**Vertical distribution of fine root area in relation to stand age and environmental factors in black locust (Robinia pseudoacacia L.) forests of the Chinese Loess Plateau**

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Vertical distribution of fine root area in relation to stand age and environmental factors in black locust (Robinia pseudoacacia L.) forests of the Chinese Loess Plateau

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Abstract

To examine the tempo-spatial characteristics of fine root area distribution and its relationship with stand age and environmental factors in black locust on the Chinese Loess Plateau, black locust stands were selected at four sites along a precipitation gradient, four stands of different ages and a transect along a hillslope were also selected at one of the sites. With increasing stand age, fine root area at tree level increased exponentially, and the rooting pattern tended to be deeper for trees up to 15-years-old and then shallower thereafter. The temporal changes of fine root distribution could be quantified using stand age and soil nutrients. At the hillslope scale, fine root area index (FRAI) was lower while the rooting pattern was deeper in the middle slope than upper and lower slope, and the fine root distribution could be quantified using elevation and soil properties. At the regional scale, FRAI decreased substantially while exhibited similar rooting patterns with decreasing soil water and nutrients availability along the precipitation gradient. Humidity index represented the regional environmental variation and could be used to quantify FRAI. These findings will be helpful for improving quantification of fine roots and enhancing the accuracy of eco-hydrological models.

Key words: fine root area; rooting pattern; stand age; hillslope; precipitation gradient
Introduction

Fine roots (diameter <2 mm) play an essential role in water, nutrient, and carbon dynamics of ecosystems. Globally, more than 50% of precipitation is recycled via root water uptake every year (Chahine 1992). Due to the relatively short lifespan and rapid turnover of fine roots, fine root production may consume 13-27% of the annual photosynthetic; fine root mortality contributes 18 to 58% of total nitrogen to forest soils (Yuan and Chen 2010). Fine roots also contribute to slope stabilization and erosion control (Reubens et al. 2007). Information about the fine root distribution is fundamental to understanding hydro-biological processes of forest systems.

Fine root distribution is believed to vary temporally and spatially, being affected by the root:shoot ratio and stand age and demonstrating plasticity in response to environmental factors. Temporal variations in fine root biomass and its vertical distribution patterns have been widely studied but still remain controversial. Over the forest life cycle, fine root biomass generally increases before canopy closure and then increases, decreases, or levels off depending on ecosystem type (Yuan and Chen 2010). Changes in rooting pattern with stand age also appear to be species-specific and might vary according to adaptive strategies of roots in relation to water and nutrient availability. Investigations about the fine root distribution of a jujube plantation in the Chinese Loess Plateau showed that, the vertical distribution pattern of fine root length density or biomass was deeper with increasing stand age (Li et al. 2017), while the opposite trend was found in some other forest systems (Claus and George 2005). Chang et al. (2012) found that rooting patterns in 8- and 30-year-old black locust stands were similar at both southern and middle sites of the Loess Plateau.

Due to the spatial heterogeneity of environmental factors at different scales, fine root distribution is largely determined by the soil water dynamics and nutrient availability, and can be
influenced by environmental variables including topography, climate, and soil properties at scales
varying from local to global (Schenk 2005). Along the soil profile, fine root distribution generally
correlates positively with soil water and nutrient availability (Zhou and Shangguan 2007). At the
stand level, fine roots have been found to increase or decrease in response to increasing soil water
and nutrients availability, which might largely depend on the balance between the stimulation and
inhibition of tree root growth by soil resources limitation (Schenk 2005; Finer et al. 2011; Dietrich
et al. 2013). Soil textures have a strong influence on fine root distribution at the local level due to
their control on soil water and nutrients availability; for example, root systems tend to be smaller
and shallower in clay soils than in coarse soils (Sperry et al. 1998; Schenk and Jackson 2002b).

Furthermore, relative rooting depth tends to increase while absolute rooting depth decreases in
different climatic regions with increasing aridity (Schenk and Jackson 2002b). A few studies have
attempted to analyze and map the global distribution of deep roots in relation to environmental
factors, showing that rooting depth is determined more by annual potential evapotranspiration and
precipitation than other factors (Schenk and Jackson 2002a).

The Chinese Loess Plateau is reputed to have the most severe soil erosion in the world. To
reduce soil erosion and improve other aspects of environmental quality, black locust (Robinia
pseudoacacia L.) has been widely planted as the pioneer species since the 1970s due to its good
adaptability to dry and infertile conditions (Tsunekawa et al. 2014; Zhang et al. 2015). However,
estensive afforestation with this non-native species has leaded to the severe soil desiccation and the
formation of a dried soil layer in the deep soil (Jia et al. 2017), which presents a considerable
obstacle to sustainable plant growth. A realistic quantification of fine root distribution is critical for
assessing the sustainability of planation forest with eco-hydrological models (Sperry et al. 2016), as
well as optimizing forest management to alleviate soil desiccation (Wang et al. 2011). In this area,
both climatic factors and soil properties show strong variability at the regional scale (Wang et al. 2011) and soil properties also change significantly along the hillslope (Duan et al. 2016; Duan et al. 2017), which might substantially impact fine root distribution. It is especially essential to quantify fine root distribution at the hillslope and regional scales for simulating soil water and vegetation dynamics at different scales (Huang and Gallichand 2006). However, few data about fine root distribution are available for this area due to the difficulty in root sampling.

The objectives of this study were to: (1) study the tempo-spatial characteristics of fine root distribution for different ages; (2) determine the spatial variation in fine root distribution at hillslope and regional scales, and (3) quantify the relationship between fine root distribution and environmental factors. This information should be useful for improving quantification of fine roots and understanding hydro-biological processes of planation forests at different scales. The hypotheses tested were that: (1) fine root distribution tends to be shallower with increasing stand age and precipitation; and (2) fine root area and its distribution pattern vary along the hillslope with soil properties.

