



Effects of fine root length density and root biomass on soil preferential flow in forest ecosystems

Yinghu Zhang, Jianzhi Niu*, Xinxiao Yu, Weili Zhu and Xiaoqing Du

Key Laboratory Soil and Water Conservation and Desertification Combating, Ministry of Education, School of Soil and Water Conservation, Beijing Forestry University, China

Abstract

Aim of study: The study was conducted to characterize the impacts of plant roots systems (e.g., root length density and root biomass) on soil preferential flow in forest ecosystems.

Area of study: The study was carried out in Jiufeng National Forest Park, Beijing, China.

Material and methods: The flow patterns were measured by field dye tracing experiments. Different species (*Sophora japonica* Linn, *Platycladus orientalis* Franco, *Quercus dentata* Thunb) were quantified in two replicates, and 12 soil depth were applied. Plant roots were sampled in the sieving methods. Root length density and root biomass were measured by WinRHIZO. Dye coverage was implied in the image analysis, and maximum depth of dye infiltration by direct measurement.

Main results: Root length density and root biomass decreased with the increasing distance from soil surface, and root length density was 81.6% higher in preferential pathways than in soil matrix, and 66.7% for root biomass with respect to all experimental plots. Plant roots were densely distributed in the upper soil layers. Dye coverage was almost 100% in the upper 5-10 cm, but then decreased rapidly with soil depth. Root length density and root biomass were different from species: *Platycladus orientalis* Franco > *Quercus dentata* Thunb > *Sophora japonica* Linn.

Research highlights: The results indicated that fine roots systems had strong effects on soil preferential flow, particularly root channels enhancing nutrition transport across soil profiles in forest dynamics.

Key words: soil preferential flow; preferential pathways; soil matrix; root length density; root biomass.

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Correspondence should be addressed to Jianzhi Niu: nexk@bjfu.edu.cn

Introduction

Soil preferential flow (e.g., macropore flow, finger flow and funnel flow) as a spatially and temporally highly random and essentially unpredictable process (Hendrickx & Flury, 2001) and a common phenomenon in pedological perspectives (Bonger *et al.*, 2008) results in complex flow patterns bypassing soil matrix and increases the risk of pollutants (e.g. Heavy Metal, Radionuclides) reaching greater soil depths (Nimmo, 2012). Lots of studies ascribed the phenomenon to macropores at the plot scale (Beven & Germann, 1982), however, more recent studies have confirmed that nonequilibrium infiltration may produce similar soil preferential flow patterns. Preferential flow has been implicated in radionuclides

and organic matter in groundwater, and pesticides into public wells (e.g., Aldicarb in Long Island, New York). Much work is underway to characterize contamination by preferential flow using simulation and modelling. Soil matrix flow and preferential flow are two typical permeating patterns of water flow and solute transport (Jarvis *et al.*, 2012). Flow in the soil matrix pores at the pedon scale results from spatial heterogeneity in texture, bulk density, stones or rock fragments and water repellency, while flow in continuous and large pores or macropores at the pore scale arises from different interactions: biopores formed by plant root systems and macrofauna, cracks formed by freeze and thaw or swell and shrinkage circles, voids formed by irrigation, cultivation, and tillage (Jarvis *et al.*, 2012).

Plant root systems situated in farmland, desert, forest soil, rangeland and grassland perform a vital role in water and nutrient uptake, and this role varies due to changes in root morphology, traits, and distribution during their growth (Wiel & Wample, 1985; Tscherning *et al.*, 1995; Puhe, 2003; Yan *et al.*, 2011). Root growth is controlled by many factors containing soil compaction (Panayiotopoulos *et al.*, 1994; Alameda *et al.*, 2012; Glab, 2013), tillage systems (Muñoz-Romero *et al.*, 2010; Kadžienė *et al.*, 2011; Vakali *et al.*, 2011), macropores, soil strength and structure (Dexter, 2004; Vocanson *et al.*, 2006) and temperature (Gladish & Rost, 1993; Finer *et al.*, 2011a) which determine much of the development of roots (Tracy *et al.*, 2013; Dastidar *et al.*, 2012). Roots are able to form well-connected macropores or channels and also normally grow into rigid pores broader than their own diameters (Logsdon & Allmaras, 1991). Channels created by plant roots may contribute to water and solute transport, especially macropore flow or preferential flow (Aber *et al.*, 1985; Li & Ghodrati, 1994; Jørgensen *et al.*, 2002; Bogner *et al.*, 2010; Germann *et al.*, 2012).

Forest soil layers are composed of fine soil particles, rock (ranging in size from fragments to boulders), liquid, and a large amount of plant roots systems (Vogt *et al.*, 1996; Sundarapandian & Swamy, 1996; Kalyn & Van Rees, 2006; Finér *et al.*, 2011b; Yuan & Chen, 2013). Particularly, the relation of plant roots systems to soil preferential flow tends to be more complicated in forest soils containing abundant rock fragments or gravels. Plant roots parameters, particularly fine root length density (total root length per soil volume) (Glab, 2013) as an important indicator of root growth (Mosaddeghi *et al.*, 2009) and root biomass usually measured by oven drying, have increased interests in forest ecosystems because of their role in regulating the cycling of water and nutrients for plants growth. However, is it consistent with our expectations that plant roots content is higher in preferential pathways than in soil matrix in forest soils with more gravels? Relevant studies are rare. To confirm the hypothesis, we carried out field dye tracing experiments in a forest soil containing approximately 20% rock fragments located in Jiufeng area, Beijing, China, with the Brilliant Blue FCF (Colour Index 42090) to visualize soil preferential flow (stained areas) and soil matrix flow (unstained areas) (Hagedorn & Bundt, 2002). Jiufeng area which influences groundwater quality and security of Beijing is a representative region evaluated by soil preferential flow. The objectives of our study were to: (1) compare fine root length density and root biomass content between preferential pathways and soil matrix, (2) evaluate effects of plant roots on soil preferential flow in forest ecosystems.

