RESEARCH ARTICLE

The distribution of fine root length density for six artificial afforestation tree species in Loess Plateau of Northwest China

Shengqi Jian[1], Chuanyan Zhao[1, *], Shumin Fang[1], Kai Yu[2]

[1] State Key Laboratory of Grassland and Agro-Ecosystems, School of Life Sciences, Lanzhou University. Huyang building 301, Tianshui south road 222, Lanzhou, China   [2] Ministry of Education Key Laboratory of Western China Environmental Systems, Lanzhou University Huyang building 301, Tianshui south road 222, Lanzhou, China

Abstract

Aim of the study: Data about the distribution of fine root length density (*FRLD*) is important to understand the ecophysiology of vegetation. This is particularly true when models are applied to describe ecohydrology and vegetation function. However, there is yet limited knowledge of root distributions in semi-arid regions. The aim of this study is to investigate the distribution of fine roots for six typical afforestation tree species in Loess Plateau and its relationships with soil environmental factors.

Area of study: Loess Plateau (NW of China).

Material and methods: We quantified the fine root length density distribution of six typical afforestation tree species by soil core method, and the soil properties also were investigated.

Main results: More than 50% of fine root length was concentrated at depths between 0 and 40 cm in vertical direction. In horizontal direction, most of fine roots concentrated near the trunk. Results showed a significant negative correlation between vertical distribution of *FRLD* and soil water content, a positive correlation between *FRLD* and organic matter and total N is significant, and a negative correlation with bulk density. No relationships were found with total C and particle size distribution in any soil layer for the six tree species. Stepwise multiple linear regression confirmed that changes in different soil properties significantly affected the variation in *FRLD* for each tree species, total N had strong and positive relationships with *FRLD*.

Research highlights: These measurements provide valuable data for modelling of ecosystem water use and productivity.

Keywords: Anjiapo catchment; Core method; Root distribution; Soil moisture; Soil properties.

Introduction

Fine roots are the most dynamic and physiologically active component of below-ground biomass, and they play an important role in nutrient and water uptake (Schenk, 2008; Aanderud & Richards, 2009). In most ecosystems, fine roots concentrate near the soil surface and exponentially decrease with increasing soil depth (Macinnis-Ng *et al*., 2010). This enables more soil resource uptake since water enters the soil profile predominantly from the soil surface in most ecosystems, and nutrient concentrations are commonly higher in the upper soil layers (Schenk, 2008). Most earlier studies focused on one-dimensional or root depth distribution (Bennett *et al*., 2009; Macinnis-Ng *et al*., 2010),

while ignoring lateral variability. Lateral extent of woody roots may exhibit a high degree of plasticity and depend on environmental conditions. Belsky (1994) found that trees from a dry site had lateral roots extending well beyond the canopy, but that trees from a wetter site concentrated their root growth beneath the canopy. She speculated that in more arid conditions trees invested in laterally extensive roots for greater water access, and that when water was less limiting, roots grew under the canopy where nutrients were more plentiful. Therefore, the properties of fine root distributions often depend on soil water and nutrient availability in soils (Iverson, 2010).

In semi-arid regions, soil water is the limiting factor for plant primary production (February & Higgins,

2010; Armas *et al.*, 2012). Many perennial plants in semi-arid regions have shallow roots to absorb soil water from rainfall and/or deep roots to access groundwater and deep soil moisture (Gwenzi *et al.*, 2011) thereby taking up water from groundwater, surface processes or both sources (Jackson *et al.*, 2008; Nagler *et al.*, 2008). Correlating the fine roots to soil water contents may lead to a greater understanding of how different plants respond to heterogeneity in soil moisture and provide a better understanding of fine root growth dynamics. Although previous studies have examined the relationship between roots and soil moisture and reported that during periods of drought, low root densities may correspond to low soil moisture levels (Nippert *et al.*, 2010), a clear correlation between fine root length densities and soil water depletion was not apparent over time (Rewald *et al.*, 2011). Some literatures have reported forest caused a dried soil layer (DSL) in the profile on Loess Plateau of China due to unbalance between water demand and water supply (Mokany *et al.*, 2006). The DSL resists forest growth, finally resulting in forest degradation (Li & Huang, 2008; Wang *et al.*, 2008a). Examining the distribution of fine roots of plants is important for understanding the water use strategy of plants. However, the number of studies on the fine root distribution of woody species is small (Zhou & Shangguan, 2007; February & Higgins, 2010; Gwenzi *et al.*, 2011).

Soil nitrogen is regarded as a secondary influential factor on plant growth in semi-arid regions (Hu *et al.*, 2013). It has been reported that trees with a substantial uptake of nutrients from deep soil layers may deplete the topsoil less than trees with a more shallow root system, since the former may utilize weathering products from the deeper layers (Hu *et al.*, 2013). Thus, it is important to understand relationships between vertical distributions of fine roots and soil moisture and N concentrations for evaluating soil resource use of plants. In addition to soil resource, bulk density, organic matter, particle size distribution and other soil characteristics possibly have an effect on plant growth and production in such regions (Janos *et al.*, 2008). Courtney and Timpson (2005) and Szota *et al.* (2007) reported that high soil bulk density and high clay content are thought to limit root growth. The accumulation of organic matter on the surface soil promotes nutrient concentration and thus fine roots accumulation in the upper layers of the soil (Scattolin *et al.*, 2008). To address the strategy of plants for water and nutrient use and environmental tolerance, it is important to understand the response of fine roots to the soil environmental factors (Jiao *et al.*, 2010). Some studies about fine roots distribution have been conducted for woody species, suggesting their association with soil moisture,

N concentration or soil properties (Zhou & Shangguan, 2007; February and Higgins, 2010; Gwenzi *et al.*, 2011).

The water and wind erosion transitional belt of China's Loess Plateau experiences severe soil erosion, vegetation degradation and soil desertification (Eastham *et al.*, 2006; Mainiero & Kazda, 2006). The vegetation practices have been implemented by the Chinese Government, e.g. planting perennial shrubs and grasses, to improve the environmental condition and to reduce water and soil losses in the area. However, the disparity between water and nutrients supply and demand is becoming particularly acute because of the initially simple, cultivated vegetation system have developed toward a more complex, cultivated and natural ecosystem capable of reversing effect (Scattolin *et al.*, 2008). Knowledge of fine roots distribution can contribute to understanding of how fine roots water and nutrients uptake and may be important information to assist in managing planted forest.

In the current study, we examined the vertical and horizontal distribution of six typical artificial afforestation tree species fine roots in single-tree scale in Anjiapo catchment, Loess Plateau, China. We also investigated the relationships between fine roots and soil environmental conditions. We hypothesized that fine roots concentrate near the soil surface and lateral roots extending well beyond the canopy in this semi-arid region, soil resource availability, especially soil moisture and N concentration would affect the fine roots distribution. We also predicted that high soil bulk density and clay content may adversely affect fine root distributions. In recent years, some of the afforestation tree species have died down, reflecting the inadaptability in the current region. This has promoted us to study the roots to understand its relationships with soil environment, providing the basis for the selection of appropriate tree species, and providing parameters for model establishment.

Materials and methods

Study site

The study was conducted in the Anjiapo catchment, Dingxi County (35°35′N, 104°39′E) of Gansu province on western Chinese Loess Plateau. The annual mean precipitation is 420 mm with great inter-annual variations. Over 60% of the precipitation falls between July and September and over 50% of it occurs during storm. The average monthly air temperature ranges from -7.4 to 27.5 °C, with mean annual temperature of 6.3 °C.

Average annual pan evaporation is 1510 mm. The predominant gray calcareous soil developed on loess parent material with silt texture has a relatively thick profile.

The six species considered in this study were tree species *Pinus tabuliformis Carr.*, *Populus tomentosa Carr.*, *Prunus armeniaca L.*, *Robinia Pseudoacacia L.* and shrub species *Caragana korshinskii Kom.*, *Hippophae rhamnoides Linn.*. They vary in traits such as aboveground growth rates, canopy height, rooting depth. The description and characteristics of the experimental sites presented in Table 1.