Materials and methods

Study area

The Loess Plateau is situated between longitudes 102° and 114° East and latitudes 35° and 41° North, covering an area of approximately 640,000 km². The mean annual precipitation (MAP, mm, 1981-2010) ranges from 700 mm in the southeast to 200 mm in the northwest, 55–78% of which falls from June to September. The MAP contours for 650, 550, 450, 350, and 250 mm are almost parallel to one other (Fig. 1a). The mean annual temperature (MAT, °C) ranges from 14.3 °C in the southeast to 3.6 °C in the northwest. Soil textures also follow a similar gradient, being more clayey in the southeast and sandier in the northwest (Zhang et al. 2015).
Based on the distribution of MAP contours and soil textural variation, flat black locust stands with slopes less than 4° were determined at four sites for this study (Fig. 1a): Yangling (YL), Changwu (CW), Ansai (AS), and Mizhi (MZ). The stand ages ranged between 15 to 20 years old and all stands had similar densities (1600-1700 trees ha\(^{-1}\)). Detailed climatic and soil parameters are provided in Table 1.

To study the temporal changes in fine root distribution, four flat black locust forest stands with trees that were 8-, 15-, 22- and 40-years-old (defined as SA8, SA15, SA22 and SA40, respectively) were selected at the Changwu site. The stands were characterized by similar climatic conditions and soil textures as shown in Table 1. Each stand had a closed canopy, with the density the highest for SA8 and the lowest for SA40 due to the difference in tree size. The details of stand characteristics, soil water and nutrient conditions are shown in Table 2.

To further study the effect of differences in environmental factors at the hillslope scale on fine root distribution, a typical hillslope (mean slope 20.0°) covered with black locust was selected in the Wangdonggou watershed (35°12′–35°16′N, 107°40′–107°42′E; total area 8.3 km\(^2\)) at the Changwu site after detailed field surveys. A detailed site description can be found in Duan et al. (2016) and Duan et al. (2017). A 165-m long transect along the hillslope with seven sampling locations (SP1-SP7) was established (Fig. 1b). The distance between sampling locations was 27.5 m. Stand characteristics did not vary at different locations. The trees were 18 years old and the stands had a density of 1700 trees ha\(^{-1}\). The height and diameter at breast height of the trees were 8.9±0.9 m and 9.3±0.4 cm, respectively. Since the vertical height difference between the summit and the footslope was only 80 m, the precipitation, potential evapotranspiration, air temperature did not appear significant difference (\(P > 0.05\)) along the slope (Duan et al., 2016). So these climatic variables were not used to characterize the variability of fine root distribution at the hillslope scale.
in this study. Elevation, soil properties and soil water storage at each sampling location are provided in Table 3.

All stands were converted from long-term cultivated cropland, and trees were planted fairly regularly by the government, which provided us the opportunity to find satisfactory stands at different sites. There were few disturbances due to occasional livestock grazing and thinning. SA40 was thinned at an age of 30 years old and there was no thinning in the other stands. There were no understory shrubs, while grasses were sparse due to the closed tree canopies and poor soil water condition in each stand.

Fine root sampling and analysis

In July and August 2016, fine roots were sampled using soil coring method (inside diameter 90 mm) as suggested by Zhou and Shangguan (2007) and Wang et al. (2013). According to previous studies, this period would feature the peak in fine roots (Burke and Raynal 1994), minimum soil water storage (Cheng et al. 2009; Duan et al. 2017), and most severe drought of the year. Therefore, the data collected should indicate the response of the fine root system to soil water shortages and other environmental factors. Based on the previous studies that roots are highly overlapped between neighboring trees and are homogeneous in the horizontal direction after canopy closure (Sun et al. 2015), three soil cores were randomly sampled in a 10 m × 10 m study plot at each sampling location (Claus and George 2005; Duan et al. 2017). Soil cores were sampled from 0.5 to 1.0 m to trees in each plot (Zhou and Shangguan 2007).

Fine roots were sampled at 10-cm increments in the upper 20-cm soil layer and at 20-cm increments in the 20- to 300-cm soil layer. Roots were separated from the soil by washing over a sieve under running tap water. Tree roots were distinguished from grass roots by morphology, color
and thickness (Sun et al. 2015). Dead roots were identified based on color (live roots were white, whereas the dead roots were dark) and discarded. Fine roots (<2 mm diameter) were separated from coarse roots (>2 mm diameter) with a vernier caliper and collected and placed on transparent plastic paper for scanning at 300 dpi (Canon LiDE 120, Canon Inc., Tokyo, Japan). Fine root area was measured with WinRHIZO (Regent Instruments Inc., Canada). Fine root area density (area of root per unit soil volume, FRAD, m² m⁻³) was determined for every 20-cm soil layer. Fine root area at the stand level for 0-300 cm soil profile was quantified with the term fine root area index (FRAI, m² m⁻²), the area of fine root per ground area, which was calculated using

\[
FRAI = \sum_{i=1}^{15} FRAD_i \times 0.2
\]

where FRADₐ is fine root area density for soil layer i. The vertical distribution pattern of fine root area was described using an asymptotic equation proposed by Gale and Grigal (1987):

\[
Y = 1 - \beta^d
\]

where Y is the cumulative root fraction from the surface to soil depth d (cm) and β is the coefficient of rooting distribution. Rooting pattern tends to be deeper with increasing β. The Eq. (2) was primarily proposed to simulate the vertical distribution of root biomass (Gale and Grigal 1987; Jackson et al. 1996). Several recent studies have demonstrated that it can be used to quantify the vertical distribution of fine root biomass (Chang et al. 2012; Chang et al. 2016). Considering that fine root biomass is proportional to fine root area, which can be obtained by multiplying specific fine root area (the ratio of fine root area to dry weight, m² g⁻¹) by fine root biomass (Meier and Leuschner 2008; Dietrich et al. 2013), we attempted to quantify the vertical distribution pattern of fine root area using Eq. (2) in this study. Therefore, the vertical distribution of FRAI can be quantified by combining Eq. (1) and Eq. (2):

\[
FRAI_d = FRAI \times (1 - \beta^d)
\]
where $\text{FRAI}_d$ is the cumulative fine root area index to soil depth $d$.