Materials and methods

Site description

Our study was a forest ecosystem in Jiufeng National Forest Park (116°28'E, 39°34'N) located in the northwest of Beijing, China (Fig. 1). Jiufeng National Forest Park is part of Beijing Forestry University and is used for teaching and scientific research. Elevation ranges from 60-1100 masl (above seal level). The climate is temperate continental with a mean annual precipitation of 630 mm, mean annual temperature 11.6°C, and mean annual potential evapo-transpiration 19,000 mm. The dominant vegetation at elevations <800 masl was plantation of *Platycladas orientalis*, *Pinus tabulaeformis*, *Quercus spp.*, *Robinia pserdoacacia* containing shrubs of *Prunus armniaca* and *Vitex chinensis*. Above 800 masl, *Pinus tabulaeformis*, *Popular chinensis*, *Lespedeza bicolon*, *Spiraca trilobata*, *Caragana rosea* dominated the sparse forest cover. The soil chemical and physical properties are described as sandy loam containing approximately 20% rock fragments and gravels. Its texture consists of sandy loam in forest soils to 0.60 m in depth. Its organic carbon (OC) content varies from 2.28 to 46.17 g kg⁻¹ in study site. The soil pH values range from pH 5.87 to 7.12 in the topsoil and subsoil (Table 1).

Experimental treatment

Six experimental plots were established within a 10 x 10 m quadrat situated in representative vegetation region at 260 masl. Experimental plots 1 and 2 were located in *Sophora japonica* Linn, experimental plots 3 and 4 in *Platycladus orientalis* Franco, and experimental plots 5 and 6 in *Quercus dentata* Thunb sections

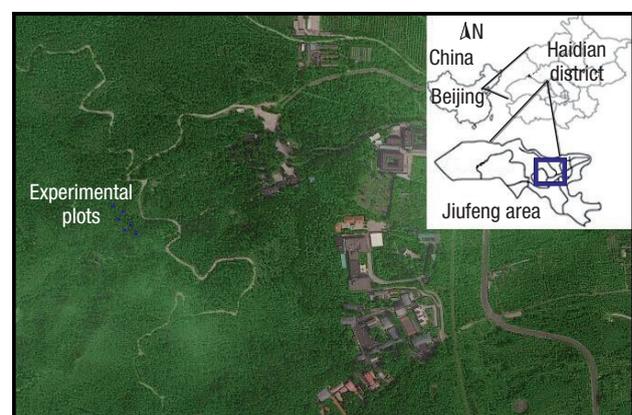


Figure 1. Location of Jiufeng area in Beijing, China and the study sites.

Table 1. Soil physical and chemical properties in the study site, Jiufeng area, Beijing, China.

Experimental plots	Horizon	Depth interval (cm)	Particle size distribution			Soil texture	Gravel	Stand age (a)	Organic carbon (g kg ⁻¹)	pH	Cation exchange capacity
			Sand	Silt	Clay						
Plot1	A	0-15	55.5%	26.8%	17.7%	Sandy loam	13.9%	45	38.65	7.12	22.95
	B1	15-30	63.7%	19.9%	16.4%	Sandy loam	18.3%		11.32	6.05	16.74
	B2	30-50	67.7%	19.7%	12.6%	Sandy loam	19.5%		4.72	6.01	19.62
	C	50-60	65.5%	22.9%	11.6%	Sandy loam	19.2%		2.28	6.31	20.76
Plot2	A	0-15	56.2%	25.4%	18.4%	Sandy loam	11.2%	43	36.82	6.89	23.04
	B1	15-30	62.8%	20.2%	17.0%	Sandy loam	16.8%		13.12	6.10	17.21
	B2	30-50	68.9%	21.3%	9.8%	Sandy loam	19.4%		3.98	5.98	18.43
	C	50-60	63.5%	23.7%	12.8%	Sandy loam	18.9%		2.37	6.04	20.14
Plot3	A	0-15	59.4%	23.1%	17.5%	Sandy loam	12.1%	35	44.58	5.97	24.56
	B1	15-30	65.2%	18.2%	16.6%	Sandy loam	15.6%		15.17	6.10	18.18
	B2	30-50	66.4%	18.4%	15.2%	Sandy loam	18.8%		6.87	5.87	19.10
	C	50-60	63.8%	19.7%	16.5%	Sandy loam	19.4%		3.45	6.03	20.01
Plot4	A	0-15	58.7%	24.1%	17.2%	Sandy loam	12.8%	46	46.17	6.00	25.31
	B1	15-30	64.8%	20.8%	14.4%	Sandy loam	16.7%		17.20	6.05	19.87
	B2	30-50	67.3%	21.5%	11.2%	Sandy loam	19.5%		5.89	5.97	19.01
	C	50-60	63.4%	22.9%	13.7%	Sandy loam	18.4%		3.64	6.04	18.78
Plot5	A	0-15	57.3%	23.5%	19.2%	Sandy loam	13.5%	41	44.70	6.10	24.56
	B1	15-30	64.8%	24.4%	10.8%	Sandy loam	16.4%		16.80	6.08	19.74
	B2	30-50	65.7%	21.5%	12.8%	Sandy loam	19.8%		4.58	5.98	19.54
	C	50-60	63.4%	22.4%	14.2%	Sandy loam	18.7%		3.97	5.96	18.42
Plot6	A	0-15	56.9%	24.9%	18.2%	Sandy loam	11.8%	45	42.80	6.00	23.54
	B1	15-30	63.8%	21.8%	14.4%	Sandy loam	16.8%		15.21	6.04	18.12
	B2	30-50	66.3%	23.5%	10.2%	Sandy loam	18.9%		4.87	6.21	19.65
	C	50-60	62.7%	21.6%	15.7%	Sandy loam	18.4%		2.89	6.11	20.15

of the quadrat. Two replicates for each vegetation type were conducted in the quadrat. Fifty millimeters of enriched Brilliant Blue FCF dye solution (5g L⁻¹) was applied to the relevant experimental plots. The solution was uniformly applied to a 1.2 x 1.2 m area centered on the experimental trees to avoid border effects (Hagedorn & Bundt, 2002). Horizontal and vertical soil profiles were excavated when the solution had infiltrated the soil (Hu *et al.*, 2013). Horizontal profiles were excavated from 0.5 x 0.5 m quadrats and vertical profiles with maximum dyeing depth were extracted respectively from points centered on the experimental trees one day after dye tracer application (Hagedorn & Bundt, 2002). For the horizontal and vertical sections, soil cores were replicated and extracted from preferential pathways and soil matrix to observe plant roots content at the soil profile scales. During field experiments, camera should be taken to record preferential pathways (stained areas) and soil matrix (unstained areas) (Hagedorn & Bundt, 2002) (Fig. 2).

