding trees. Findings highlighted differences between the stands with CvS 1994 showing a lower number of small roots ($2 \leq ø < 5$ mm), a higher mean cross-sectional area (CSA) of coarse roots ($5 \leq ø < 20$ mm) and different root depth distribution as compared to CpS 1968 and CvS 2004 whose values were close to each other. The three diameter classes selected in this study showed significant relationships in terms of number of roots, scaling down from coarse- to small- and fine-roots. Forest management practices significantly affected only the number of small roots. The number of fine roots ($0.5 \leq ø < 2$ mm) was isometrically related to their root length density (RLD, cm cm^{-3}). No relationship occurred with RLD of very fine roots ($ø < 0.5$ mm). In conclusion, forest management practices in terms of conversion thinnings significantly affected belowground biomass distribution of beech forest in space and time. In particular, frequency of coarse roots was related to the stand tree density, frequency of small roots was related to the cutting age. Size of coarse roots was related to tree density but only several years after felling. The allometric relationship occurring between fine- and small-roots highlighted how fine root number and RLD were only indirectly affected by forest management practices. These findings suggest that future investigations on the effect of forest thinning practices on fine-root traits like number, length and biomass several years after felling cannot ignore those on small roots.

Keywords Very fine roots · Fine roots · Coarse roots · Cross-sectional area · Forest management · Tree density

Introduction

Belowground biomass is a significant component of carbon stocks in terrestrial ecosystems and knowledge of root profiles is essential for measuring and predicting ecosystem dynamics and function (Jackson et al. 1996; Mokany et al. 2006; Zeppel et al. 2008). Within the belowground compartment, although it may be considered a particular shape variable of a root system, root depth is nevertheless an intrinsic and inevitable consideration when modelling root systems (Tobin et al. 2007). The spatial pattern of root systems may vary in a wide range depending on a variety of internal (e.g. genotype) and external abiotic (e.g. temperature, precipitation, soil properties, slope conditions,

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nutrient availability) and biotic (mycorrhiza, competition between plants, herbivory) factors (Majdi et al. 2005; Di Iorio et al. 2005). In forest ecosystems, a major external factor is the effect of direct anthropogenic disturbances like management practices (Diaci et al. 2010; Rötzer et al. 2010). Forest management practices such as coppice conversion to high forest routinely involve thinning operations. These practices modify stand characteristics (i.e. tree density, canopy cover, stand basal area) and related environmental variables (i.e. soil moisture and temperature, irradiance), leading to changes in the ecophysiological behaviour of trees (Aussenac 2000). Moreover, forest harvesting will generally result in the partial or complete death of root systems of harvested trees causing changes in root density and production. A recent review for the three main types of North-European forest ecosystems (Finér et al. 2007, 2011) showed that fine-root (the smallest root portion <2 mm in diameter) biomass in beech forests varied considerably in relation to aboveground stand characteristics. Similarly, in a previous work carried on the same site, a strong influence of forest management practices on fine-root dynamics was found (Montagnoli et al. 2012a, b), as the fine-root biomass increased from recently thinned stand to dense old coppice. However, studies examining forest harvest effects on carbon flux have yielded quite inconsistent results (Laporte et al. 2003). Even within the same general ecological system, for example in mixed deciduous hardwoods, either large increases or decreases in carbon flux have been reported after logging operations (Edwards and Ross-Todd 1983; Londo et al. 1999). One likely factor contributing to this variation is the differences in the length of time following harvest among different studies (Peng and Thomas 2006). The coarse root portion (diameter >2 mm in general) undergoes variations in relation to aboveground stand characteristics to similar extent. When forests are harvested, some fractions of coarse roots begin to decay (O'Loughlin and Watson 1979). So far, little is known about how forest management practices may influence the decay rate of coarse structural roots and their consequent spatial distribution at stand level.

Collecting root depth distribution data is not straightforward, especially for species having deep roots, or in stony and compact soils, which may be very difficult to access. To tackle this problem different methods have been developed for characterising the spatial distribution of root systems in soil (Böhm 1979; van Noordwijk et al. 2000). The profile wall- or trench wall-method can give detailed information on overall spatial pattern of root distribution (van Noordwijk et al. 2000). The number of root intersections can be counted and recorded using a simple grid or the positions of the roots can be mapped on polythene (plastic) overlays. Afterwards, in order to