**Measurements of climatic, soil and stand structure parameters**

The coordinates and elevation of each sampling location were measured using differential kinematic GPS. Mean annual precipitation (MAP, mm), temperature, and sunshine duration data for 1981 to 2010 were collected from the nearest weather stations. Mean annual potential evapotranspiration (MPET, mm) for 1981 to 2010 was calculated using the Penman equation (Penman 1948, 1956) with collected meteorological parameters. The humidity index (HI) was defined as:

$$\text{HI} = \frac{\text{MAP}}{\text{MPET}}$$  \hspace{1cm} (4)

Disturbed soil samples were collected at 20-cm increments during root sampling and soil moisture by dry weight using the oven-drying method. Undisturbed soil samples were collected at the depth of 30 cm as suggested by Zhang et al. (2018) at each sampling location with a cutting ring (5 cm diameter, 100 cm$^3$ volume) to measure soil bulk density ($\text{BD}$, g cm$^{-3}$), and it was further used to calculate soil water storage of 0-300 cm profile. This simplification was very common when estimating soil water and carbon storage (Wang et al. 2010; Liu et al. 2011; Zhang et al. 2018), and the error could be accepted since soil bulk density generally shows low variation along the 0-300 cm soil profile in the Loess Plateau based on previous studies (Chang et al. 2012; Qiao et al. 2018). There was no rainfall throughout the sampling period, so the SWS measurements could represent soil water condition of each sampling location (Jia et al. 2017). Soil samples were collected at the top 30 cm of depth for physico-chemical analysis as suggested by Dietrich et al. (2013) since nutrient uptake mostly occurs in the topsoil (Jobbagy and Jackson 2001). The organic soil layer was thin (on average 1.0–1.5 cm) in all stands so it was not separated from the mineral soil layer (Chang et al. 2012). In the laboratory, soil samples were air-dried, crushed to pass through either a 0.25-mm...
or a 2-mm mesh. Soil particle sizes were measured using a Mastersizer 2000 (Malvern Instruments, Malvern, England). Soil organic carbon concentration (SOC, g kg$^{-1}$) was analyzed using the Walkley–Black method (Nelson and Sommers 1996). Soil total nitrogen concentration (TN, g kg$^{-1}$) was analyzed using the Kjeldahl digestion procedure (Bremner and Tabatabai 1972). The C:N ratio was then calculated. Soil total phosphorus concentration (TP, g kg$^{-1}$) was determined by alkaline digestion followed by molybdate colorimetric measurement (Murphy and Riley 1962).

Mean diameter at breast height and tree density were determined for all stems in the 10 m × 10 m plot at each sapling location. Five dominant trees were randomly chosen within each study plot and measured for tree height with an optical tree height meter (Vertex III, Haglöf, Sweden).

**Statistical analyses**

The temporal pattern of fine root distribution was characterized by a single treatment of stand age with four levels (SA8, SA15, SA22, and SA40). Fine root area at tree level (FRA$_T$, m$^2$ tree$^{-1}$) was calculated by dividing the fine root area index by the tree density thus stand density variation among stands can be omitted, making it more appropriate for studying the temporal dynamics of fine root system (Finer et al. 2007; Chang et al. 2012). The spatial pattern of fine root distribution along a hillslope was considered as a sequence treatment with seven locations (SP1 to SP7) due to the same stand age. The tempo-spatial patterns of fine root distribution at four sampling sites (YL, CW, AS, MZ) along the precipitation gradient were considered as the comprehensive treatments of stand age with four levels and sequence with four sites. Replicated measurements at each sampling location were treated as true replications as suggested by Claus and George (2005) and Meier and Leuschner (2008). Means and standard errors of FRAD at each soil layer and FRAI were calculated from each 3 replications per sampling location. The means of FRAI and $\beta$ were compared among
different stand ages and slope positions at Changwu site and different sites along the precipitation
gradient with one-way ANOVA followed by Tukey’s test ($P < 0.05$). Principal components analysis
and Pearson correlation analysis were used to determine relationships between the environmental
variables and the tempo-spatial patterns of fine root distribution at the hillslope and regional scales.
FRAI (or FRA_T) and $\beta$ were regressed with stand age and environmental variables as independent
variables. Only significant independent parameters and equations were accepted ($P < 0.05$). The
study year 2016 received average rainfall at most parts (Table 1) so only mean annual precipitation
was taken into analysis like many other studies (Meier and Leuschner 2008). To ensure that the
established models were reliable and stable, SWS was not used as a predictor in any case due to its
high temporal variation (Duan et al. 2017). All analyses were conducted with SPSS 11.0 (SPSS Inc.,
Chicago, USA).