Root sampling

Each experimental plot was excavated from horizontal sections in 10 cm depth increments 24 h after

application of Brilliant Blue FCF dye solution. Undisturbed soil samples were taken at each depth using soil corers (7 cm diameter, 5 cm height, 200 cm³ volume) with two field replications in preferential pathways and soil matrix. Samples were taken to a depth of 60 cm (0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-35, 35-40, 40-45, 45-50, 50-55, 55-60 cm) in all experimental plots. Soil cores were stored at -2 °C (Castellanos *et al.*, 2001) and soil was separated from plant roots using 5 mm sieves. When necessary, samples were placed in dishes with 4-5 mm deep water so that plant roots spread and soil particles could easily be removed. Soil-free roots were dried for 48 hours in an oven at 70 °C to constant weights (Helmisaari *et al.*, 2007) and then weighed using an electronic balance (DV215CD). Fine root length density was measured using WinRHIZO (STD4800) (Yan *et al.*, 2011). And fine root biomass was calculated by root dry weight on the basis of the cross-sectional area of soil cores.

Root content contribution to preferential flow

Root content contribution to preferential flow was characterized by evaluating comparison of root content

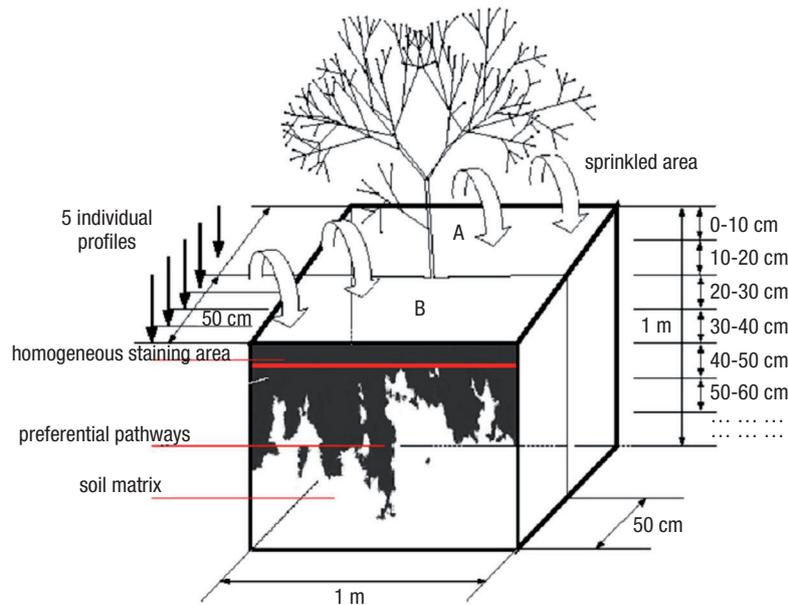


Figure 2. Experimental treatment: extracting soil cores from preferential pathways and soil matrix at the soil profile scales (0-60 cm) after solution application.

(root length density and root biomass) between soil preferential flow and soil matrix. Relevant equation was based on root content. Simplified equation is

described by $\eta = \frac{\alpha_{PP} - \alpha_{SM}}{\alpha_{PP}}$ or $\eta = \frac{\alpha_{PP} - \alpha_{SM}}{\alpha_{SM}}$, where

η is root content contribution to preferential flow (%), α_{PP} is root length density (mm 100 cm⁻³) or root biomass (g 100 cm⁻³) in preferential pathways, α_{SM} is root length density (mm 100 cm⁻³) or root biomass

(g 100 cm⁻³) in soil matrix. In general, $\eta = \frac{\alpha_{PP} - \alpha_{SM}}{\alpha_{PP}}$

will be appropriate when α_{PP} is higher than α_{SM} , while

when α_{PP} is smaller than α_{SM} , $\eta = \frac{\alpha_{PP} - \alpha_{SM}}{\alpha_{SM}}$ will be

appropriate.

Preferential flow indices

Dye coverage: proportion of the dye-stained areas to sum of the dye-stained and non-stained areas (Kassteel *et al.*, 2013) (equation (1)). In preferential pathways, water and solute flows through this way, bypassing the soil matrix.

$$DC = 100 \cdot \left(\frac{D}{D + ND} \right) \quad (1)$$

where DC (%) is Dye Coverage, D is the dye-stained areas (cm²), and ND is the non-stained areas (cm²).

Maximum depth of dye infiltration: dye tracers move through soil preferential pathways to deep soil layers even groundwater levels. In vertical soil profiles,

relevant profiles would be excavated to the maximum depth.

Statistical analysis

One-way ANOVA was used to access differences in mean root length density and root biomass between preferential pathways and soil matrix and to characterize effects of root parameters on soil preferential flow. Comparison for the evaluation of plant roots content between the two regions was analyzed by SPSS software.