analyse data from trench wall observations, root maps are digitised at an appropriate level of precisions for further analysis. The main drawbacks are that inaccuracies may arise at all the above-mentioned steps and the method is highly labour-intensive and time-consuming. An alternative method shorter in time but as accurate as the plastic or grid overlays, was the use of digital photo subsequently rectified and analysed by means of GIS softwares (Schmid and Kazda 2005). To overcome these drawbacks, a semi-automatic digitising device (3 Space Fastrak plus Long Ranger, Polhemus Inc., VT, USA) provides a precise and rapid localisation of coordinates. Three-dimensional digitising in plant science has been used primarily to measure topology and geometry for architectural analysis of the aerial parts of trees (Sinoquet and Rivet 1997), and secondly of root systems (Danjon et al. 1999; Di Iorio et al. 2005; Tamasi et al. 2005; Nicoll et al. 2006). As far as it is known, this is the first attempt to apply a 3D digitiser device to the trench wall method, although only two dimensions (2D) of the wall plane were processed. The work presented here firstly aimed at understanding how forest management practices may influence root biomass distribution. Trench walls are usually made near the base of a plant, where applicable. In the present study, trench locations were established according to the stand tree density, i.e. as far as evenly distant from the surrounding trees, in order to be representative of the current standing crop in relation to the stand tree density. Indeed, this work is coupled with a previous one on fine-root dynamics in order to give a full frame of *Fagus sylvatica* stands subject to conversion thinnings from coppice to high standard. Secondly, this work aimed at improving the trench wall method by enhancing data quality with accurate digital instrumentation and reducing drastically the time required. To this aim, the time per person required to analyse one trench wall with the 3D digitiser was compared to that reported for the conventional method described in van Noordwijk et al. (2000). For these purposes, in July 2009, root distribution was digitally recorded directly in the field by a 3D digitiser tool in a 41-year-old coppice stand and two coppice stands converted to high forest during 1994 and 2004. Diameters of detected roots ranged between 0.5 and 20 mm, and were classified according to Böhm (1979) and Zobel and Waisel (2010). In response to the different stand characteristics due to forest management practices, the specific objectives of the present study include: (1) determining changes, if any, in frequency and depth distribution of fine, small and coarse roots; (2) evaluating how these changes differ depending on the diameter class considered; (3) assessing variations, if any, in cross-sectional area (CSA) of coarse roots. The hypothesis tested was that the observed reduction in fine-root biomass following thinning operations was driven by

the reduction in the amount of small and large roots at least to an extent. Accordingly, it was hypothesised a coarse–small–fine roots direct scaling relationship. Information on this relationship could provide a good opportunity for improving fine root biomass estimates.

Materials and methods

Site description

The study area is located in the catchments of the Telo stream in the Lombardy Alps (Intelvi Valley, NW Italy, 45°59′N, 9°07′E) approximately from 1,160 to 1,200 m above sea level between Lakes Como and Lugano. General characteristics of this area were already described in a previous work carried out on the same site (Montagnoli et al. 2012b). Three beech stands were selected and labelled by ascending cutting age: two conversion thinnings from coppice to high forest cut in 2004 (Conversion Stand [CvS] 2004) and 1994 (CvS 1994), respectively; a residual coppice stand (CpS 1968), the only one left in the area, cut more than 40 years ago and then allowed to re-grow from stools. The three stands were adjacent to each other and located on the same slope facing south-west, with slope inclination averaging between 28° and 30°. To determine the root distribution along with the aboveground stand characteristics such as stand basal area (m^2 ha^{-1}), tree density (no. tree ha^{-1}) and mean tree height, a new setup of six sampling plots circular-shaped (20 m diameter) per stand were surveyed along a transect almost 120 m long for a total of 1,884 m^2 area per stand. In the case of CpS 1968 each stool was counted as a single tree. In July 2009, canopy cover was measured by hemispherical photos analysed with the Can-eye freeware (https://www4.paca.inra.fr/can-eye, 2012). Sampling time was chosen to correspond with the growth peaks of fine roots examined by Montagnoli et al. (2012b) on the same site.

3D-digitiser and root measurements

A number of six trenches, one per plot, were excavated for each stand, 18 in total. In order to be representative of the current standing crop in relation to the stand characteristics (tree density), the location of the trench was set centrally as equidistant as possible from all surrounding trees. Trench wall dimension (160 cm width and 60 cm depth, ≈ 1 m^2) was established according to the soil site characteristics (Fig. 1).

Position coordinates of all emerging living roots larger than 0.5 mm in diameter were measured using a semi-automatic contact 3D digitising device with a Long

Ranger transmitter (Fastrak, Polhemus Inc., Colchester, VT, USA). No grid frames were necessary because of the reference frame proper of the 3D digitiser. No smaller diameters were registered because of the low accuracy of the calliper method. Device characteristics were broadly explained in previous works (Danjon et al. 1999; Di Iorio et al. 2005; Tamasi et al. 2005; Nicoll et al. 2006; Danjon and Reubens 2008), but the specific characteristics of its application on a trench wall is provided below. The system consists of a magnetic generator (long ranger transmitter) (Fig. 1a), a small pointer (receiver) directed towards the points to be measured (Fig. 1b) and an electronic unit (Fastrak) (Fig. 1c). The transmitter was located with the trench wall plane perpendicular to the positive x direction, i.e. in the up-slope side of the trench in slope condition (Fig. 1d).

The three-dimensional position coordinates (x, y, z) and diameter were digitised and logged by using the DIPLAMI software (Sinoquet and Rivet 1997), starting from the top of the trench wall and following a recursive path along the depth. The first point was digitised in correspondence of the Oa organic layer. This point represents the zero, i.e. the soil surface, to which all z values were scaled. As the trench wall is a vertical 2D plane, the x coordinate (Fig. 1d) of each digitised root was not considered for calculation but only those on the trench plane, y and z accordingly. Root diameters were entered by the operator and measured by plastic calliper. When a root cross-section was not circular, the largest and smallest diameters were recorded. No topological information was recorded because it is impossible to detect and not pertinent for the addressed issue. As a consequence, output data file was analysed directly with Microsoft Excel and SPSS 12.0 softwares. The manufacturer has indicated the resolution of this device to be 0.05 % with a standard error of 0.08 cm for each x, y, z receiver position. Moulia and Sinoquet (1993) experienced a measuring standard error of <1 mm in an active volume of about 1 m^3.