**Results**

**Distribution patterns of fine root area for stands of different ages**

FRAI and $\beta$ co-varied with soil water and nutrient conditions across the four stand ages. SOC,
TN, and NP concentrations showed increasing trends after a slight decrease from SA8 to SA15
(Table 2), suggesting that afforestation with black locust enhanced the soil nutrients. FRAI at SA8
was higher than at SA15 and SA22 due to the high tree density at SA8 (Table 2) and showed
positive correlation with SWS ($r = 0.99$, $P < 0.01$) and TP ($r = 0.92$, $P < 0.05$), while FRA_T
increased exponentially with stand age (Fig. 3a). Stepwise regression analysis showed that the
nature logarithm of FRA_T could be quantified using stand age (SA, years) and total nitrogen:

\[
\ln(FRA_T) = 0.115SA - 1.32TN + 3.13 \\
(R^2 = 0.999, P = 0.009)
\]
In all stands, FRAD decreased with soil depth (Fig. 2). FRAD in the 100- to 300-cm soil layer was less variable than in the upper soil layers. $\beta$ first increased and then decreased with stand age, reaching its highest value at SA15 ($\beta = 0.991$; Fig. 3b). $\beta$ negatively correlated with SWS ($r = -0.98$, $P < 0.01$) and TP ($r = -0.99$, $P < 0.01$), while stepwise regression analysis showed that the linear regression equation could not give reliable estimation of $\beta$ ($P > 0.05$). The quadratic polynomial stepwise regression method was then conducted, which indicated that $\beta$ could be quantified using stand age and C:N ratio (CN):

$$\beta = -4.16 \times 10^{-5} SA^2 - 0.00578 CN + 1.04 \quad (R^2=0.999; \ P=0.038)$$  \hspace{1cm} (6)

**Distribution patterns of fine root area along the hillslope**

Along the hillslope, clay content ($W_{clay}$) and SWS were higher in the upper and lower slopes than the middle slope, while sand content ($W_{sand}$) and TP showed the opposite trend. FRAD decreased with soil depth (Fig. 4) at all sampling locations but showed different rooting patterns. FRAI ranged from 7.6 to 10.3 m$^2$ m$^{-2}$ along the hillslope, which showed a decreasing trend from SP1 to SP4 and then increased with decreasing elevation. $\beta$ varied from 0.985 to 0.992 along the hillslope and showed the opposite trend with FRAI (Table 3), indicating that trees have more roots and rooted shallower in the upper and lower slopes than the middle slope.

Principal components analysis on the similarity of the seven sampling locations in terms of environmental factors revealed a continuous distribution of the sampling locations along four different axes that explained 92.4% of the total variance (Table 4). Axis 1 (eigenvalue of 3.9) correlated strongly with TP and soil physical properties including sand, silt, and clay contents, among which clay content negatively correlated with sand ($r = -0.97$, $P < 0.01$) and silt contents ($r = -0.80$, $P < 0.05$), while TP positively correlated with silt content ($r = 0.73$, $P < 0.05$). Soil bulk density, SWS and SOC correlated strongly with Axis 2 (eigenvalue 2.4). TN and elevation...
correlated strongly with Axis 3 (eigenvalue 1.9) and Axis 4 (eigenvalue 1.0), respectively. FRAI
negatively correlated with sand content, while $\beta$ negatively correlated with elevation and positively
correlated with TP; correlations between SWS and FRAI or $\beta$ were not significant ($P > 0.05$). Since
both soil physical and chemical properties exhibited variation along a hillslope which might in turn
influence tree growth and fine root distribution, it was necessary to quantify FRAI and $\beta$ using these
variables. According to the stepwise regression analysis, both FRAI and $\beta$ could be quantified with
linear functions using elevation (Ele) and soil properties:

$$\begin{align*}
FRAI & = 37.52 - 0.0146\text{Ele} + 5.90\text{BD} - 2.15W_{\text{sand}} - 1.17W_{\text{clay}} + 0.706\text{CN} \\
\beta & = 1.05 - 4.42 \times 10^{-3}\text{Ele} + 1.08 \times 10^{-3}W_{\text{sand}} - 9.82 \times 10^{-4}\text{CN}
\end{align*}$$

(7) (8)

**Distribution patterns of fine root area along the precipitation gradient**

Along the precipitation gradient, soil texture was sandier with decreasing SWS and total N
concentration, while the C:N ratio increased from the southern to the northern sites. FRAI
decreased more than 50% from YL to MZ, with MAP decreasing about 35% and stand age ranging
between 15-20 years old (Table 1). Vertical distribution of FRAD at each study site is shown in Fig.
5. $\beta$ was similar among stands with an average of about 0.989 (Table 1), indicating that
approximately 70% of the fine root area accumulated in the top 100-cm soil layer for all stands.

According to the principal components analysis, the first two axes explained 93.3% of the total
variance of the dataset (Table 5). Climate factors including MAP, HI, MSD, soil properties
including soil bulk density, sand content, clay content, SWS, TN and TP were strongly correlated
with Axis 1 (eigenvalue 11.4), indicating a strong correlation among climate factors and soil
properties along the transect from the wet to the dry sites. FRAI was significantly related to those
variables which correlated highly with Axis 1 according to Pearson correlation analysis. Stand age
and elevation correlated strongly with Axis 2 (eigenvalue 3.2), but they were not correlated with FRAI significantly ($P > 0.05$). It can be inferred that variation in FRAI at the regional scale was mainly determined by the environmental factors. HI is an integrator of potential evapotranspiration and mean annual precipitation, and it correlated highly with FRAI and other climatic variables including MAP, MPET, MSD and soil properties including sand content, TN and TP. Therefore, HI was an important index for representing regional environmental variation and we used it to quantify FRAI:

$$FRAI = 20.15HI - 2.55 \quad (R^2 = 0.943, \quad P = 0.029)$$ (9)

Discussion

Fine root area index

FRAI ranged from 4.6 to 16.0 m$^2$ m$^{-2}$ in this study, which is the same magnitude as found in previous studies in this area. For example, Chang et al. (2012) reported the FRAI of the 0-100 cm soil profile ranged from 0.7 to 9.2 m$^2$ m$^{-2}$ in 8- and 40-year-old stands located in the middle and southern Loess Plateau. FRAI was found to positively correlate with SWS and soil nutrients for different stand ages and different sites along the precipitation gradient (Table 5). This finding was in accordance with the reports of Meier and Leuschner (2008) and Leuschner and Hertel (2003) and different from the result that plants could allocate more carbon to fine roots when soil water and nutrients were limited (Finer et al. 2011). According to Dietrich et al. (2013), soil resource limitation might either stimulate or reduce fine root production of trees with largely different consequences for above-ground productivity and resulted in a positive or negative correlation between fine root biomass and soil water and nutrient conditions (Schenk 2005; Finer et al. 2011; Dietrich et al. 2013). It can be inferred that the tempo-spatial variations in FRAI are largely
controlled by soil water and nutrient limitation in the Chinese Loess Plateau. In addition, positive feedback effects of root and their associated microorganism on soil environment could contribute to the positive correlation between FRAI and soil nutrients (Schenk 2005).