Root sampling and soil water content

The mean crown size was assessed using four trees for each of the six species. These four trees were selected in each plantation amongst trees with sizes approximate to the mean crown size and with a distance to neighbouring trees of more than 10 m. Tree transects were delineated around each tree, extending in N, E and SW directions from the tree bole. Root sampling was performed every 20 cm from the stem basis until very few roots were found; this was approximately 1.5 times the size of the canopy (*P. tabuliformis*, 500 cm; *P. tomentosa*, 400 cm; *P. armeniaca*, 400 cm; *R. pseudoacacia*, 300 cm; *C. korshinskii*, 300 cm; *H. rhamnoides*, 300 cm). Using a cylindrical metal corer (10 cm diameter and 10 cm height) with one sharpened edge, cores were down to 120 cm of soil depth. Each core was taken successively by increments of 10 cm to avoid soil compaction (Fig. 1) (Nissen *et al.*, 2008). Samples were transported to the laboratory in a cooler and stored at 5 °C until processing. Samples were washed with a Gillison root elutriator, and roots and organic debris were collected on 0.5 mm sieves. Roots

in each layer were divided into two size classes based on root diameter: fine roots (≤ 1 mm) and coarse roots (> 1 mm) (Stromberg *et al.*, 2009). Roots were further sorted into live and dead fractions by their color and elasticity. All of living fine roots in each layer were digitally scanned using a flatted scanner set at 600 dpi and saved as TIF files. Root images were analyzed using image analysis software (WinR-HIZO Pro 2008a, Regent Instruments Inc., Quebec City, Quebec, Canada) for root length. The fine root length density (*FRLD*, cm cm^{-3}) was calculated as follows: $FRLD = L/V_s$, where, L is fine root length in each soil block, and V_s is the volume of soil. The *FRLD* of each soil layer was calculated as follows:

$$D = \frac{\sum_{i=1}^{n}\sum_{j=1}^{k} L}{nk} \cdot \frac{1}{V_S} \qquad (1)$$

where, D is the *FRLD* of each soil layer; n is the number of soil cores of three transects (N, E and SW directions) per tree in vertical direction; k is the number of soil cores of three transects per tree in horizontal direction; L, V_s have the same meanings as above mentioned. Kriging interpolation method was used to analyze the fine roots two-dimensional distribution, and vertical profiles were divided into 10×20 cm grid cells based on the root sampling rules. Although the planted species wholly dominated the canopy, the plots were not monocultures; they contained other species (herbaceous plant) regenerating beneath the canopy. We did not sort roots by individual species, so it must be noted that for all variables measured, the effect of "species" refers to the entire treatment effect of the planted species. 12 fiber tubes with 120 cm length were installed in the sampling section of each sample tree to measure soil water content (Fig. 1), which was measured at 10 cm
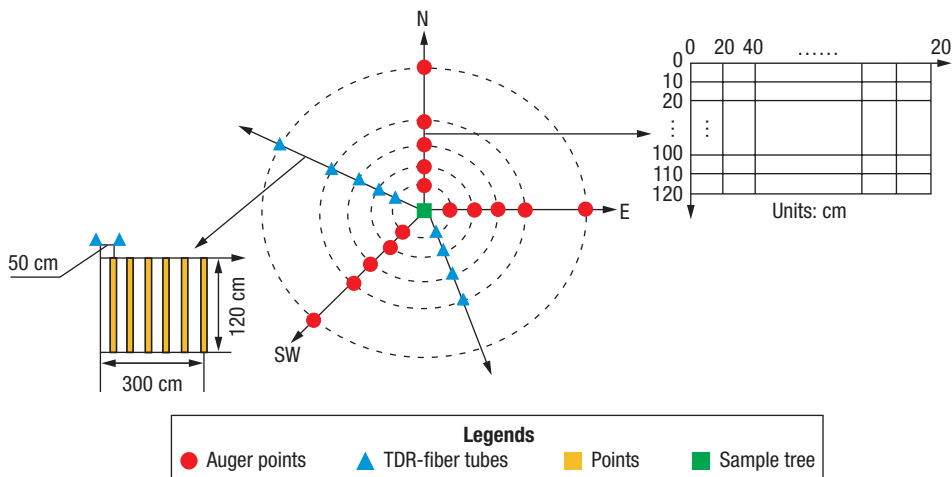

Figure 1. The sketch map of root sampling.

intervals in each tube and at 7-day intervals from June to October in 2012 using a TDR (Campbell, CS-610). The mean value of soil moisture was presented in the analysis.

Soil properties

Soil samples were collected at 20 cm increments from the surface to bottom on the walls using a cylindrical soil core (100 cm^3). These samples were placed in zip-lock plastic bags, which were then transported in cooler-boxes to the laboratory. One set of samples from each sampling position was oven dried at 105 ˚C for 2 days to determine bulk density. Core samples of a known volume were weighed after drying and bulk density was expressed as the dry mass divided by the soil volume (g cm^{-3}). Another set of samples was to estimate clay, sand and silt content by weight according to the United States Department of Agriculture (USDA) method, which employs the following size standards: gravel > 2 mm, 2 mm < sand < 0.05 mm, 0.05 mm < silt < 0.002 mm, and clay < 0.002 mm (Soil Survey Staff, 1999). In this paper, we only considered fractions of less than 2 mm. The set of samples was used to determine total organic matter of the soil using the loss on ignition technique in a blast furnace (Armas *et al.*, 2012). Dried samples of a known mass were combusted at 550 °*C* for 5 h. The samples were weighed again and the lost portion was the organic content. The last set of samples was used to measure total soil C and N concentrations with a CN corder (MT-700CN analyzer, Yanaco, Kyoto, Japan). Each measurement was with three replications.

Data analysis

Vertical root distribution was modeled by the equation (Gale & Grigal, 1987):

$$Y = 1 - \beta^z \qquad (2)$$

where z is depth (cm), Y is the proportion of roots from the surface to depth z and β is a numerical index of rooting distribution. High values of β indicate greater proportion of roots with depth (Jackson *et al.*, 1996). The proportional length of roots in the profile was calculated to depths of 120 cm with the interval at 10 cm using mean values from each tree. Differences among species in root depth distribution were tested with linear regression analysis of the log-transformed β data. The values of *FRLD* in vertical direction were averaged at 20 cm intervals. Relationships between soil environ-

mental factors and averaged values of *FRLD* were examined in each soil layer for all three transects (N, E and SW directions). An *f*-test was used to depth and *FRLD* on each soil environmental factors. Pearson correlation analysis was conducted between *FRLD* and soil environmental factors. A Kruskal-Wallis test was used to determine the effects of depth on each soil environmental parameter. Stepwise linear regression analyses were performed using *FRLD* as the dependent variable and soil environmental factors as the independent variables. We also removed soil environmental factors described above from regression analyses to avoid multicollinearity among independent variables. The total fine root length in each core was estimated by integrating the function to find the area under the curve using SigmaPlot version 11.0 (Systat Software Inc. Chicago IL, USA 2008). These analyses were conducted by using SPSS software version 18.0.0 (SPSS, Chicago, IL, USA). For all test a level of significance for $P < 0.05$ was used.

Results

The distribution of fine roots

Vertical distribution

All the species had relatively shallow fine root systems. Fine root length declined exponentially with depth for all species with β values averaging 0.947. *R. pseudoacacia* had the lowest index of rooting distribution ($\beta = 0.941$) and *P. tabuliformis* had the highest value ($\beta = 0.953$). Nevertheless, values of β did not differ significantly among species ($P = 0.29$; Fig. 2).