According to Böhm (1979) and Zobel and Waisel (2010), roots were classified into fine ($0.5 \leq \emptyset < 2$ mm), small ($2 \leq \emptyset < 5$ mm), and coarse ($\emptyset \geq 5$ mm), the latter including the medium ($5 \leq \emptyset < 10$ mm), and large ($10 \leq \emptyset < 20$ mm) classes. All the detected roots were woody; few doubtful samples were collected for anatomical investigations resulting woody at the same extent. To calibrate counts versus root length density, and to have an estimation of the finest root portion ($\emptyset \leq 0.5$ mm), two soil cores (4 cm diameter, 30 cm depth) per trench wall (12 per stand) were collected 50 cm from the trench wall (cf Fig. 1d). Cores were stored in plastic bags, transported to the laboratory, and stored at 4 °C until sample processing. Each sample was washed over a 1-mm sieve, fine and very fine roots collected with tweezers. WinRHIZO (Version

Fig. 1 Photos and sketch of the trench wall-3D digitiser setup. **a** Front view of the 1 m^2 wide trench plane with the transmitter located in the up-slope side; **b** first operator with the receiver pointing to each intersecting root; **c** second operator entering diameter measurements in the laptop connected to the Fastrak electronic unit; **d** sketch of the trench plane—transmitter orientation—soil coring location setup (*top view*). Transmitter X^+ axis is oriented parallel to the slope direction and perpendicular to the trench plane direction, Z^+ axis perpendicular below the sketch plane (*X symbol*)
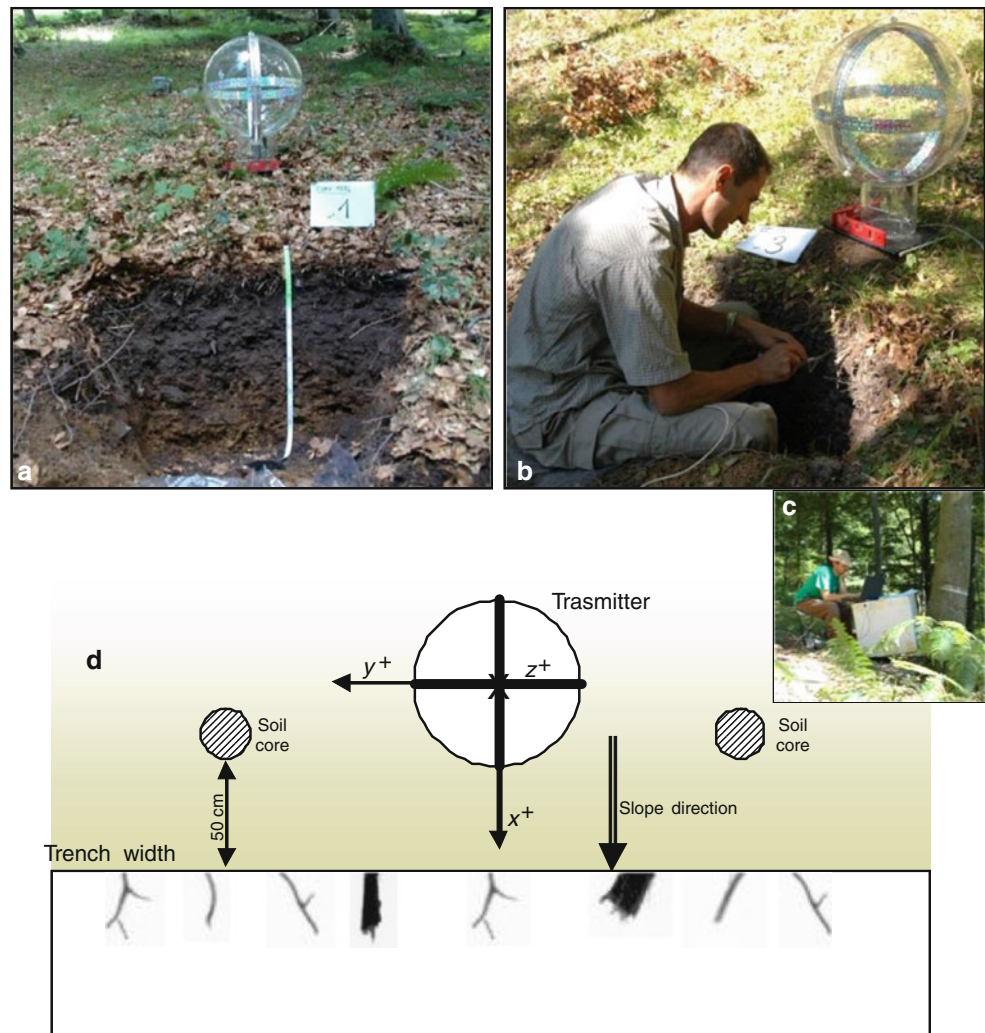
2007) was used to make scans and to calculate fine root length density (RLD cm cm^{-3}) by two diameter classes: very fine roots ($\phi < 0.5$ mm) and fine roots ($0.5 \leq \phi < 2$ mm).