In this study, stand density decreased with increasing stand age when tree size became big, resulting in higher FRAI in SA8 than SA15 and SA22. Similar results have been reported in previous studies (Claus and George 2005; Finer et al. 2007; Borja et al. 2008). Tree growing stage, stand density, and the canopy closure strongly influence the fine root biomass (Borja et al. 2008).

Differences in stand density might represent gradients of competition for limiting resources, which can cause great uncertainty in fine root distribution. Ideally, stands of different ages with similar stand densities should be surveyed to investigate the temporal pattern of fine root distribution, but these stands are very hard to find in our study sites. With the purposes of conserving soil and water and maintaining vegetation productivity in this area, the young trees generally have high stand density and then trees will be thinned several times with trees growing (Tsunekawa et al. 2014). The surveyed stand densities in this study represent a common succession process in this area. Borja et al. (2008) pointed out that, a young dense stand with small diameter would have a larger proportion of fine root biomass than an older stand with large diameter. With the standard of closed canopy for surveyed stands in this study, the effect of stand age on fine root distribution involves both direct and indirect impacts via stand densities due to different tree sizes. Therefore, the variation in fine root distribution from SA8 to SA40 can be attributed to different stand ages. Similar to the exponential growth of other organs with time in early growth stages, fine root area at the tree level increased exponentially from 8- to 40-year-old stands, which is in line with the finding that fine root biomass is better correlated with stand characteristics at the tree level than at the stand level for different stand ages (Finer et al. 2007). We also find that fine root area at the stand level is better
correlated with soil water storage in this study. This is probably due to the strong influence of stand
density on soil water balance (Zou et al. 2008).

Along the hillslope, the non-monotonic trend of soil physical and chemical properties along the
study hillslope was in line with Duan et al. (2016) and Wei and Shao (2007) at different hillslopes
of the Loess Plateau. A significant lower FRAI was found in the middle slope than in the upper and
lower slopes, which is in agreement with a recent study about black locust in the Loess Plateau
(Chang et al. 2016). Schimel et al. (1985) in Colorado found that variation in root biomass along the
hillslope is probably related to the distribution of soil properties. The significant relationship
between FRAI and sand content ($r = 0.75, P < 0.05$; Table 4) in the present study supports this
concept. Unlike the results for different stand ages and precipitation gradient, the correlation
between SWS and FRAI was not statistically significant at the hillslope scale, although SWS and
FRAI did demonstrate similar trends along the hillslope (Table 3). This discrepancy might be
attributed to the weak variability of SWS and FRAI at the hillslope scale. Other factors, such as leaf
area index, might weaken or mask the correlation between SWS and FRAI. Previous hillslope scale
studies show that models integrating the effects of topography and soil properties have the potential
to estimate tempo-spatial variations in soil water storage (Duan et al. 2016; Duan et al. 2017) and
link landscape biogeochemical patterns to short-term processes (Jia et al. 2011; Jia et al. 2013).

Based on the relationship between fine root distribution and environmental variables, we made
regression analyses for FRAI and $\beta$ using elevation and soil properties at the hillslope scale. The
empirical equations established in this study demonstrated good precision and could be used to
quantify the relationship between fine root distribution parameters and environmental factors at the
hillslope scale.
FRAI showed a decreasing trend from the wetter southern site to the drier northern site, which is in accordance with findings of Meier and Leuschner (2008) and can be partially explained by the decrease of plant size with decreasing soil water and nutrients availability (Table 1). The positive correlation between FRAI and SWS, SOC and TP also supports this conclusion (Table 5). The relatively stable deep dry soil layer could decrease the root elongation rate and increase fine root mortality, thus reducing fine roots (Meier and Leuschner 2008). Fine root biomass is related to both climate factors and soil properties at the regional scale according to many experimental and review studies (Finer et al. 2011). We also found strong correlation between FRAI and numerous environmental factors (Table 5), suggesting that the more difficult-to-measure FRAI can be determined through empirical equations. Climate factors, especially precipitation, are strongly related to soil texture in the Loess Plateau due to their control over soil formation (Wang et al. 2011). MAP was strongly related to FRAI and soil texture in this study (Table 5), making it a good predictive variable to quantify FRAI at the regional scale. Several studies has found a linear relationship between MAP and fine root biomass in the other forest systems (Meier and Leuschner 2008), and suggested that plants meet their water demand in drier environments by reducing fine root biomass. Besides MAP, we also found a significant correlation between HI with FRAI and climatic and soil variables. Because HI is a function of various climate variables including precipitation, temperature, sunshine duration, vapor pressure and wind speed (Penman 1948, 1956), the method using HI to quantify FRAI at the regional scale actually involves more climate factors’ effect compared with using only MAP.