The *FRLD* of all six tree species showed significant ($P < 0.001$) depth effects, *FRLD* decreased exponentially with soil depth. Nevertheless, the differences among six tree species were significant (Fig. 3). Considering the 120 cm profile, as much as 66.4-81.7% of the fine root length occurred between 0 and 40 cm depth and 81.4-95.0% occurred between 0 and 80 cm. Of the six tree species, the averaged *FRLD* was in order of *R. pseudoacacia* (0.0599 ± 0.0092 cm cm^{-3}) > *P. tabuliformis* (0.0413 ± 0.0087 cm cm^{-3}) > *P. armeniaca* (0.0329 ± 0.0072 cm cm^{-3}) > *P. tomentosa* (0.0292 ± 0.0031cm cm^{-3}) > *C. korshinskii* (0.00709 ± 0.00088 cm cm^{-3}) > *H. rhamnoides* (0.00686 ± 0.00067 cm cm^{-3}). *R. pseudoacacia* had consistently more fine roots at any given depth than other tree species. The exponential relationship between soil depth and *FRLD* was strongest in *H. rhamnoides* and weakest in *C. korshinskii* (Table 2).
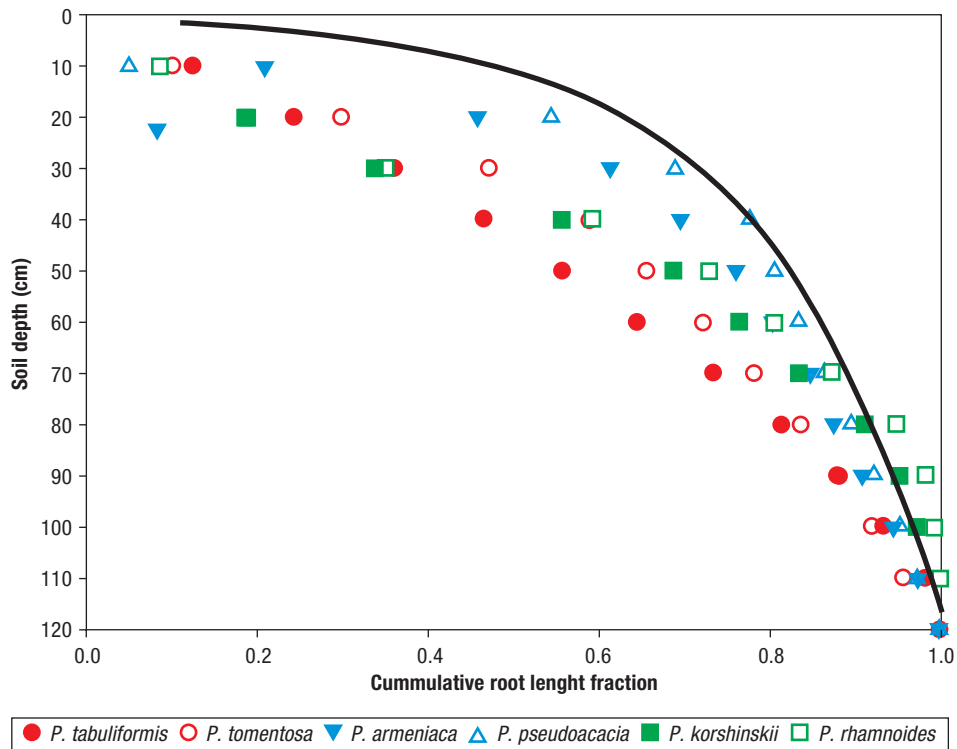
Figure 2. Cumulative root distribution as a function of root depth for six species in 21-year-old plantations on the Loess Plateau. The fitted equation is $Y = 1 - \beta z$, where Y is the cumulative root fraction (proportion between 0 and 1) with depth (z in cm) and β is the fitted parameter (Gale and Grigal 1987). The curve indicates the least square fit of β for all species ($\beta = 0.947$).

Table 1. Tree species, aspect, slope, slope position, plantation age, height, DBH and crown size in July 2012 of the experimental sites in the Anjiapo catchment, Loess Plateau, China.

Species	Aspect	Slope(°)	Slope position	Age	Height(m)	DBH (cm)	Crown size (cm)
P. tabuliformis	NW	12	Middle	21	11±0.7	10±1.6	330±15
P. tomentosa	N	10	Down	21	13±0.9	12±0.9	260±16
R. pseudoacacia	SE	9	Up	21	7±0.7	8±0.7	216±19
*P. armenia*ca	W	7	Middle	21	8±0.6	6±0.5	246±21
C. korshinskii	SE	15	Middle	21	1.7±0.2	4±0.6	180±17
H. rhamnoides	N	19	Up	21	2.1±0.3	–	191±21

*40 trees of each of the six tree species were investigated. Values = mean±standard deviation.

Radial distribution

The relationships between *FRLD* and different radial distances from the sample trees are presented in Fig. 4. Data have been combined from horizontal and vertical cores and samples representing distances have been divided into 20 cm intervals. *FRLD* decreased exponentially ($P < 0.001$) with increasing horizontal distance for *P. armeniaca* (Fig. 4C). The other species showed quadratic polynomial relationships between *FRLD* and horizontal distance (Fig. 4). The peak *FRLD* was independent of the location of each species, the peak values appeared at 200-220, 60-80, 0-20, 40-60, 60-80 and 60-80 cm for *P. tabuliformis*, *P.tomentosa*, *P. armeniaca*, *R. pseudoacacia*, *C. korshinski* and *H.*

rhamnoides, respectively (Fig. 4). The fitting equations are presented in table 3.

Two-dimensional distributions

Kriged maps of *FRLD* for six species show concentrations of fine roots. The areas where roots were concentrated to be upper layers of soil (*P. tabuliformis* concentrated in $0 < z < 40$ cm, $100 < r < 350$ cm; *P.tomentosa*, $0 < z < 40$ cm, $0 < r < 200$ cm; *P. armeniaca*, $0 < z < 40$ cm, $0 < r < 120$ cm; *R. pseudoacacia*, $0 < z < 30$ cm, $0 < r < 220$ cm; *C. korshinskii*, $20 < z < 50$ cm, $40 < r < 180$ cm and *H. rhamnoides*, $20 < z < 50$ cm, $30 < r < 190$ cm). The kriged maps of *FRLD* illustrate the vari-
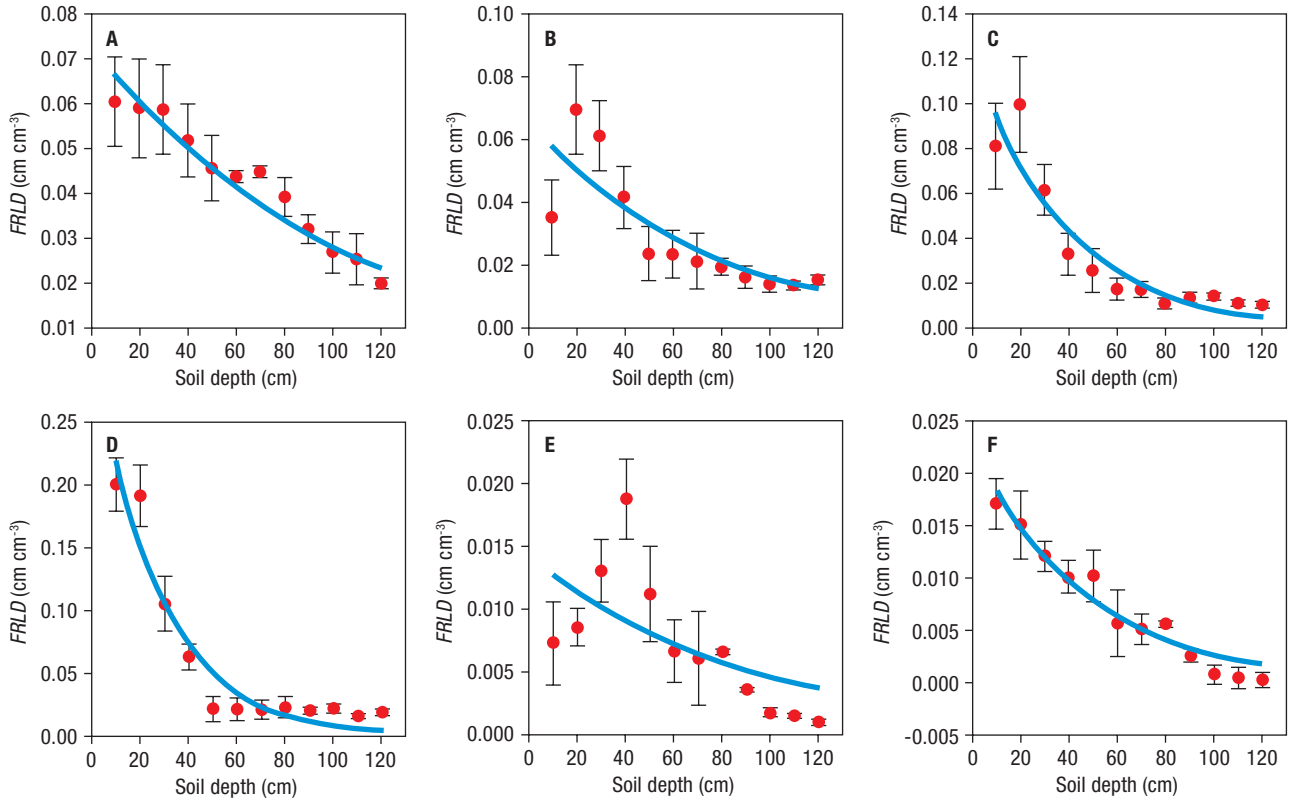
Figure 3. Vertical distribution of fine root length density for six tree species in the Anjiapo catchment of the Loess Plateau in China. Data are mean values ± S.E, *n* = 12. A, *P. tabuliformis*; B, *P.tomentosa*; C, *P. armeniaca*; D, *R. pseudoacacia*; E, *C. korshinski*; F, *H. rhamnoides*.
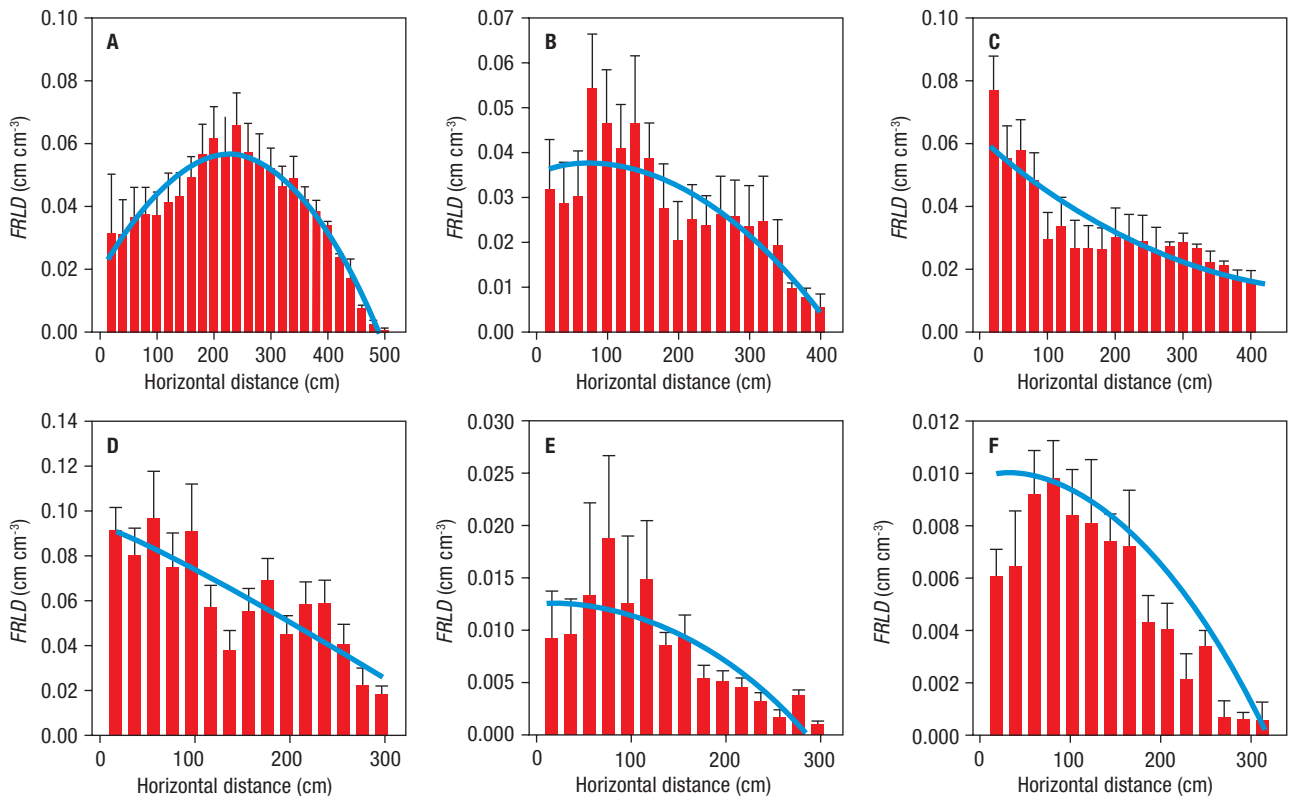