Statistical analysis

To compare the three beech stands, six permanent plots were established within each stand and considered independent replicates. This is a point comparison approach rather than a replicated experiment at the ecosystem scale. The results are given as means and standard errors. To test differences among the three stands for stand basal area, number and mean and total root cross-sectional area (CSA), a one-way unbalanced ANOVA or a non-parametric Kruskal–Wallis test was carried out on means or medians, respectively, depending whether the distribution met the normality and homoscedasticity assumptions or not. Post hoc multiple comparisons were performed accordingly with a parametric Bonferroni or non-

parametric Dunn (Sprent 1993) test. Two-sample Kolmogorov–Smirnov was used to test for significant different distributions between stands (root depth distribution, root diameter distribution). As the different root diameter classes are topologically dependent on each other, one-way ANCOVA was performed with forest management as fixed factor and coarse-, small- and fine-root number as covariates. Linear or non-linear regression analysis was performed to model the scaling relationship between the number of coarse- and small-roots and between the number of small- and fine-roots. All tests were performed with a 5 % rejection level. Statistical analysis was performed with SPSS 12.0 (SPSS Inc, Chicago, IL, USA) and Unistat 6.0 (Unistat Ltd, UK) for non-parametric Dunn test only.

Results

Stand basal area increased from CvS 2004 to CvS 1994 and CpS 1968 (Fig. 2), the latter being significantly higher than
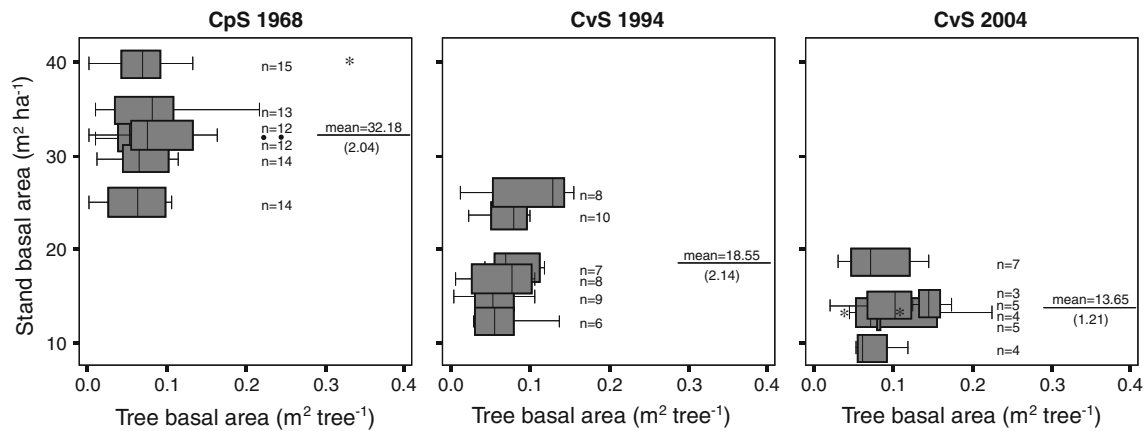
Fig. 2 Boxplot of the stand basal area plotted versus the tree basal area. Each boxplot represents one experimental plot, six in total per stand. *Circles* refer to outlier values, *asterisks* to extreme values. Number of trees per plot and means ± (SE) of stand basal area are shown in the panel

both conversions (Bonferroni' test, $P < 0.05$) (Table 1). In the six CvS 2004 plots, one half had 75 % and the other half 100 % of tree basal area values higher than 0.05 m^2 tree^{-1}, respectively (Fig. 2), whereas in the other two stands all plots showed 30–50 % of values lower than 0.05 m^2 tree^{-1}. In fact, the general median tree basal area decreased with increasing stand basal area (and cutting age accordingly), 0.08, 0.07 and 0.06 m^2 tree^{-1}, respectively, although not significantly (Kruskal–Wallis test, $P = 0.127$; data not shown). In contrast, stand basal area was significantly and directly related to the tree density (stand basal area $= 3.24 + 0.07 \times$ tree density, $R^2 = 0.81$; graph not shown) rather than the tree size (tree basal area).

Diameters of detected roots ranged between 0.5 and 18.7 mm (Fig. 3). All medium and large roots were regularly circular shaped. Root diameter distributions significantly differed among stands (two-sample Kolmogorov–Smirnov test, $P < 0.05$) (Fig. 3). In particular, CvS 1994

had the highest number of large roots ($10 \leq \varnothing < 20$ mm) and the lowest number of fine roots, whereas CvS 2004 did not have large roots. In Fig. 4 all the detected roots larger than 2 mm intercepting the six trench wall profiles are shown with symbol size proportional to their diameter. Symbol size clearly showed the average larger size of coarse roots in CvS 1994. Most of detected roots were within 30 cm depth and CvS 1994 did not show roots under 35–37 cm depth. In fact, root depth frequency distribution in the CvS 1994 stand was significantly different from CpS 1968 and CvS 2004 stands (two-sample Kolmogorov–Smirnov test, $P < 0.05$).