Results

Characteristics of soil preferential flow paths

Dye coverage

In our study, dye coverage was almost 100% in the upper 5-10 cm, but then decreased rapidly with the increase of soil depth for all experimental plots (Fig. 3). As seen from the figure, dye coverage displayed at the same site was not similar to some extent, which was probably due to soil heterogeneity, particularly abundant rock fragments and gravels in the study sites. Generally speaking, it was widely considered that dye coverage from *Platycladus orientalis* Franco decreased quickly at the soil profile scales. Based on our results, we fully took degree of soil preferential flow into consideration, and the relationship between degree of soil

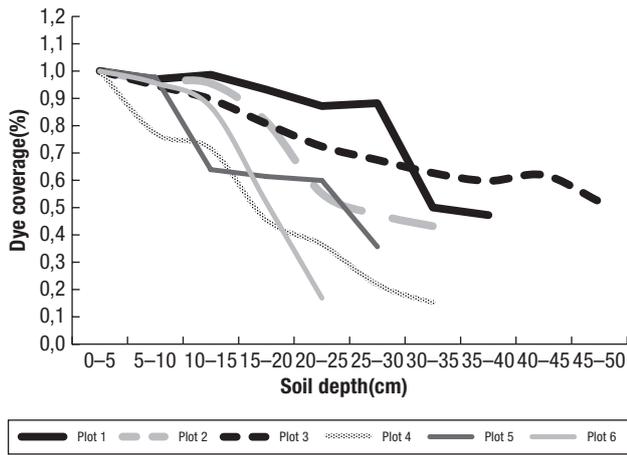


Figure 3. Changes in dye coverage with soil depth in all experimental plots.

preferential flow and dye coverage was also illustrated. From dye patterns (Fig. 4), we proposed that degree of soil preferential flow was medium in Jiufeng area. The degree of soil preferential flow showed in *Platycladus orientalis Franco* located in plot 3 and plot 4 was more pronounced than that showed in *Sophora japonica Linn* and *Quercus dentata Thunb.* In general, dye coverage in the soil profiles tend to be lower as a higher degree of soil preferential flow occurs.

Maximum depth of dye infiltration

Maximum depth of dye infiltration was different from soil profiles in all experimental plots because of differ-

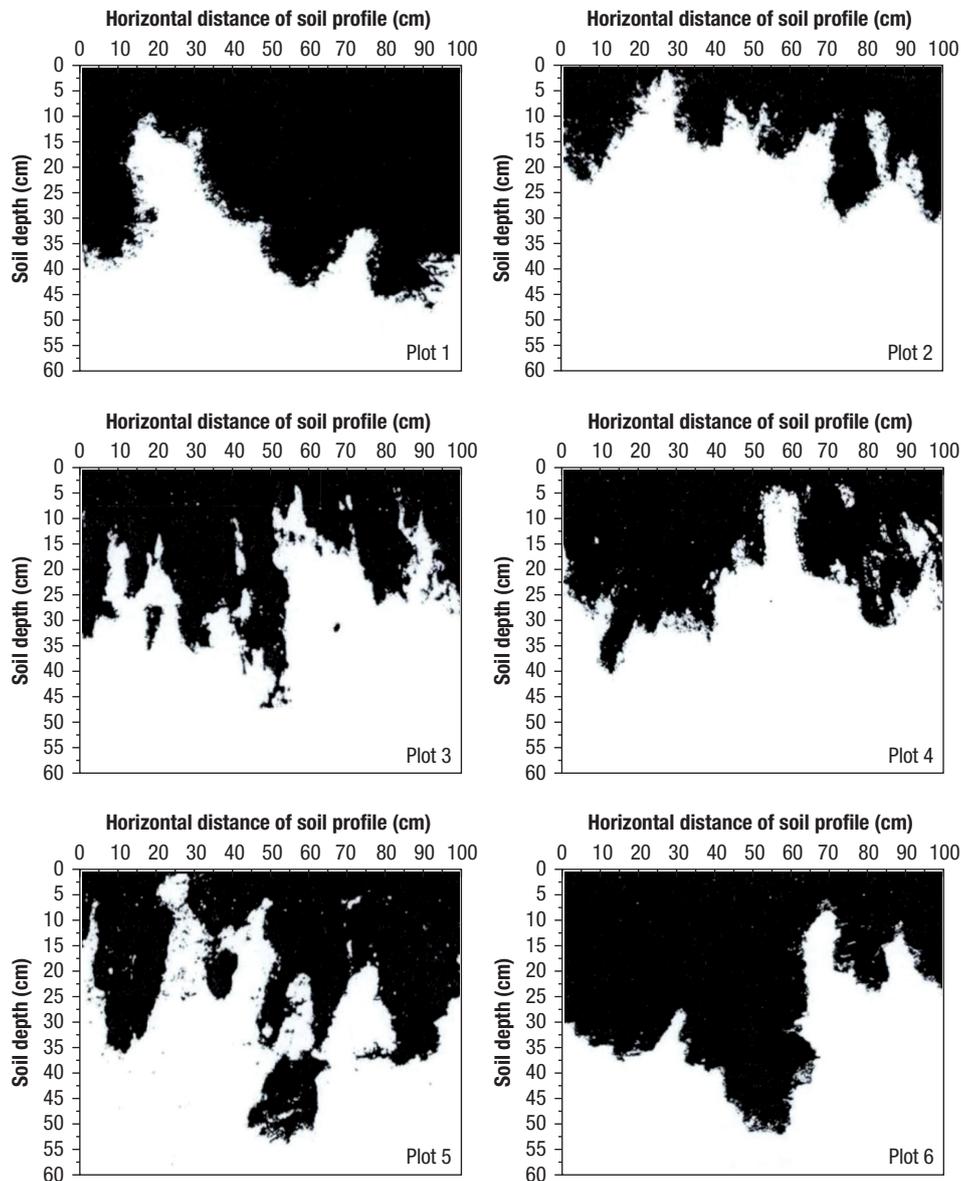


Figure 4. Dye patterns of soil preferential flow in all experimental plots.

ent plant roots content and soil spatial heterogeneity. On the basis of all surveyed data, maximum depth of dye infiltration was almost 50 cm from all soil profiles in plot 4 with a higher variance 132.4 ($n = 9, p < 0.05$), while a smaller variance 21.4 ($n = 9, p < 0.05$) in plot 1.