Figure 4. Radial distribution of fine root length density for the six species in the Anjiapo catchment of the Loess Plateau in China. Data are mean values ± S.E, *n* = 12. A, *P. tabuliformis*; B, *P.tomentosa*; C, *P. armeniaca*; D, *R. pseudoacacia*; E, *C. korshinski*; F, *H. rhamnoides*.

ability from a two-dimensional perspective, clearly showing that *FRLD* changed more rapidly in the vertical than in horizontal direction. Higher root densities oc-curred in the central part of the profiles rather than on left or right hand sides (Fig. 5). The fitting results with a normal function are presented in Table 4.

Table 2. The fitting equations of Figure 3.

Species	Fitting equation	R^2	F	P
P. tabuliformis	$FRLD = 0.088e^{-0.13z}$	0.862	62.44	< 0.0001
P. tomentosa	$FRLD = 0.062e^{-0.14z}$	0.796	28.84	< 0.001
P. armeniaca	$FRLD = 0.13e^{-0.27z}$	0.866	72.36	< 0.0001
R. pseudoacacia	$FRLD = 0.32e^{-0.37z}$	0.922	130.42	< 0.0001
C. korshinski	$FRLD = 0.021e^{-0.22z}$	0.721	27.71	< 0.001
H. rhamnoides	$FRLD = 0.047e^{-0.39z}$	0.940	173.28	< 0.0001

*z is the soil depth (cm), the same below.

Table 3. The fitting equations of Figure 4

Species	Fitting equation	R^2	F	P
P. tabuliformis	$FRLD = -0.0003r^2 + 0.0071r + 0.0168$	0.935	172.11	< 0.0001
P. tomentosa	$FRLD = -0.0001r^2 + 0.0011r + 0.0353$	0.716	19.43	< 0.0001
P. armeniaca	$FRLD = 0.063e^{-0.067r}$	0.766	40.75	< 0.0001
R. pseudoacacia	$FRLD = -0.00005r^2 - 0.0038r + 0.0948$	0.781	15.92	< 0.001
C. korshinski	$FRLD = -0.00007r^2 + 0.0002r + 0.0121$	0.797	18.85	< 0.001
H. rhamnoides	$FRLD = -0.00005r^2 + 0.0002r + 0.0099$	0.714	13.28	< 0.001

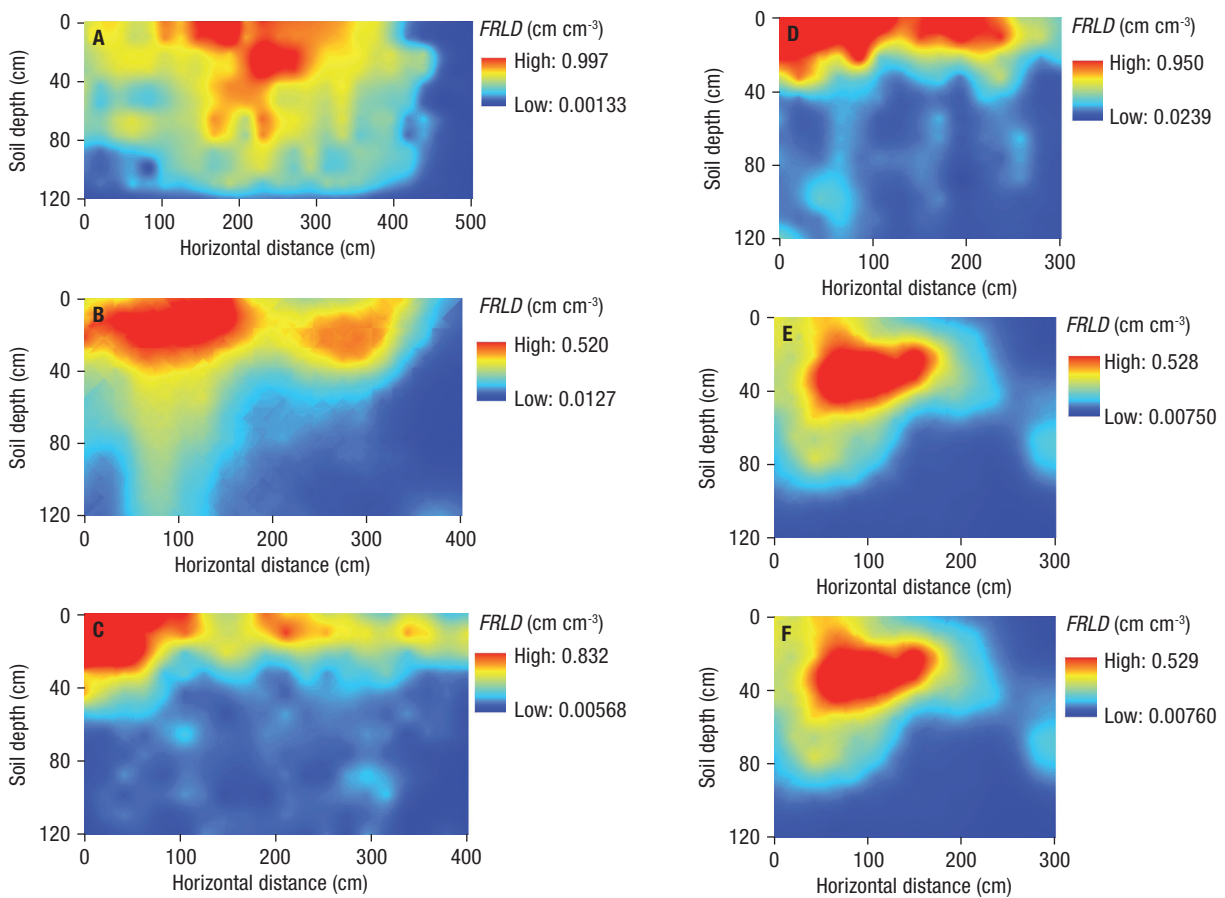*r is the horizontal distance (cm), the same below.