The number and total CSA of coarse roots increased with increasing stand basal area (Table 1); the difference between CpS 1968 and CvS 1994 was higher in terms of number than total CSA. This different behaviour is explained by the mean CSA of CvS 1994 coarse roots which was significantly higher than CpS 1968 and CvS

Table 1 Stand basal area and fine, small and coarse root traits for the three examined stands

	Stands		
	CpS 1968	CvS 1994	CvS 2004
Basal area (m^2 ha^{-1})	32.18 (2.05)a	18.55 (2.14)b	13.65 (1.21)b
No. coarse roots ($5 \leq \varnothing < 20$ mm) (no. m^{-2})	11.33 (2.6)a	5.67 (2.03)ab	4.33 (0.67)b
No. small roots ($2 \leq \varnothing < 5$ mm) (no. m^{-2})	41.67 (12.2)a	9 (2.08)b	19 (1.53)ab
No. fine roots ($0.5 \leq \varnothing < 2$ mm) (no. m^{-2})	119.51 (11.94)a	42.51 (7.01)b	76.83 (7.53)c
No. fine roots ($0.5 \leq \varnothing < 2$ mm) 0–30 cm depth (no. m^{-2})	209.34 (14.56)a	59.02 (6.57)b	134.7 (18.24)c
c.r. mean CSA (cm^2)	0.49 (0.06)b	0.87 (0.2)a	0.37 (0.04)b
s.r. mean CSA (cm^2)	0.07 (0.002)	0.06 (0.01)	0.07 (0.002)
Total c.r. CSA (cm^2 m^{-2})	5.54 (1.45)	4.94 (1.45)	1.58 (0.35)
Total s.r. CSA (cm^2 m^{-2})	3.38 (1.01)a	0.77 (0.18)b	1.40 (0.25)ab

Values are means (SE). For each variable, if written, the means of the three stands without a common letter are significantly different (Bonferroni or Dunn tests at $P < 0.05$ depending whether the distribution met the normality or not)
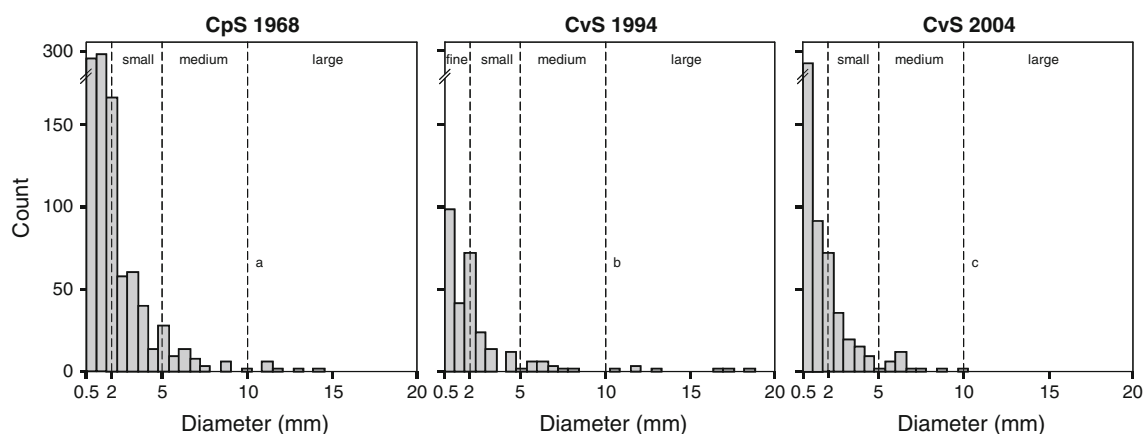
c.r. coarse roots, *s.r.* small roots

Fig. 3 Root diameter distribution for the three stands. *Dashed lines* define the diameter classes. Distributions without a common letter (*shown in the centre*) are significantly different (two-sample Kolmogorov–Smirnov test at $P < 0.05$)

2004 (Dunn's test, $P < 0.05$). In contrast, small roots showed a different pattern with CvS 1994 number and total CSA values lower than CvS 2004 and significantly lower than CpS 1968 stands (Dunn's test, $P < 0.05$) (Table 1). The number of fine roots ($0.5 \leq \emptyset < 2$ mm), whose mean diameter was 1.24 ± 0.4(SD) mm, significantly decreased from CpS 1968 to CvS 2004 and CvS 1994 (Table 1), and followed the same pattern of small roots.

The ANCOVA highlighted the significant covariate effect of the number of coarse roots to the number of small roots and of the number of small roots to the number of fine roots (Table 2), highlighting an inherently scaling relationship between them. In fact, the number of small roots increased allometrically with the number of coarse roots by a second-order polynomial ($R^2 = 0.67$; Fig. 5a), whereas the number of fine roots increased isometrically with the number of small-roots ($R^2 = 0.84$; Fig. 5b). Forest management significantly affected only the number of small roots ($P < 0.001$, Table 2) rather than the number of fine roots ($P = 0.321$, Table 2). For only 30-cm soil depth, a significant isometric relationship emerged for fine roots between their number, whose values came from the trench method, and their RLD obtained from the soil coring method ($P < 0.001$, Table 2; $R^2 = 0.69$, Fig. 6a). No relationship was observed between the number of fine roots and the RLD of very fine roots ($P = 0.489$, Table 2; $R^2 = 0.08$, Fig. 6b).

From a methodological perspective, a rough estimate of the time involved in the present work for the analysis of one trench wall is given in Table 3. Labour time required for the 3D acquisition was compared with the time required for the conventional wall profile analysis by root map drawing and digitising as shown in the root method handbook (van Noordwijk et al. 2000). The comparison showed that the method applied in the present study needed

almost half of the time labour per person required in the conventional method.

Discussion

The present work highlighted that different stand characteristics due to forest management practices influenced the number, cross-sectional area and depth distribution of coarse and small roots. These influences scaled down to fine roots in terms of root length density and biomass, at least to some extent. The present tree density and related tree basal area, marginal stem radial increment included, derives from thinning operations, including also periodic understory removal, rather than the development of new densities following the last cutting.