Root length density evaluation in preferential pathways and soil matrix

In this study, fine root length density ≤ 5 mm in diameter decreased with increasing distance from soil surface both in preferential pathways and soil matrix to some extent with respect to all experimental plots (Fig. 5). Fine root length density was greatest on the soil surface, with appropriately half root length den-

sity in the top 20 cm of the soil for experimental plot 1, and 15 cm for plot 2, plot 3, plot 4 and plot 6, and 10 cm for plot 5; 90% in the top 40 cm of the soil for experimental plot 1 and plot 3, and 25 cm for plot 5 and plot 6, and 30 cm for plot 2 and plot 4 whether in preferential pathways or soil matrix. Fine root length density ($\text{mm (100cm}^3\text{)}^{-1}$) was also different from species (Table 2): *Platyclusus orientalis* Franco > *Quercus dentata* Thunb > *Sophora japonica* Linn. The greatest plant roots concentration was found in the upper soil layer within a depth of 25-40 cm (topsoil). On the basis of all data from experimental plots, fine root length density ≤ 5 mm in diameter was 75.0-87.5% higher in preferential pathways than in soil matrix.

Meanwhile, we found that the contribution of fine root length density to soil preferential flow was sig-

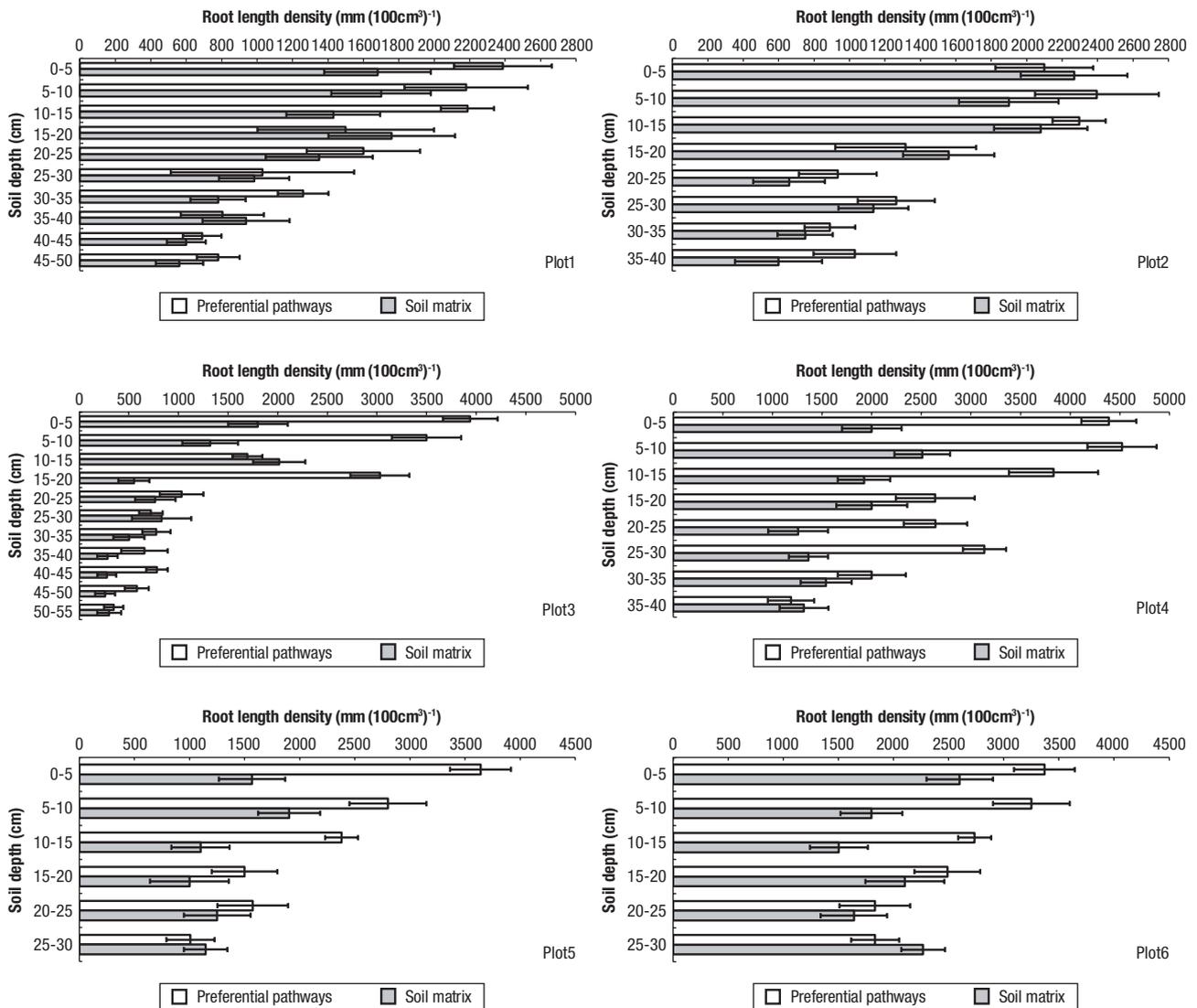


Figure 5. Changes in root length density between preferential pathways and soil matrix in all experimental plots. The relationship between root length density and soil depth was illustrated. The difference of root length density between preferential pathways and soil matrix was significant to some extent.

Table 2. Root length density located in 0-15 cm, 15-30 cm and below 30 cm in preferential pathways and soil matrix from experimental plot 1 to plot 6.

Experimental plots		Plot1	Plot2	Plot3	Plot4	Plot5	Plot6
Preferential pathways	RLB(mm (100cm ³) ⁻¹) (0-15 cm)	2252	2264	3045	4248	2940	3118
	RLB(mm (100cm ³) ⁻¹) (15-30 cm)	1377	1172	1594	2806	1360	2050
	RLB(mm (100cm ³) ⁻¹) (below 30 cm)	884	960	629	1593	–	–
	Average	1504	1465	1756	2882	–	–
Soil matrix	RLB(mm (100cm ³) ⁻¹) (0-15 cm)	1603	2083	1778	2143	1523	1968
	RLB(mm (100cm ³) ⁻¹) (15-30 cm)	1364	1165	880	1540	1133	2003
	RLB(mm (100cm ³) ⁻¹) (below 30 cm)	720	675	325	1428	–	–
	Average	1229	1308	994	1704	–	–
Total		2733	2773	2750	4586	–	–

RLB represents root length density in this paper.

nificant also (Fig. 6). Among those data, reference value of root length density contribution to preferential flow (19.2%) was fully considered for all experimental plots. From those data which exceeded 19.2%, we supposed that root length density was higher in soil preferential pathways than in soil matrix and that soil preferential flow was positively correlated with root length density. Furthermore, such accounted for 63.3% of all experimental data. While with respect to those data which were below 19.2%, we stated that the impacts of root length density in preferential flow was ambivalent (positive/negative), because some experimental data illustrated that root length density was higher in preferential pathways than in soil matrix,

while the others were on the contrary. Besides, the percentage ratio (root length density was higher in preferential pathways than in soil matrix or not) was 50% respectively among those experimental data which was below 19.2%.