**Vertical distribution of fine root area**
Similar to the vertical distribution of fine root biomass, the vertical distribution of fine root area fit well with the model proposed by Gale and Grigal (1987). Quantifying the vertical distribution of fine root area is more essential for modelling some eco-hydrological processes such as root water uptake and hydraulic redistribution (Sperry et al. 2016). The coefficient $\beta$ varied from 0.983 to 0.991 in this study, indicating that rooting patterns vary in time and space, although this variation is much smaller than that for different growth forms (Jackson et al. 1996). The values of $\beta$ are slightly larger than the 0.974 to 0.979 for the 0-100 cm soil profile reported for this area by Chang et al. (2012), reflecting a larger fine root biomass/area in the deep soil. This difference might largely be attributed to the different detected soil depths or the changes in fine root morphology with soil depth (Bakker 1999). The dried soil layer in the deep soil might have a marked influence on fine root morphology which should be investigated in future studies. $\beta$ was significantly and negatively related to SWS for different stand ages and different sites along the precipitation gradient, while the correlations between $\beta$ and soil nutrients were less significant and consistent. Significant correlation between $\beta$ and soil nutrients were only found in TP. $\beta$ negatively correlated with TP for different stand ages ($r = -0.99, P < 0.01$), while positively correlated with TP along the hillslope ($r = 0.80, P < 0.05$). The discrepancy might be attributed to the differential magnitude of TP. TP ranged between 0.57 to 0.68 for different stand ages (Table 2), which was higher than that along the hillslope (0.51~0.56, Table 3). The increase of phosphorus could induce trees root deeper at low concentration while exhibit adverse effect at high concentration (Schenk 2005). The mechanism should be studied in more details in the further studies. Overall, it could be inferred that soil water condition plays a critical role in the rooting pattern with plants tending to root deeper when water conditions are poor (Schenk 2005). Moreover, rooting patterns of black locust forest show special
tempo-spatial variations in the Chinese Loess Plateau due to its unique natural conditions (i.e., thick
loess deposits, widespread dry soil layer, diverse and complex terrain, etc.).

Variation in FRAI with stand age might be largely attributed to the differences in FRAD of the
top 100-cm layer but not deeper soils (Fig. 2), resulting in the different rooting patterns as reflected
by the variation in $\beta$ (Table 2). Rooting patterns can become shallower (Bouillet et al. 2002), deeper
(Sun et al. 2015; Wang et al. 2015a), or stay constant (Claus and George 2005) with increasing
stand age. Conflicting study results might be due to the time span considered or species-specific
adaptations to the environment. In this study, rooting pattern tended to be deeper at first and then
shallower with increasing stand age and the peak of $\beta$ around SA15 was a key in this dynamic.

According to Fig. 3, the $\beta$ of 30-year-old stand was similar to that for an 8-year-old stand, which
aligns with the results reported by Chang et al. (2012) and indicates the two-stage pattern
discovered in this study might be more reliable than a single trend to describe changes in rooting
patterns with stand age in this area. This temporal pattern could be caused by the ecological and
biological mechanisms. When land use type was initially converted into forest land from previous
non-forest land, soil water content was high in the deep soil (Wang et al. 2015b). Trees could root in
the deep soil to extract soil water for meeting transpiration requirements. After trees grew
approximately 15 years (Cheng et al., 2009), soil water in the deep soil was depleted and the dry
soil layer was formed (Wang et al., 2015a; Jia et al., 2017). In order to adapt the new soil water
condition, trees reduced the root distribution in the deep soil and increased the root distribution in
the shallow soil layer. Therefore, the 30-year-old and 8-year-old trees had similar rooting pattern.

According to the regression analysis, the function combining stand age and C:N ratio can well
estimate the dynamics of $\beta$ (Eq. 6). A second-order polynomial in SA could approximate the
curvilinear relationship between $\beta$ and SA. The results highlight the importance of taking into
consideration the temporal changes of rooting patterns and its interaction with soil water and
nutrient conditions into the forest process-based models.

In accordance with the results of Chang et al. (2016), rooting pattern varied along the hillslope. Rooting patterns were shallower in the lower slope than the upper slope and middle slope, reflected in the negative relationship between $\beta$ and elevation (Table 4). This could be partially explained by the accumulation of clay content in the lower slope, as fine root distribution tends to be shallower in clayey soils (Sperry et al. 1998; Schenk and Jackson 2002b). Insignificant correlation between $\beta$ and SWS might be due to the effect of other factors affecting SWS as discussed above. Stepwise regression analysis showed that the spatial variation in $\beta$ at hillslope scale could be quantified with a linear function using elevation, sand content and C:N ratio (Eq. 8). Moreover, variations in soil properties and soil water conditions with topographic position might also be influenced by other topographic factors, such as slope aspect and inclination, which will in turn influence fine root distribution patterns along the hillslope. These variables should be taken into consideration in the further studies for better estimating fine root distribution at the hillslope scale.

Fine roots showed similar rooting patterns along the precipitation gradient in this study, which supports the results of Chang et al. (2012) for this area but not the first hypothesis herein and the results of several previous studies (Schenk and Jackson 2002b; Meier and Leuschner 2008). This disagreement might be due to changes in stand characteristics (e.g., tree density, tree height) that seemed to offset the effect of environmental gradient on fine root distribution at the regional scale as discussed by Chang et al. (2012). Another possibility is that, the density of the investigated stands was relatively high, with the wetter through to the drier sites of the Loess Plateau all suffering from gradual severe drought stress with increasing water demand as the trees grew bigger. This resulted in the rooting patterns tending to be deeper in the early years (Fig. 3b) and $\beta$ reaching
a maximum value in all of the sampled stands. The maximum $\beta$ was probably reflective of the genotype of black locust. Given that black locust was introduced to the Loess Plateau less than 50 years ago (Tsunekawa et al. 2014), alteration in the genetic constitution has not likely occurred, resulting in the similar maximum $\beta$ in mature trees among sites with considerably different environmental conditions.