The direct relationship between the stand basal area, strongly dependent on the tree density, and the number and total cross-sectional area of coarse roots (diam ≥ 5 mm) is fully expected because the probability that roots intersect the trench plane increases with the tree density. Conversely, the lack of a direct relationship at the level of mean coarse-root size highlighted an interaction between the tree density and the time elapsed since felling. Considering that CvS 2004 and CvS 1994 are both conversion thinnings from similar coppice structure, and that CvS 2004 was the most recent, the similar diameter size of coarse roots between CvS 2004 and CpS 1968 clearly indicate that the radial growth increase of coarse roots in response to reduced tree density becomes evident several years after felling, in CvS 1994 exactly. Readjustments in crown closure, which affect the production of photosynthate, may contribute to the radial growth increase in structural roots (Fayle 1975). Moreover, trees continuously alter their morphology in response to changes in wind exposure due to thinning practices. Wilson

Fig. 4 *Left column*: two-dimensional representations of root distribution (diameter ≥ 2 mm) in Cps 1968, CvS 1994 and CvS 2004 stands obtained with the 3D digitiser. Each intersection is represented by a *circle* proportional to root diameter (see inserted scale). Different colours for illustrative purpose only (*red*, *blue*, *light green*, *dark green*, *brown*, *violet*) represent six different trench walls per stand; *right column*: root number distribution with soil depth. Distributions without a common letter (*shown in the centre*) are significantly different (two-sample Kolmogorov–Smirnov test at $P < 0.05$) (colour figure online)
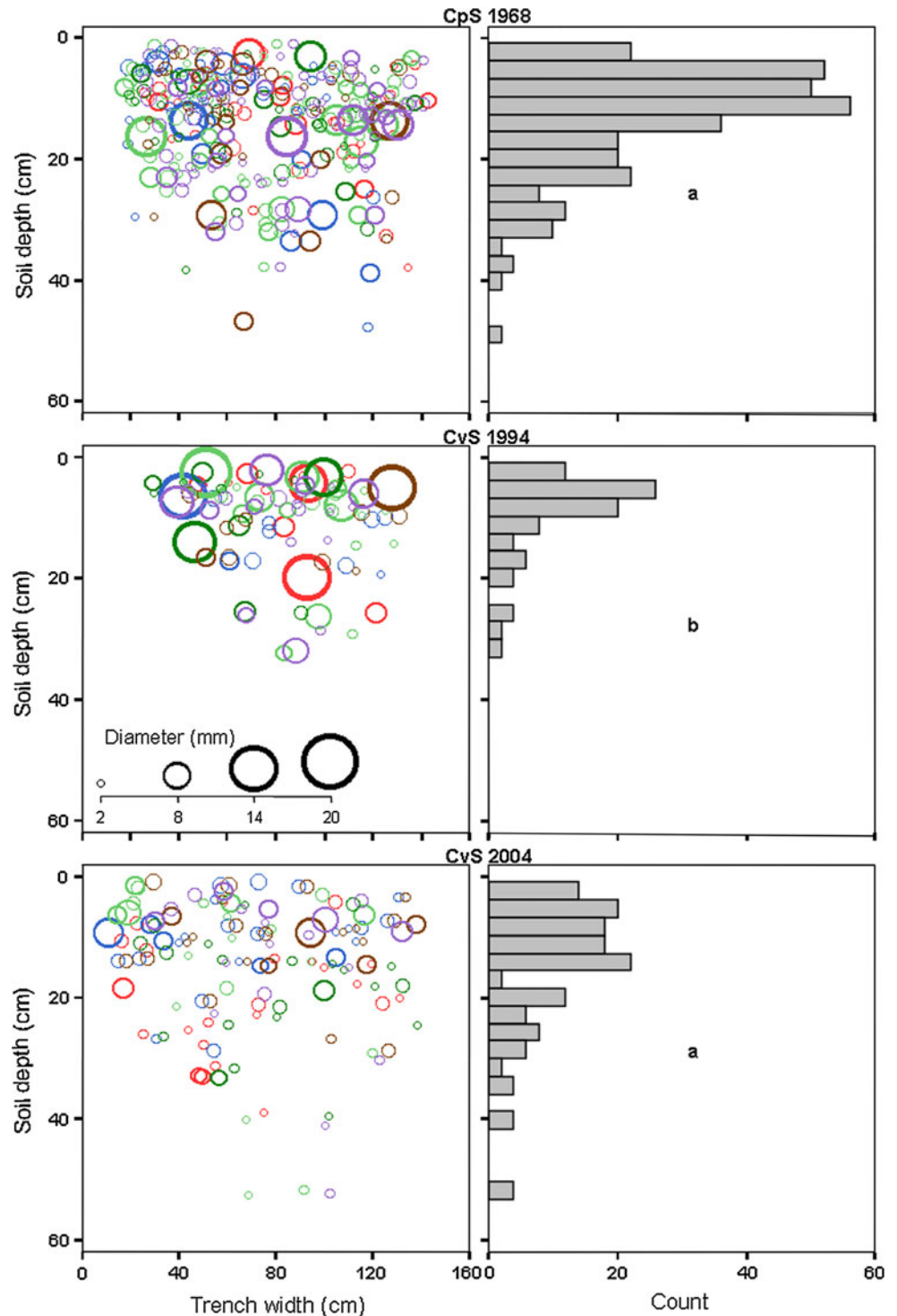
(1975) found increases in growth ring width both in the lower stem and at the base of structural roots of *Pinus strobus* trees in response to increased wind movement after stand thinning. Urban et al. (1994) reported that, after removal of neighbouring trees, there was an immediate increase in thickening of structural roots of *Picea glauca*, but a 4-year delay before an increase in stem diameter growth occurred. Similar temporal differences between stem and root thickening of *Pinus resinosa* trees in response to thinning were reported by Fayle (1983). Allocation of assimilates to those parts of the tree under the greatest stress optimises the use of available resources to stabilise the tree and to moderate increases in wind movement.