Root biomass evaluation in preferential pathways and soil matrix

In general, fine root biomass ≤ 5 mm in diameter also decreased with increase of soil depth in preferential pathways and soil matrix (Fig. 7). Fine root biomass was greatest on the soil surface, with appropriately 70-80% root biomass in the top 20 cm of the soil at the soil profile scale. Based on those data from experimental plots, fine root biomass ≤ 5 mm in diameter was, 66.7% for plot 1, 2, 4 and 5, 100% for plot 3, and 33.3% for plot 6, higher in preferential pathways than in soil matrix. Average fine root biomass was also different from species: *Platycladus orientalis* Franco (1.474 g (100cm³)⁻¹) > *Quercus dentata* Thunb (1.332 g (100cm³)⁻¹) > *Sophora japonica* Linn (0.837 g (100cm³)⁻¹). With respect to different soil depth, fine root biomass was 50% higher in preferential pathways than in soil matrix for soil depth 0-10 cm, and 83.3% for 10-20 cm and 66.7% for 20-40 cm respectively. Among all surveyed data, root biomass was 66.7% higher in preferential pathways than in soil matrix on the whole. Fine root biomass as a proportion of total tree biomass was 9% for plot 1, 14% for plot 2, 10% for plot 3, 30.5% for plot 4, 16.5% for plot 5 and 20.1% for plot 6 respectively.

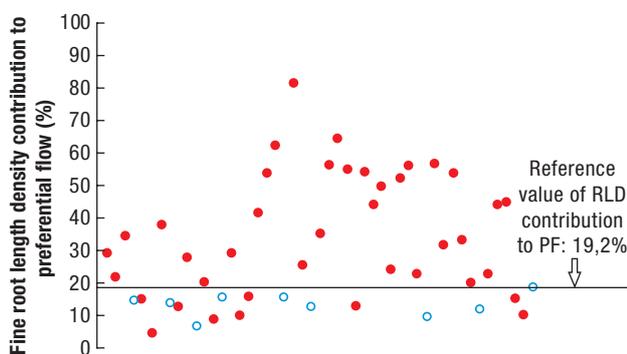


Figure 6. Fine root length density contribution to soil preferential flow in all experimental plots. Two circles were listed in the line overpass or below 19.2%. Open circles are below 19.2%, and the other shaded circles represent that either root length density contribution to preferential flow overpass 19.2% or below 19.2%. RLD represents root length density and, PF represents preferential flow.

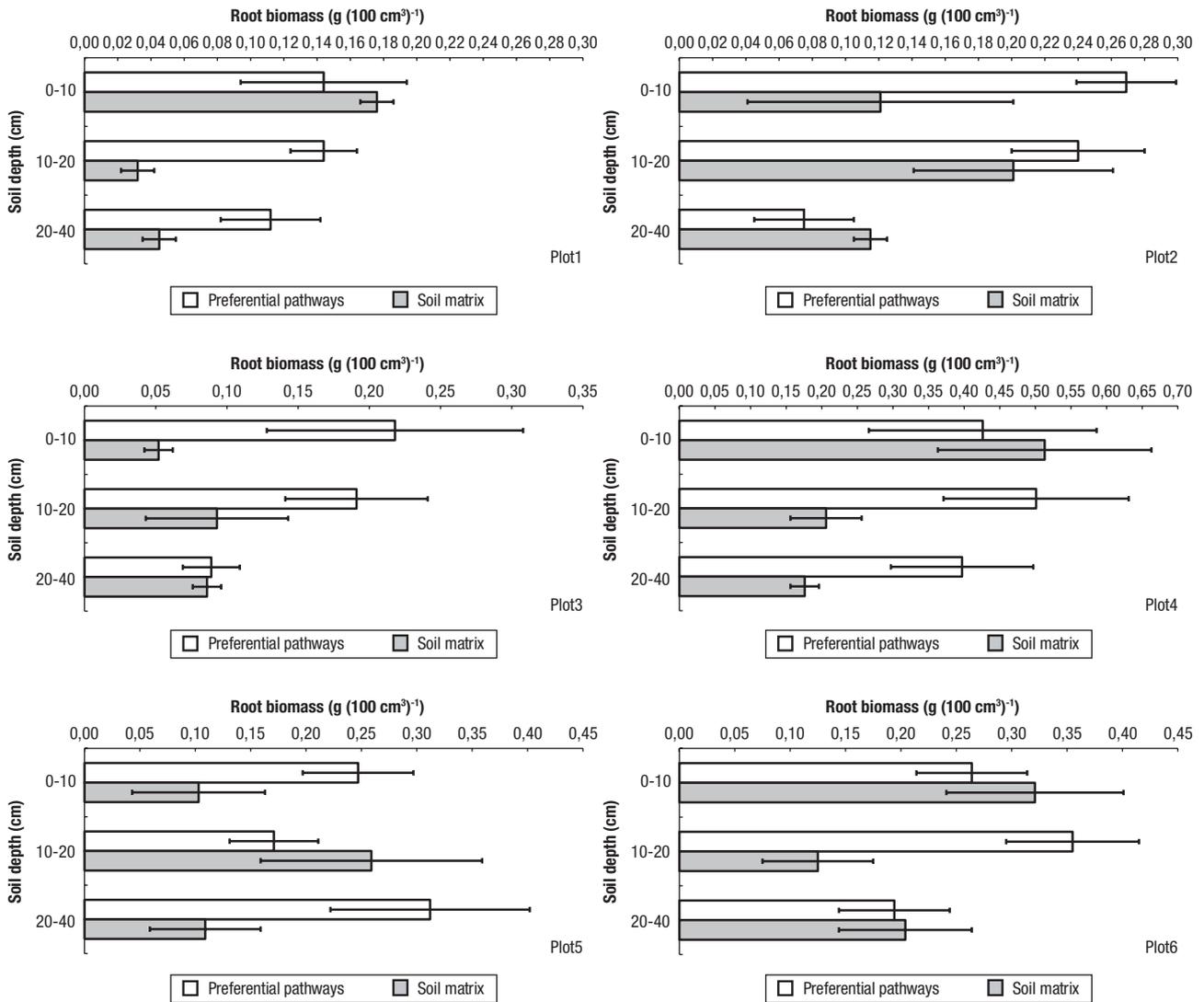


Figure 7. Changes of root biomass with the increasing depth from soil surface between preferential pathways and soil matrix with respect to all experimental plots.