Figure 5. Kriged maps of fine roots distribution for the six species in the Anjiapo catchment, Loess Plateau, China. A, *P. tabuliformis*; B, *P.tomentosa*; C, *P. armeniaca*; D, *R. pseudoacacia*; E, *C. korshinski*; F, *H. rhamnoides*.

Soil moisture and *FRLD*

The negative correlation between *FRLD* and soil water content was significant in each soil layer for each of the six tree species (Table 5). The upper layer of soil (0-40 cm) had the relative lowest soil water content and highest *FRLD*, indicating the root system of these trees through a high density of their roots at the top of the profile, were capable of capturing more of the water available from rainfall. Soil moisture increased with decreasing *FRLD* in the layer (40-90 cm), and below 90 cm, soil moisture remained stable because of few fine roots and no evaporation loss for the six tree species (Fig. 6).

Soil properties and *FRLD*

Particle size distribution (sand, silt and clay) was not significantly different among depth (Kruskal-Wallis test, *P. tabuliformis*, $P = 0.085$; *P.tomentosa*, $P = 0.07$; *P. armeniaca*, $P = 0.076$; *R. pseudoacacia*, $P = 0.077$; *C. korshinski*, $P = 0.069$ and *H. rhamnoides*, $P = 0.072$), total C was nearly uniform throughout the profile (Kruskal-Wallis test, *P. tabuliformis*, $P = 0.093$; *P.tomentosa*, $P = 0.077$; *P. armeniaca*, $P = 0.081$; *R. pseudoacacia*, $P = 0.083$; *C. korshinski*, $P = 0.092$ and *H. rhamnoides*, $P = 0.062$). In general, organic matter and total N decreased with increasing soil depth (Kruskal-Wallis test, *P. tabuliformis*, $P = 0.015$; *P.tomentosa*, $P = 0.006$; *P. armeniaca*, $P = 0.026$; *R. pseudoacacia*, $P = 0.0187$; *C. korshinski*, $P = 0.011$ and *H. rhamnoides*, $P = 0.016$), and was inversely related to bulk density for the six tree species (Kruskal-Wallis test, *P. tabuliformis*, $P = 0.021$; *P.tomentosa*, $P = 0.19$; *P. armeniaca*, $P = 0.02$; *R. pseudoacacia*, $P = 0.017$; *C. korshinski*, $P = 0.019$ and *H. rhamnoides*, $P = 0.022$) (Table 6). Averaged bulk density, organic matter and total N were 0.94-1.22 g cm^{-3}, 0.53-0.82% and 0.065-0.11% in the top 60 cm depth, and 1.11-1.50 g cm^{-3}, 0.31-0.53% and 0.046-0.068% at 60-120 cm depth for the six tree species (Table 6). Vertical distribution of *FRLD* was positively correlated with organic mat and Total N, negatively correlated with bulk density, no relationships was found with total C and particle size distribution (sand, silt and clay) for six tree species (Table 7). Stepwise multiple linear regression confirmed that changes in bulk density signifi-

Table 4. The fitting equations of Figure 5.

Species	Fitting equation	R^2	F	P
P. tabuliformis	$FRLD(z,r) = 0.890e^{-0.5[(\frac{z-2.000}{0.909})^2 + (\frac{r-1.000}{0.455})^2]}$	0.660	16.42	< 0.001
P. tomentosa	$FRLD(z,r) = 0.521e^{-0.5[(\frac{z-2.000}{1.365})^2 + (\frac{r-1.000}{0.455})^2]}$	0.768	28.13	< 0.0001
P. armeniaca	$FRLD(z,r) = 0.547e^{-0.5[(\frac{z-1.000}{1.818})^2 + (\frac{r-1.000}{0.455})^2]}$	0.893	40.75	< 0.0001
R. pseudoacacia	$FRLD(z,r) = 0.062e^{-0.5[(\frac{z-1.120}{0.127})^2 + (\frac{r-2.083}{0.038})^2]}$	0.920	152.11	< 0.0001
C. korshinski	$FRLD(z,r) = 0.791e^{-0.5[(\frac{z-3.891}{0.959})^2 + (\frac{r-1.029}{0.514})^2]}$	0.607	13.34	< 0.001
H. rhamnoides	$FRLD(z,r) = 0.245e^{-0.5[(\frac{z-4.135}{1.777})^2 + (\frac{r-1.137}{0.298})^2]}$	0.745	21.75	< 0.001

Table 5. Correlation analysis of soil moisture with fine root length density in the Anjiapo catchment on the Loess Plateau, China (Units: soil moisture, %; *FRLD*, cm cm^{-3}).