Table 2 General linear model analysis (one-way ANCOVA) for the effects of different forest management practices on morphometric traits of different root diameter classes

	Parameter	df	F	P	R^2_{adj}
No. small roots ($2 \leq \varnothing < 5$ mm) (no m^{-2})	Forest management	2	14.440	**<0.001**	0.837
	No. coarse (c)	1	12.539	**0.003**	
No. fine roots ($0.5 \leq \varnothing < 2$ mm) (no m^{-2})	Forest management	2	1.233	0.321	0.835
	No. small (c)	1	16.252	**0.001**	
Fine RLD 0-30 cm depth (m m^{-3})	Forest management	2	2.674	0.104	0.724
	No. fine roots 0–30 cm (c)	1	21.650	**<0.001**	
Very-fine RLD 0-30 cm depth (m m^{-3})	Forest management	2	1.006	0.391	0.019
	No. fine roots 0–30 cm (c)	1	0.504	0.489	

Boldface P values are significant at a probability level of <0.05

RLD root length density

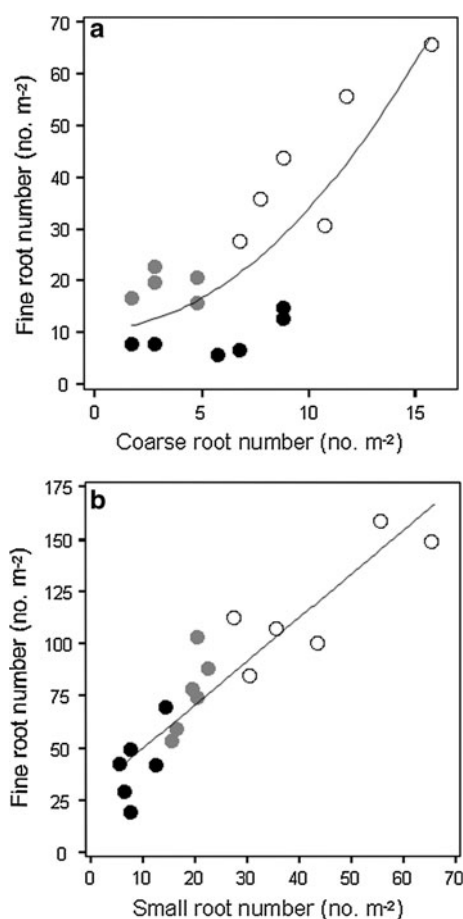The letter (c) indicates covariate

Fig. 5 Relationship between the number of small- versus the number of coarse-roots (**a**) and the number of fine- versus the number of small-roots (**b**) for the whole 60 cm depth soil profile. Different *grey levels* represent three stands (*closed circle* CvS 1994, *grey circle* CvS 2004, *opened circle* CpS 1968). Regression equations are as follows: small-root number $= 11.41 + 0.217 \times$ coarse-root number^2 ($P < 0.001$, $R^2 = 0.67$); fine-root number $= 29.02 + 2.09 \times$ small-root number ($P < 0.001$, $R^2 = 0.84$)
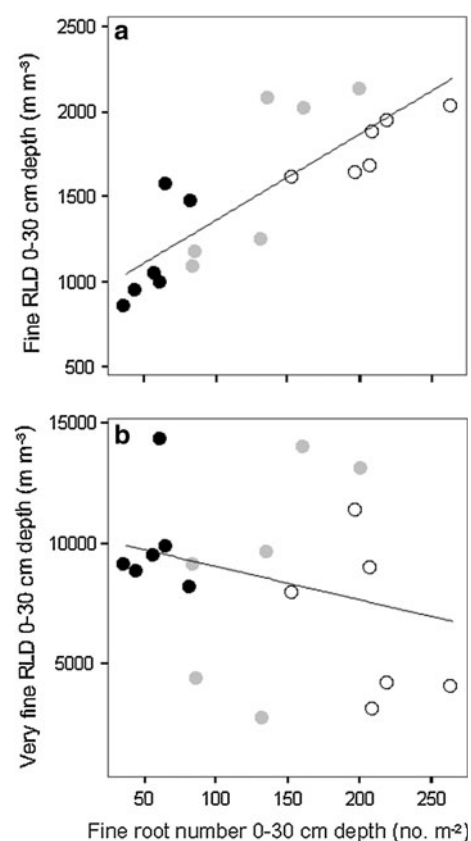

Fig. 6 Relationship between the root length density (RLD) of fine- (**a**) and very fine-roots (**b**) versus the number of fine roots for the 30 cm depth soil only. Different *grey levels* represent three stands (*closed circle* CvS 1994, *grey circle* CvS 2004, *opened circle* CpS 1968). Regression equations are as follows: fine RLD $= 854.86 + 5.06 \times$ fine-root number ($P < 0.001$, $R^2 = 0.69$); very fine RLD $= 10442.61 - 13.93 \times$ fine-root number ($P > 0.05$, $R^2 = 0.08$)