Conclusions

Vertical distribution of fine root area in black locust forest showed special temporal and spatial variations on the Loess Plateau, as determined by soil water and nutrient conditions and influenced by stand age and environmental factors at different scales. Fine root area at the tree level increased exponentially with stand age, while the rooting pattern of younger and older stands differed due to changes in soil water and nutrient conditions. Fine root area and rooting patterns varied with soil properties along the hillslope, while along the precipitation gradient the rooting pattern differed little and fine roots responded to the decreasing soil water and nutrients availability mainly by reducing fine root area. Empirical relationships relating the fine root area distribution parameters to stand age and environmental factors were given at different scales. More comprehensive fine root sampling in relation to spatial and temporal variation in the further studies would enhance the quantification of fine root distribution and improve our understanding of the tempo-spatial variation of fine root systems.

Acknowledgements
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References


Table 1

Summary of environmental factors, stand characteristics, and root-related variables of the four stands along the precipitation gradient.

<table>
<thead>
<tr>
<th>Site code</th>
<th>YL</th>
<th>CW</th>
<th>AS</th>
<th>MZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordinates</td>
<td>34°18′ N</td>
<td>35°14′ N</td>
<td>36°51′ N</td>
<td>37°51′ N</td>
</tr>
<tr>
<td>Elevation (m a.s.l.)</td>
<td>344.7</td>
<td>1186.7</td>
<td>1155.2</td>
<td>944.2</td>
</tr>
<tr>
<td>Mean annual temperature (°C)</td>
<td>13.5</td>
<td>9.4</td>
<td>9.2</td>
<td>9.5</td>
</tr>
<tr>
<td>Mean annual precipitation (mm)</td>
<td>645.9</td>
<td>575.0</td>
<td>506.5</td>
<td>421.9</td>
</tr>
<tr>
<td>Annual precipitation 2016</td>
<td>663.9</td>
<td>567.1</td>
<td>502.3</td>
<td>455.1</td>
</tr>
<tr>
<td>Mean annual potential evapotranspiration (mm)</td>
<td>1065.4</td>
<td>1029.1</td>
<td>1127.0</td>
<td>1292.6</td>
</tr>
<tr>
<td>Humidity index</td>
<td>0.61</td>
<td>0.56</td>
<td>0.45</td>
<td>0.33</td>
</tr>
<tr>
<td>Mean annual sunshine duration (h)</td>
<td>1770.5</td>
<td>2051.4</td>
<td>2395.6</td>
<td>2761.2</td>
</tr>
<tr>
<td>Soil bulk density (g cm$^{-3}$)</td>
<td>1.40</td>
<td>1.29</td>
<td>1.28</td>
<td>1.24</td>
</tr>
<tr>
<td>Sand content (%)</td>
<td>7.28</td>
<td>6.30</td>
<td>33.90</td>
<td>33.66</td>
</tr>
<tr>
<td>Silt content (%)</td>
<td>65.61</td>
<td>76.78</td>
<td>56.97</td>
<td>56.58</td>
</tr>
<tr>
<td>Clay content (%)</td>
<td>27.11</td>
<td>16.93</td>
<td>9.13</td>
<td>9.76</td>
</tr>
<tr>
<td>Stand age (years)</td>
<td>18</td>
<td>15</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Mean tree height (m)</td>
<td>6.5</td>
<td>7.2</td>
<td>5.9</td>
<td>3.6</td>
</tr>
<tr>
<td>Mean diameter at breast height (cm)</td>
<td>9.5</td>
<td>8.4</td>
<td>8.8</td>
<td>10.2</td>
</tr>
<tr>
<td>Soil water storage (mm)</td>
<td>507.0</td>
<td>368.7</td>
<td>244.6</td>
<td>298.1</td>
</tr>
<tr>
<td>Soil organic carbon concentration (g kg$^{-1}$)</td>
<td>8.65</td>
<td>10.93</td>
<td>5.41</td>
<td>7.18</td>
</tr>
<tr>
<td>Total nitrogen concentration (g kg$^{-1}$)</td>
<td>0.73</td>
<td>0.63</td>
<td>0.31</td>
<td>0.35</td>
</tr>
<tr>
<td>Total phosphorus concentration (g kg$^{-1}$)</td>
<td>0.55</td>
<td>0.56</td>
<td>0.52</td>
<td>0.51</td>
</tr>
<tr>
<td>C:N ratio</td>
<td>11.81</td>
<td>17.49</td>
<td>17.57</td>
<td>20.62</td>
</tr>
<tr>
<td>Fine root area index (m$^2$ m$^{-2}$)*</td>
<td>10.13</td>
<td>8.72</td>
<td>5.66</td>
<td>4.60</td>
</tr>
<tr>
<td>$\beta^2$</td>
<td>0.987</td>
<td>0.990</td>
<td>0.990</td>
<td>0.988</td>
</tr>
</tbody>
</table>

Mean annual precipitation (MAP), temperature, and sunshine duration data for 1981 to 2010 were collected from the nearest weather stations. Mean annual potential evapotranspiration (MPET) for 1981 to 2010 was calculated using the Penman equation with collected meteorological parameters. The humidity index (HI) was calculated using MAP and MPET. Soil physical and chemical properties were measured at each study site.

* Different letters within a row indicate a significant difference at the 0.05 level.
Table 2
Stand characteristics, soil properties, and root-related variables for different stand ages at the Changwu site.