In our study, we also realized that the contribution of fine root biomass to preferential flow was pivotal (Fig. 8). Like root length density, reference value of root biomass contribution to preferential flow (50%) was fully taken into account. There was no doubt that fine root biomass was higher in preferential pathways than in soil matrix as those data exceeded 50%. Therefore, we hypothesized that soil preferential flow was also positively correlated with fine root biomass as those data were considered. Meanwhile, such accounted for 55.6% of all surveyed data. As those data were below 50%, the influences of fine root biomass on preferential flow was ambivalent. And the percentage ratio that fine root biomass was higher in preferential pathways than in soil matrix was 20%, while the percentage ratio that fine root biomass was smaller in preferential pathways than in soil matrix was 80% among those data which was below 50%.

Discussion

Soil preferential flow in the soil profiles

Our field dye tracing experiments conducted in forest ecosystems containing abundant rock fragments illustrated that soil preferential flow was more obvious and that finger flow was predominant in Jiufeng area. The results were in agreement with Noguchi *et al.* (1997) and Hagedorn & Bundt (2002). Dye coverage decreased with the increasing soil depth from soil surface which supported more studies (Öhrström *et al.*, 2002; Kramers *et al.*, 2009), while some studies also indicated that the amount of stained area per depth (dye coverage) decreased to a depth and afterwards increased (Bogner *et al.*, 2013). Ecologists attribute the results to macropores density (e.g., root channels, rock

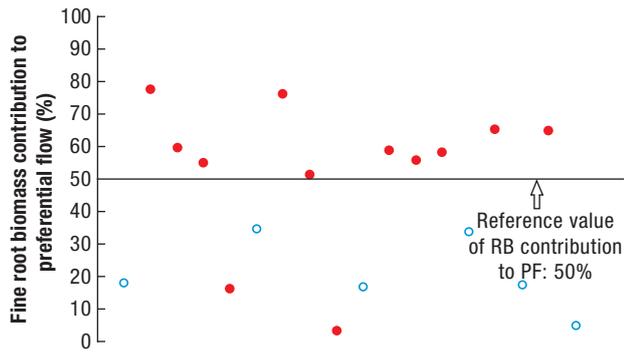


Figure 8. Fine root biomass contribution to soil preferential flow in all experimental plots. Two circles were listed in the line overpass or below 50%. Open circles are below 50%, and the other shaded circles represent that either root biomass contribution to preferential flow overpass 50% or below 50%. RB represents root biomass, and PF represents preferential flow.

soil interface and cracks). And sandy soil may also lead to the results. In the study site, forest soils contain abundant rock fragments and soil texture is not homogeneously distributed which makes higher soil spatial heterogeneity at the soil profile scale. Therefore, preferential pathways continuity is better because more plant fine roots on the soil surface. Particularly, the sandy loam will enhance plant roots into the macropores, meanwhile plant roots will also form corresponding channels to make soil water and solute transport through them. Lots of studies confirmed that degree of soil preferential flow in the upper soil layers was higher than that in the subsoil which led to smaller dye coverage, because preferential pathways were densely distributed in the topsoil. Maximum depth of dye infiltration was not similar greatly though experimental plots at the same site. At the soil profile scale, soil heterogeneity depended on preferential pathways continuity. In general, dye tracers could infiltrate into the deepest soil depth even groundwater levels which was not calculated by Richards equation, Mobile-immobile model and other mathematical models.

Role of fine root length density in soil preferential flow of forest ecosystems

Our results indicate that fine root length density decrease with increasing distance from soil surface which supports early and recent studies (Mitchell *et al.*, 1995; Tracy *et al.*, 2013). Those results collected from fine root length density imply that plant roots content are higher in preferential pathways than in soil matrix, supporting studies like Bundt *et al.* (2000, 2001), and the results are also in agreement with Bonger *et al.* (2010) and Bengough (2012), because plant fine roots usually form root channels called pref-

erential pathways (Li & Ghodrati, 1994; Jørgensen *et al.*, 2002) to prompt water infiltration after their decay (Beven & Germann, 1982). Soil preferential pathways in forest soils include higher organic carbon content and microbial biomass compared with soil matrix (Backnäs *et al.*, 2012). Plant fine roots themselves tend to release more organic matters to the soils as the rhizosphere decays. During plant roots decomposition, root channels are filled with organic matters derived from roots themselves (Ghestem *et al.*, 2011). Plant fine roots constitute a dynamic component of forest ecosystems (Dastidar *et al.*, 2012). By means of accumulating soil organic matters and redistributing nutrients at the soil profile scale, fine roots play significant role in their surrounding environment (Persson, 2000). Meanwhile, plant fine roots longevity is variable ranging from a few months to years because the process of plant roots turnover making new roots to replace decaying or dead roots is more related with soil nutrient availability (Yavitt *et al.*, 2011). Changes of fine root length density is a complex network with millions of lateral branches associated with mycorrhizal hyphae (Majdi *et al.*, 2005).

Our field experiments were carried out during rainy season, particularly during heavy rain, soil water flow in preferential pathways and cracks increases, and fine roots may become asphyxiated even die. Clusters of fine roots are sometimes observed along or at the end of coarse roots and correspond to zones of major organic nutrients and water uptake. Fine roots have high decay and emission rates, and clusters may soak up water during rainy season and may contribute to decayed flow paths (Ghestem *et al.*, 2011).