Unlike the findings obtained for coarse roots, the number of small roots showed no direct relationship with the stand basal area. The three stands considered in this study

Table 3 Estimated time involved in the main steps in both conventional and 3D digitiser root mapping methods

Number of steps in the root map conventional method (from van Noordwijk et al. 2000)	Person–days per 1 m² sample trench wall	Number of steps in the 3D digitiser method (from the present fieldwork)	Person–days per 1 m² sample trench wall
1. Field work to prepare trench wall	0.15	1. Field work to prepare trench wall	0.15
2. Field work to make analogical map	0.25	2. Field work to make digital map	0.75
3. Digitising (from analogical map)	1.5		
Total time required per sample in person–day	**1.9**		**0.9**

Estimates are based on an experienced crew and soils which are easy to work

Boldface font highlights the total time required and is for illustrative purpose only

may be safely considered three different stages in a beech forest successional development with CvS 2004 and CpS 1968 representing the younger and older stage, which can vary from canopy closure to maturity, respectively. If 41 years since the last cutting is considered enough for almost full aboveground biomass recovery (canopy cover 94.2 %), setting the coppice stand (CpS 1968) to time "zero" highlights a decrease in the small root number with increasing cutting age, 5 years for CvS 2004 and 15 years for CvS 1994 (no. small-root $= 38.14 - 2.09 \times$ time, $R^2 = 0.63$; graph not shown). Natural root decay could explain the decreasing number of small roots with increasing time elapsed since felling. O'Loughlin and Watson (1979) observed in *Pinus radiata* the disappearance of small roots (ø < 5 mm) already 29 months after cutting operations, i.e. <5 years of our most recent felling. Thus, forest management in terms of tree density and cutting age had manifold effects: frequency of coarse roots (ø ≥ 5 mm) was related to the stand tree density, frequency of small roots (2 ≤ ø < 5 mm) was related to the cutting age. Size of coarse roots was related to tree density but several years after felling.

In accordance with other authors (Schmid and Kazda 2001, 2005; Jackson et al. 1996), most of fine roots (0.5 ≤ ø < 2 mm) (on average 86 %) were located within 30 cm depth. Assuming a topological approach with the fine-root portion being the first at least two branching order classes (Pregitzer et al. 2002) and the small- and coarse-roots the higher order (sensu Fitter 1987), the close scaling relationship of the number of fine- to small-roots and in turn of the number of small- to coarse-roots featured a strong hierarchical control on root distribution in field conditions supporting the stated hypothesis. Indeed, forest management practices in terms of tree density and cutting age affected the number of small roots but not that of fine roots, highlighting an environmental effect superimposed on the scaling hierarchical control. The allometric relationship occurring between them highlighted how fine root number and RLD were only indirectly affected by forest management practices, at least down to 0.5 mm in diameter. These findings suggest that investigations on fine root traits like

number, length and biomass several years after felling cannot ignore those on small roots. The lack of similar estimates for coarse roots larger than those considered in this study (5 ≤ ø < 20 mm) do not exclude the occurrence of an allometric control also on these latter, but the significant difference observed among the surveyed stands make the forest management practices effect highly probable.

The lack of a relationship between very fine (ø < 0.5 mm) and fine roots highlighted the occurrence of a different functional behaviour of the former, validating the hypothesised occurrence of a fine–small roots direct allometric relationship till the proper fine (0.5 ≤ ø < 2 mm) diameter class. In fact, very fine roots represent the most dynamic portion of root systems (Montagnoli et al. 2012a and references therein). The variation of fine-root traits like specific root length, production and turnover rate is mainly due to this very fine portion which is more sensitive to soil condition. Hence, these findings highlighted a forest management effect on the root systems scaling down from large roots (10 ≤ ø ≤ 20 mm) to fine roots.

In terms of biomass, considering as a whole, very fine plus fine root biomass showed similar values in CvS 1994 and CvS 2004 (data not shown), in accordance with data obtained from previous work carried out on the same site in July of the previous year (Montagnoli et al. 2012b). These findings highlighted important relationships between fine plus small roots and stand tree density, raising questions about the accuracy of the soil coring method for fine root (diam <2 mm) biomass estimation. Soil coring protocols differ in sampling location among regular grid with fixed distance used both in plantations (Jourdan et al. 2008) and natural forests (Santantonio and Hermann 1985), fixed distance from scattered selected trees (Richter et al. 2013) and random sampling in most of studies reported in literature. One way to address this issue is by coupling random and even-distance from surrounding tree locations of soil corings, the latter representative of stand tree density.

From a methodological perspective, comparison between conventional (plastic overlay) and 3D digitiser methods showed that the latter needs almost half of the time labour per person required in the conventional method

for both trench preparation and digitising step. Moreover, the accuracy of the 3D approach is much higher than the map drawing approach. In fact, the step of root map digitisation is avoided, reducing the errors occurring in the data transfer process from plastic overlay to an *x*, *y* digital reference frame. These results suggest the use of the 3D digitiser approach for speeding field survey.

In conclusion, forest management significantly affects belowground biomass distribution of beech forest in space and time. Though *F. sylvatica* is a shallow rooted species, outcomes from this study may be safely extrapolated to temperate broadleaf and mixed forest because of the similar root deployment in these ecosystems.

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