| Species	Variables	N	Mean±SD	Max	Min	r	F	P
P.tabuliformis	Soil moisture	12	5.51±0.67	7.51	3.28			
	FRLD	12	0.00709±0.00057	0.0187	0.00092	−0.853	26.722	<0.0001
P.tomentosa	Soil moisture	12	7.30±0.66	9.37	5.95			
	FRLD	12	0.00708±0.00084	0.01878	0.00083	−0.541	7.413	<0.05
P. armeniaca	Soil moisture	12	9.67±1.24	14.3	6.20			
	FRLD	12	0.0292±0.0034	0.06915	0.0132	−0.583	8.726	<0.05
R.pseudoacacia	Soil moisture	12	8.61±1.11	11.3	6.64			
	FRLD	12	0.0413±0.0033	0.0605	0.00768	−0.577	7.671	<0.05
C.korshinskii	Soil moisture	12	8.15±0.93	9.61	5.87			
	FRLD	12	0.0599±0.0071	0.199	0.0154	−0.55	7.987	<0.05
H.rhamnoides	Soil moisture	12	5.66±0.71	7.72	4.11			
	FRLD	12	0.03292±0.0049	0.0996	0.0104	−0.63	6.589	<0.05
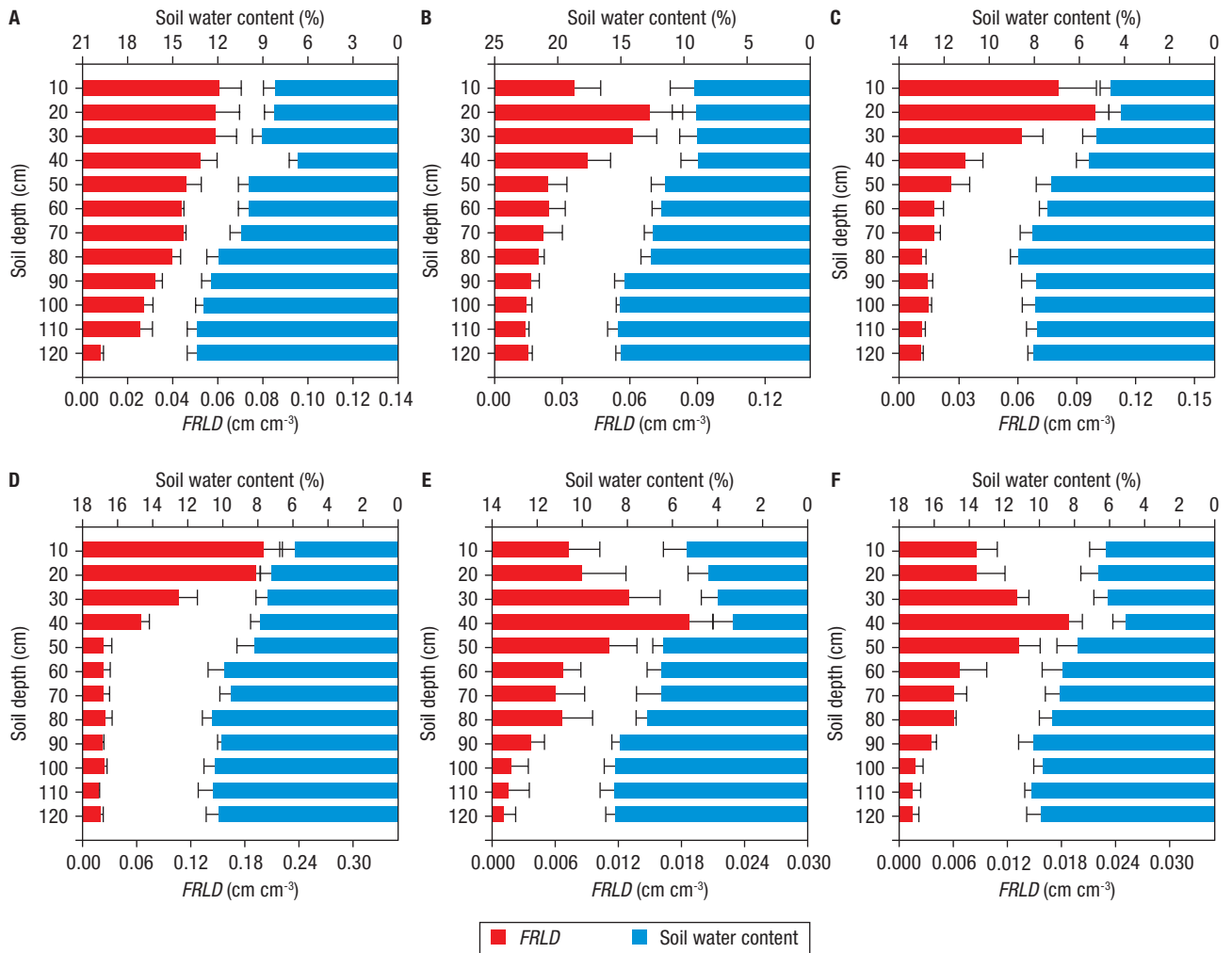
Figure 6. Relationship between soil moisture and vertical distribution of fine roots for the six species in the Anjiapo catchment, Loess Plateau, China. Data are mean values ± S.E, n = 12. A, *P. tabuliformis*; B, *P.tomentosa*; C, *P. armeniaca*; D, *R. pseudoacacia*; E, *C. korshinski*; F, *H. rhamnoides.*

cantly affected the variation in *FRLD* for *P. tabuliformis* ($R^2 = 0.783$, $P < 0.0001$), organic matter significantly influenced *FRLD* for *R. pseudoacacia* ($R^2 = 0.780$, $P < 0.0001$), and the other tree species were significantly influenced by total N ($R^2 = 0.831$, $P < 0.0001$ for *P. tomentosa*; $R^2 = 0.791$, $P < 0.0001$ for *P. armeniaca*; $R^2 = 0.707$, $P < 0.0001$ for *C. korshinskii*; $R^2 = 0.811$, $P < 0.0001$ for *H. rhamnoides*).

Discussion

The distribution of fine roots

The depth distribution of fine roots is of crucial importance in ecosystem water and nutrients use and productivity. The index of rooting distribution in our plots indicated that fine-root systems in our plots are shallower than the average for this biome (Jackson

et al., 1997). Such a shallow fine root distribution, improves root water uptake in water-limited environments, where rainfall occurs as scarce shallow pulses. However during prolonged dry periods, plants may encounter severe water stress. The vegetation in the current study region can be regarded as most similar to other deciduous vegetation such as temperate deciduous woodland (β = 0.966) or sclerophyllous shrubland (β = 0.964), or possibly temperate coniferous woodland (β = 0.976). Comparison with other forest ecosystems based on the Jackson *et al.* (1996) model showed that the computed root extinction coefficient (β) value was lower than that expected for sclerophyllous, temperate deciduous and temperate coniferous woodlands. The root extinction coefficient and the depth distribution of cumulative fine roots length in for the current study site obviously indicated a shallow fine root distribution, resembling that of grasslands and boreal forests (β = 0.947) (Jackson *et al.*, 1996).

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Table 6. Soil properties of the six tree species plantations in the Anjiapo catchment, Loess Plateau, China. N = 3, values = mean ± standard deviation.

Species	Soil layer (cm)	Bulk Density (g cm⁻³)	Org.mat (%)	N (%)	C (%)	Particle size distribution (%)		
						Sand	Silt	Clay
P. tabuliformis	0-20	1.07±0.21	0.9±0.12	0.11±0.013	2.21±0.31	22.48±2.34	77.44±8.41	0.08±0.007
	20-40	1.09±0.11	0.51±0.036	0.075±0.0034	2.79±0.25	31.04±2.31	68.38±6.51	0.58±0.042
	40-60	1.13±0.09	0.43±0.054	0.064±0.0035	2.39±0.031	22.53±3.24	76.31±7.41	1.16±0.011
	60-80	1.23±0.087	0.46±0.064	0.056±0.0024	2.26±0.22	19.47±1.65	79.94±8.54	0.59±0.045
	80-100	1.25±0.13	0.41±0.024	0.060±0.0054	2.48±.21	20.18±1.25	79.46±9.21	0.36±0.023
	100-120	1.26±0.054	0.38±0.035	0.059±0.0066	2.48±0.36	19.18±2.64	80.01±8.54	0.81±0.12
P. tomentosa	0-20	1.09±0.06	0.83±0.075	0.07±0.0057	2.15±0.24	23.41±3.51	75.26±6.21	1.33±0.014
	20-40	1.14±0.094	0.75±0.024	0.069±0.0021	2.37±0.12	26.78±4.54	72.56±5.66	0.66±0.032
	40-60	1.18±0.065	0.66±0.036	0.055±0.0036	2.22±0.34	19.68±4.65	78.59±4.25	1.73±0.015
	60-80	1.23±0.024	0.58±0.025	0.051±0.0054	2.22±0.16	18.91±4.68	80.21±6.25	0.88±0.011
	80-100	1.24±0.12	0.53±0.064	0.045±0.0059	2.11±0.24	23.45±5.41	76.24±6.38	0.31±0.002
	100-120	1.25±0.11	0.50±0.055	0.041±0.0047	2.23±0.35	20.08±6.21	79.15±7.56	0.77±0.012
P. armeniaca	0-20	0.89±0.13	1.09±0.21	0.15±0.0069	2.46±0.24	20.87±6.35	78.30±9.48	0.83±0.002
	20-40	0.97±0.16	0.75±0.032	0.094±0.0035	2.17±0.36	15.11±2.45	83.28±9.68	1.61±0.021
	40-60	0.97±0.08	0.62±0.068	0.063±0.0024	2.31±0.64	18.51±3.14	80.66±7.54	0.83±0.003
	60-80	1.07±0.054	0.48±0.024	0.061±0.0016	2.27±0.45	21.93±3.21	77.44±8.21	0.63±0.002
	80-100	1.12±0.16	0.45±0.022	0.054±0.0035	2.29±0.27	17.84±4.21	81.35±8.69	0.81±0.014
	100-120	1.14±0.12	0.41±0.036	0.051±0.0062	2.26±0.26	18.56±4.55	79.46±5.67	1.98±0.021
R. pseudoacacia	0-20	1.15±0.13	0.67±0.021	0.12±0.0011	2.88±0.31	18.90±6.32	79.94±5.69	1.16±0.031
	20-40	1.21±0.12	0.58±0.035	0.11±0.0012	2.8±0.24	26.28±3.21	73.13±9.54	0.59±0.004
	40-60	1.29±0.15	0.42±0.036	0.072±0.0034	2.5±0.13	20.70±2.25	78.50±7.84	0.80±0.011
	60-80	1.47±0.21	0.34±0.062	0.078±0.0065	2.52±0.14	6.70±1.05	91.51±8.52	1.79±0.21
	80-100	1.50±0.14	0.31±0.031	0.066±0.0024	2.29±0.36	18.49±1.35	81.26±8.62	0.25±0.032
	100-120	1.52±0.20	0.28±0.025	0.058±0.0064	2.30±0.025	20.16±1.47	77.56±5.67	2.28±0.31
C. korshinskii	0-20	0.98±0.14	0.72±0.024	0.065±0.0066	2.52±0.45	11.27±1.25	87.48±7.54	1.25±0.21
	20-40	1.05±0.064	0.48±0.059	0.097±0.0031	2.33±0.46	12.46±1.36	86.29±5.26	1.25±0.33
	40-60	1.27±0.057	0.39±0.036	0.090±0.0064	2.28±0.24	11.96±1.05	86.49±6.32	1.55±0.26
	60-80	1.36±0.087	0.37±0.024	0.063±0.0033	2.29±0.15	7.60±1.06	89.08±4.53	3.32±0.25
	80-100	1.39±0.15	0.34±0.015	0.061±0.0021	2.28±0.31	8.65±1.11	90.12±9.41	1.23±0.31
	100-120	1.43±0.13	0.31±0.036	0.056±0.0067	2.31±0.25	10.26±1.20	88.56±9.25	1.18±0.12
H. rhamnoides	0-20	0.97±0.087	0.73±0.025	0.069±0.0031	2.49±0.26	21.44±2.54	77.70±10.3	0.86±0.005
	20-40	1.04±0.10	0.56±0.034	0.099±0.0021	2.28±0.28	18.04±1.64	81.20±9.54	0.76±0.006
	40-60	1.05±0.064	0.42±0.054	0.073±0.0012	2.35±0.27	23.22±2.13	76.11±7.58	0.67±0.004
	60-80	1.13±0.087	0.4±0.064	0.070±0.0061	2.35±0.34	20.00±1.31	78.75±10.2	1.25±0.013
	80-100	1.15±0.064	0.38±0.068	0.071±0.0042	2.31±0.36	11.25±1.25	87.13±7.54	1.62±0.13
	100-120	1.21±0.21	0.35±0.011	0.063±0.0032	2.36±0.41	21.06±1.06	76.58±6.21	2.36±0.30