Furthermore, the highest fine root length density was found in the upper soil layer within a depth of 25-40 cm (topsoil). The result was in agreement with Lipiec *et al.* (2003), Bonger *et al.* (2008), Glab (2013). Fine roots on the soil surface are pivotal in forest nutrient cycling (Bengough, 2012). Despite forest nutrient cycling, fine roots may account for 50% of the Net Primary Production in forest ecosystems, and some studies proposed it up to 75% (Vogt *et al.*, 1996) and 33% (Gill & Jackson, 2000), which was beneficial to examine forest dynamics. To better understand forest dynamics with climate changes, studies on fine roots dynamics tend to be necessary. However, characterizing fine root dynamics are tedious and time-consuming. Fine root length density as an index of root dynamics also changes with climate. Therefore, fine root length density dynamics could lead to carbon and nutrient fluxes during forest dynamics process although fine roots contribute little to total forests biomass (<5%).

And fine roots located in the soil surface layers could also improve soil physical and chemical proper-

ties (e.g., soil bulk density, porosity, organic carbon, cation exchange capacity and so on). For example, the topsoil tend to have higher recharge rate that brings the soil moisture close to saturation compared with the subsoil (Vogt *et al.*, 1996; Schmid & Kazda, 2002). In the topsoil, fine roots which are short-lived and non-woody (Vogt *et al.*, 1996) in forest ecosystems may have more preferential root channels. The conclusion is in agreement with Noguchi *et al.* (1997) who stated that decaying fine roots of alfalfa could create more stable preferential pathways than wheat. Meanwhile, the results indicate that 100% of all fine root length density are within a depth of 55 cm in study site which is agreement with Schenk & Jackson (2002).

Role of root biomass in soil preferential flow of forest ecosystems

In this paper, fine root biomass was densely concentrated in the upper soil layers. The result was in agreement with Ford & Deans (1977) and Raizada *et al.* (2013). Change of fine root biomass is more pronounced in the upper soil layers than in deeper soil layers because of the higher organic matters and nutrition in the topsoil. Some studies imply that fine root biomass increases in nutrient rich zones, while some species also have a high fine root biomass in nutrient poor zones. The average of fine root biomass of the forest ecosystems in this study ($1.214 \text{ g (100cm}^3\text{)}^{-1}$) was substantially lower than estimates from Safford (1974), but not all temperate forest ecosystems. It is likely that gravels constitute the large portion of soil profiles in Jiufeng area: 10% in the top soil of 15 cm, 15% to a soil depth of 30 cm and 20% at soil depths below 30 cm. However, gravels constituted only 9% of the soil profiles studied by McClaugherty *et al.* (1984) and Safford (1974) did not state gravels.

Our results indicated that fine root biomass accounting for the total tree biomass in forest ecosystems varied between 9% and 30.5%. Fine roots' share of total biomass rarely represents more than 5% of total biomass of trees, while Santantonio *et al.* (1977) and Fogel (1983) reported that root biomass (coarse and fine roots) as a proportion of total tree biomass varied between 18 and 45%. Brassard *et al.* (2011) stated that coarse root biomass (diameter > 1 cm) could account for approximately 30% of total biomass in forest ecosystems. Maybe fine root biomass has been found to be variable in relation to forest stand characteristics (e.g., species, stand age, density, basal area and soil properties) or environmental factors (e.g., temperature, precipitation, geographical location and elevation) (Finer *et al.*, 2007). Jackson *et al.* (1997) estimated fine

root biomass and reported that live fine root biomass ranged from 130 g m^{-2} in deserts to 950 g m^{-2} in temperate grasslands.

Past results have shown that fine root biomass increases with stand age, for example, Grier *et al.* (1981) stated that there was an increase in fine root biomass with years, and Persson (1983) also. Those results are in agreement with us to some extent. With regard to *Platyclusus orientalis Franco* located in plot 3 and 4 and *Quercus dentata Thunb* located in plot 5 and 6, we found that fine root biomass increased with years, while there was no significant differences in fine root biomass for *Sophora japonica Linn*, and such supported Vogt *et al.* (1985), Ruark & Bockheim (1987) and Finer *et al.* (1997).

Change in fine root biomass may alter organic nutrient availability in forest soils. In previous studies, changes in fine root biomass were found to be the results of internal factors (e.g., plant species) and external factors (e.g., soil properties, stand age and climate). As was mentioned, fine root biomass only accounted for little of the total forest biomass, but such may exerts significant influences on carbon and nitrogen cycling in forest dynamics. Meanwhile, forest dynamics may affects on root biomass dynamics correspondingly.

In summary, the highest plant root concentration was found in the upper soil layer (Bonger *et al.* 2008; Himmelbauer *et al.*, 2010). More plant root channels would increase macropores network density and continuity (Shi *et al.*, 2012). Not only plant roots grow into macropores but also create macropores (biopores, cracks and burrows) (Noguchi *et al.*, 1997). More decaying or decayed plant roots as well as fine plant roots are distributed on the soil surface. Compared with living plant roots, decayed roots were more effective to create preferential pathways (Mitchell *et al.*, 1995). Furthermore, plant roots could release complex organic compounds (e.g., amino acids and organic acids) into the soils to prompt plant growth (Bengough, 2012).

Conclusions

Measurements of plant roots systems in forest ecosystems showed that significant effects of root length density and root biomass on soil preferential flow. In general, root length density was greater in preferential pathways than in the soil matrix, and root biomass was also. Particularly, some preferential flow indices (e.g., dye coverage and maximum depth of dye infiltration) were measured in all experimental plots, presumably reflecting the degree of soil preferential flow in the study site. Field dye tracing experiments were used to visualize flow patterns in the soil profiles and to quan-

tatively characterize plant roots content located in the preferential pathways and soil matrix. Despite soil spatial heterogeneity due to abundant rock fragments in the experimental plots, our results showed that plant roots systems played a significant role in soil preferential flow.

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