Table 7. Pearson correlation coefficients between *FRLD* and bulk density, Org. mat, N, C and Particle size fractions in each soil layer for per six tree species in the Anjiapo catchment on the Loess Plateau, China

Species	Bulk density (g cm⁻³)	Org.mat (%)	N (%)	C (%)	Sand (%)	Silt (%)	Clay (%)
P. tabuliformis	−0.799***	0.608**	0.501*	0.102	0.042	0.007	0.233
P. tomentosa	−0.804***	0.542*	0.621**	0.347	0.121	0.034	−0.025
P. armeniaca	−0.767***	0.511*	0.577*	0.423*	0.075	−0.089	0.014
R. pseudoacacia	−0.611***	0.621**	0.539*	0.361	0.009	0.241	0.136
C. korshinskii	−0.882***	0.667***	0.600*	0.201	−0.045	−0.142	0.111
H. rhamnoides	−0.625**	0.726***	0.592*	−0.119	0.247	0.255	0.047

N = 12. Marked correlations are significant at $P < 0.05^*$, $P < 0.01^{**}$ and $P < 0.001^{***}$.

In this study, the distance of root lateral extent for six species is about 1.5 times of canopy. The current region is the low rainfall, where soil moisture is limiting, trees extend their roots laterally to seek water farther from the tree. Where rainfall is less limiting, root extension may be responding more to the high soil fertility under their crowns. These differences in lateral root extension by trees at the low- and high-rainfall sites were probably related to differences in soil moisture conditions. At the drier site, roots had to extend farther and explore larger volumes of soil to acquire adequate supplies of soil moisture. At the wetter site where water was less limiting, more tree roots terminated within or near the tree-crown zone, where they could take advantage of the more nutrient-rich soils (Stromberg *et al.*, 2009). Similar differences in wet vs. dry environments are evident from other studies. In a relatively mesic old field in South Carolina, Valverde-Barrantes *et al.* (2007) found that fine roots of *Pinus taeda* (loblolly) concentrated beneath the canopy, and in a moderately arid area (422 mm annual rainfall) in South Africa, lateral extent of woody roots is about 1.5–2 times of their crowns.

Soil moisture and *FRLD*

Soil moisture decreased with increasing *FRLD* for six tree species in each soil layer (Table 5). The *FRLD* of the six tree species were significantly correlated with soil moisture during the experimental period in Anjiapo catchment, Loess Plateau, China. A significantly negative correlation between *FRLD* and soil moisture was found. In our study site, little rain, surface evaporation strongly, resulting in soil moisture dramatic change of soil layer 0-40 cm. Although these results seem counter-intuitive, the roots tend to favor well-drained soils that are generally drier. Furthermore, the above-ground growth of the six species in this area has been found to be largely independent of rainfall and to increase as soil moisture reached its lowest values (Wang *et al.*, 2008). These results suggest that the six species have same root foraging strategies as related to soil moisture The soil layers (0-10 cm for *P. tabuliformis* and *R. pseudoacacia*; 10-20 cm for *P.tomentosa* and *P. armeniaca*; 30-40 cm for *C. korshinski* and *H. rhamnoides*) had the lowest soil water content and highest *FRLD*, indicating each of the six tree species has the dried soil layer (DSL) of different soil depth due to fine roots water uptake and soil evaporation.

The sequence of "plant root water uptake-deep soil water transport upwards through the roots-water arrival in the above ground parts of plants-water evaporating through plant transpiration into the atmosphere"

is a primary mechanism of soil water loss, and consequently can lead to soil desiccation (Wang *et al.*, 2008; Zhu & Shao, 2008). However, information about the relationships between plant root indices and soil water in the interior of a DSL is scarce (Amato & Ritchie, 2002). During the process of vegetation succession, plants develop their root distributions to adapt to the competition for sunshine, space, soil water and nutrition. The root distribution then feeds back to affect and change the community ecosystems, further affecting succession processes (Long *et al.*, 2012). In addition, the nature and extent of the DSL also serves as a final indicator for evaluating soil desiccation processes and the soil water status, as well as reflecting the functional root status in the proximity of the DSL for different plant communities. Although the DSLs have not been systemically studied to the degree necessary, our results proved that co-relationships do exist between the DSL and soil moisture.

Soil properties and *FRLD*

A significantly negative correlation was found between *FRLD* and soil bulk density for six species. Low dry soil bulk density values below 1.6 g cm^{-3} considered to be the upper threshold value for optimum root growth (Courtney & Timpson, 2005; Szota *et al.*, 2007) was attributed to the coarse-textured and highly porous nature of the material (Gwenzi *et al.*, 2011). Accordingly, dry soil bulk density was related to root density, indicating physical impedance to root growth. This contrasts with previous studies on root architecture conducted on rehabilitated mine sites (Szota *et al.*, 2007) and reconstructed profiles in mined *Banksia* woodlands (Rokich *et al.*, 2001) close to the present study site, where high mechanical impedance and bulk densities restricted root growth and development due to underlying hardened iron-rich concretions (Rokich *et al.*, 2001) and lateritic layers (Szota *et al.*, 2007). Macinnis-Ng *et al.* (2010) also reported that increasing bulk density increased mechanical resistance and reduced root extension. The effect of density on uptake per unit length is not likely to vary greatly with factors such as soil type, but the effect on root extension will vary. Plant species differ slightly in the magnitudes of their responses to compaction and increased mechanical resistance (Courtney & Timpson, 2005), whilst the effect of increasing bulk density on mechanical resistance varies greatly, depending upon soil type and water content (Long *et al.*, 2012).

The massive clay with poor aeration, high sodicity and alkalinity are conditions which will also impede root growth (Nambiar & Sands, 1992). Fuentes *et al.*

(2008) reported that at Norwood Park sub-soil (>1.5 m depth) conditions were harsh. The clay content reaches 50% and the structure is massive, exchangeable sodium percentage exceeds 20%, the capillary fringe inhibited root growth. However, Macinnis-Ng *et al*. (2010) found that the clay layer underlying the sand reduces the rate of deep percolation of water because of its reduced hydraulic conductance and larger capacity to store water, thereby increasing the duration of the presence of water in the upper profile, and roots can redistribute water (hydraulic lift) from the moist clay (or the interface of the two soil horizons) to rehydrate the upper soil profile. These processes are consistent with the conclusion of Zeppel *et al*. (2008) who found that tree water use at this site was independent of water content in the upper 70 cm of the soil profile, particularly during dry periods and the results suggested that fine roots are found within the clay layer and therefore contribute to the uptake of water for transpiration. These results suggest that the differences of clay content have various effects on root growth. Our results showed particle size distribution (including the clay content) was unrelated to *FRLD*, the reason may lie in the soil clay content, soil in the current area is the silt texture, soil clay content is very low (0.08—0.26%). Thus, no correlation was found between *FRLD* and clay content, and conflict with our hypothesis.

In the present study, the soil organic matter and *FRLD* showed positive correlation. Roy and Singh (1995) reported that litterfall is the primary contribution to the soil organic matter. Data from numerous studies have shown that the greatest proportion of the root systems of many forests is located in the upper soil horizons. These root systems may be heavily infected by mycorrhizal fungi, and many are predominantly located in the organic fraction (Zeppel *et al*., 2008). The accumulation of litter and soil organic matter on level micro sites and topographic depressions, close to standing dead trees or their remains and the channels created by the decaying thick roots, may create nutrient patches where fine roots proliferate (Roy & Singh, 1995). Fine root proliferation in fertile patches had been shown in different ecosystems (Gwenzi *et al*., 2011). Similarly, on a vertical gradient, the accumulation of litter on the surface soil promotes nutrient concentration and thus fine root accumulation in the upper layers of the soil (Courtney & Timpson, 2005). However, in coastal Pacific northwestern United States conifers (Szota *et al*., 2007) and hardwood and conifer stands in southeastern United States (Zhou & Shangguan, 2007), soil organic matter tend to limited root growth. The different patterns of root distribution observed in mineral and organic horizons may also be a

response to varying levels of nutrient availability. Roots tend to concentrate in nutrient-rich zones in the soil (Gwenzi *et al*., 2011). The increase root growth in the mineral horizon with increased nutrient availability is also due to a reduction in the space available for rooting because of a reduced forest floor biomass.

Fine root distribution is largely influenced by soil resource availability (Zhou & Shangguan, 2007; Iverson, 2010). In this study, *FRLD* was strongly and positively correlated with total N concentration in the soil (Fig. 7). Fine roots tend to proliferate at a zone with high N concentration (February & Higgins, 2010) in order to capture more N from the zone (Jackson *et al*., 2008). The six species were likely to distribute its fine roots at the layers where N concentrations were higher, since soil N concentration is associated with organic matter pool (Jobbágy & Jackson, 2000). Our result is consistent with previous findings indicating that soil N concentration was closely related to fine-root distribution patterns of tree and grass species in a broad-leafed woody savanna (February & Higgins, 2010) and roots of native shrubs in the Mojave Desert (Nagler *et al*., 2008).

Conclusions

We found that each of the six tree species in the Anjiapo catchment, Loess Plateau, China distributed fine roots at shallower layers in vertical direction, most fine roots concentrate near the soil surface. On average, estimated total fine root density in the top 40 cm depth for the six species (*P. tabuliformis*, 66.40%; *P. tomentosa*, 65.54%; *P. armeniaca*, 76.12%; *R. pseudoacacia*, 81.70%; *C. korshinskii*, 68.73% and *H. rhamnoides*, 73.01%). Lateral roots extending well beyond the canopy for the six species (*P. tabuliformis*, 1.52 times; *P.tomentosa*, 1.54 times; *P. armeniaca*, 1.63 times; *R. pseudoacacia*, 1.39 times; *C. korshinskii*, 1.67 times and *H. rhamnoides*, 1.57 times of their crowns). Soil N concentration was strongly and positively correlated with fine root length and biomass, suggesting that the fine root distribution may be influenced by soil N availability. Soil moisture had a significantly negative correlation with *FRLD* in any soil layer, indicating that fine roots distribution would result in dried soil layer. A negative correlation was found between soil bulk density and *FRLD*, suggesting that high soil compaction impede root growth. Soil organic matter also promotes root growth, the accumulation of litter on the surface soil promotes nutrient concentration and thus fine root accumulation in the upper layers of the soil. However, the soil clay content in this study area is very low, there is no relationship with *FRLD*, and conflict with our
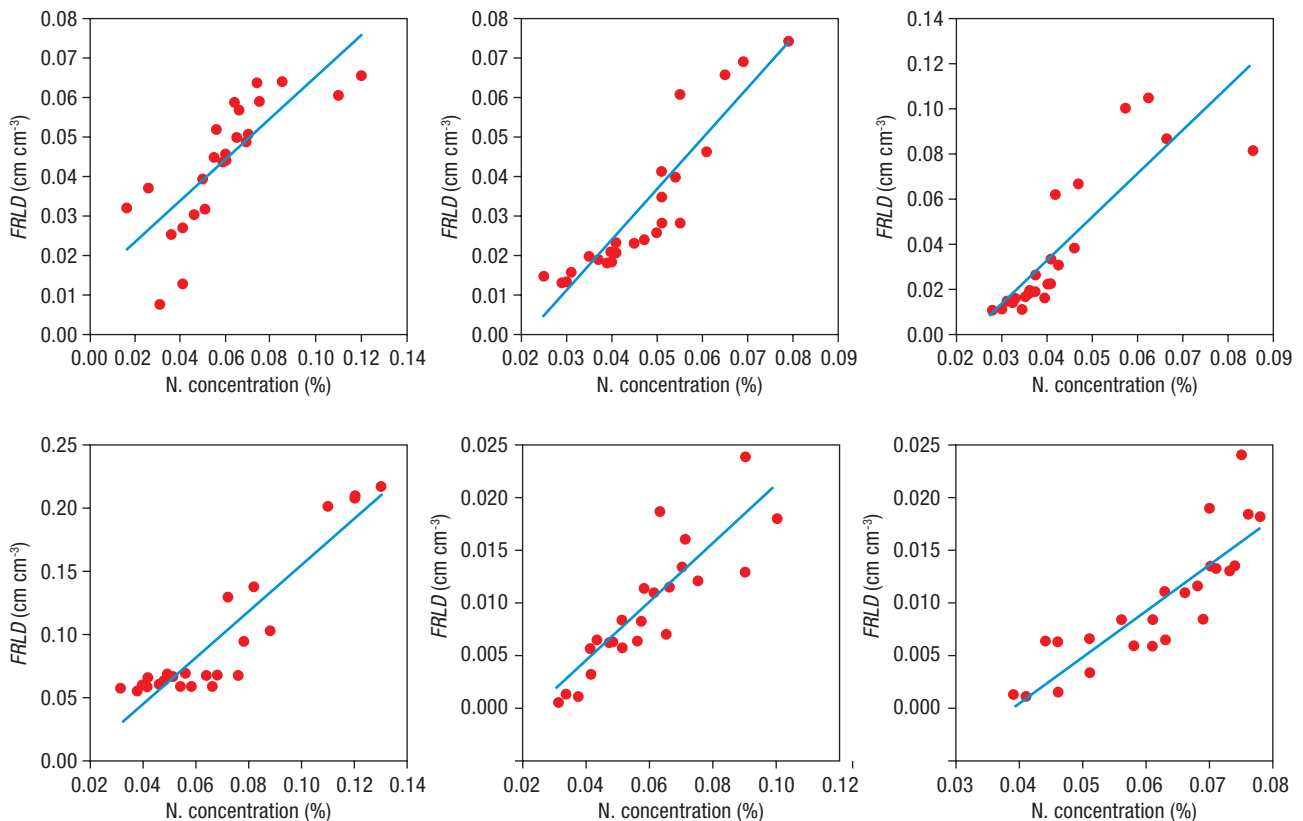
Figure 7. Relationships of *FRLD* with N concentration in each of the six tree species in the Anjiapo catchment, Loess Plateau, China. A, *P. tabuliformis*; B, *P.tomentosa*; C, *P. armeniaca*; D, *R. pseudoacacia*; E, *C. korshinski*; F, *H. rhamnoides*.

hypothesis. In addition to enhancing our understanding of root ecology on recently constructed ecosystems, the high spatial resolution data presented in this paper are crucial for operational decision-making. For example, besides making inferences on zones of root water uptake, the data may provide a basis for management practices such as species selection and optimum stand density. Moreover, two-dimensional water balance and biogeochemical models (Vrugt *et al*., 2001) will require data accounting for horizontal and vertical variability of roots and soil properties.

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