<table>
<thead>
<tr>
<th>Site code</th>
<th>SA8</th>
<th>SA15</th>
<th>SA22</th>
<th>SA40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand age (years)</td>
<td>8</td>
<td>15</td>
<td>22</td>
<td>40</td>
</tr>
<tr>
<td>Tree density (trees ha(^{-1}))</td>
<td>10000</td>
<td>1667</td>
<td>1667</td>
<td>555</td>
</tr>
<tr>
<td>Mean tree height (m)</td>
<td>2.2</td>
<td>6.8</td>
<td>11.5</td>
<td>13.4</td>
</tr>
<tr>
<td>Mean diameter at breast height (cm)</td>
<td>5.2</td>
<td>8.9</td>
<td>10.3</td>
<td>27.5</td>
</tr>
<tr>
<td>Soil water storage (mm)</td>
<td>413.2</td>
<td>290.9</td>
<td>321.1</td>
<td>429.3</td>
</tr>
<tr>
<td>Soil organic carbon concentration (g kg(^{-1}))</td>
<td>18.47</td>
<td>11.89</td>
<td>21.40</td>
<td>26.39</td>
</tr>
<tr>
<td>Total nitrogen concentration (g kg(^{-1}))</td>
<td>1.01</td>
<td>0.71</td>
<td>1.26</td>
<td>1.55</td>
</tr>
<tr>
<td>Total phosphorus concentration (g kg(^{-1}))</td>
<td>0.68</td>
<td>0.57</td>
<td>0.60</td>
<td>0.65</td>
</tr>
<tr>
<td>C:N ratio</td>
<td>18.25</td>
<td>16.73</td>
<td>16.95</td>
<td>16.97</td>
</tr>
<tr>
<td>Fine root area index (m(^{-2}) m(^{-2}))</td>
<td>15.18(^{a})</td>
<td>8.33(^{b})</td>
<td>8.80(^{b})</td>
<td>16.02(^{a})</td>
</tr>
<tr>
<td>(\beta)</td>
<td>0.983(^{c})</td>
<td>0.991(^{a})</td>
<td>0.989(^{ab})</td>
<td>0.984(^{bc})</td>
</tr>
</tbody>
</table>

All variables were measured at the study site.

*Different letters within a row indicate a significant difference at the 0.05 level.
### Table 3
Environmental factors and root-related variables of the seven sampling locations along the hillslope.

<table>
<thead>
<tr>
<th>Site code</th>
<th>SP1</th>
<th>SP2</th>
<th>SP3</th>
<th>SP4</th>
<th>SP5</th>
<th>SP6</th>
<th>SP7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation (m a.s.l.)</td>
<td>1181</td>
<td>1156</td>
<td>1138</td>
<td>1120</td>
<td>1110</td>
<td>1105</td>
<td>1102</td>
</tr>
<tr>
<td>Soil bulk density (g cm(^{-3}))</td>
<td>1.35</td>
<td>1.27</td>
<td>1.23</td>
<td>1.34</td>
<td>1.31</td>
<td>1.27</td>
<td>1.28</td>
</tr>
<tr>
<td>Sand content (%)</td>
<td>3.80</td>
<td>4.37</td>
<td>6.30</td>
<td>6.30</td>
<td>5.23</td>
<td>3.71</td>
<td>2.51</td>
</tr>
<tr>
<td>Silt content (%)</td>
<td>73.74</td>
<td>75.87</td>
<td>76.78</td>
<td>75.91</td>
<td>76.98</td>
<td>75.47</td>
<td>75.71</td>
</tr>
<tr>
<td>Clay content (%)</td>
<td>20.46</td>
<td>19.36</td>
<td>16.93</td>
<td>17.79</td>
<td>17.79</td>
<td>20.81</td>
<td>21.78</td>
</tr>
<tr>
<td>Soil water storage (mm)</td>
<td>432.5</td>
<td>313.9</td>
<td>277.3</td>
<td>379.6</td>
<td>364.1</td>
<td>351.0</td>
<td>362.6</td>
</tr>
<tr>
<td>Soil organic carbon concentration (g kg(^{-1}))</td>
<td>18.34</td>
<td>21.58</td>
<td>16.50</td>
<td>19.00</td>
<td>23.20</td>
<td>19.21</td>
<td>13.52</td>
</tr>
<tr>
<td>Total nitrogen concentration (g kg(^{-1}))</td>
<td>0.94</td>
<td>1.26</td>
<td>0.87</td>
<td>1.02</td>
<td>1.32</td>
<td>1.04</td>
<td>0.78</td>
</tr>
<tr>
<td>Total phosphorus concentration (g kg(^{-1}))</td>
<td>0.54</td>
<td>0.57</td>
<td>0.59</td>
<td>0.58</td>
<td>0.59</td>
<td>0.55</td>
<td>0.58</td>
</tr>
<tr>
<td>C:N ratio</td>
<td>19.58</td>
<td>21.11</td>
<td>19.02</td>
<td>18.66</td>
<td>17.53</td>
<td>18.46</td>
<td>17.33</td>
</tr>
<tr>
<td>Fine root area index (m(^2) m(^{-2}))</td>
<td>9.88(^{ab})</td>
<td>7.62(^{c})</td>
<td>8.18(^{abcd})</td>
<td>7.83(^{bc})</td>
<td>9.28(^{abc})</td>
<td>9.49(^{abc})</td>
<td>10.28(^{a})</td>
</tr>
<tr>
<td>(\beta)</td>
<td>0.985(^{c})</td>
<td>0.990(^{a})</td>
<td>0.991(^{a})</td>
<td>0.992(^{a})</td>
<td>0.991(^{a})</td>
<td>0.988(^{b})</td>
<td>0.990(^{ab})</td>
</tr>
</tbody>
</table>

All variables were measured at the study hillslope.

* Different letters within a row indicate a significant difference at the 0.05 level.
Table 4
Pearson coefficients for correlations between fine root area index (FRAI), the coefficient of rooting distribution ($\beta$), and environmental factors as well as principal components analyses of the environmental factors along the hillslope. Numbers in bold mark the variables with closest correlation to the respective axis.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Pearson correlation coefficients</th>
<th>Principal components analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FRAI</td>
<td>$\beta$</td>
</tr>
<tr>
<td>Elevation</td>
<td>-0.21</td>
<td>-0.71*</td>
</tr>
<tr>
<td>Soil bulk density</td>
<td>0.21</td>
<td>-0.41</td>
</tr>
<tr>
<td>Sand content</td>
<td>-0.75*</td>
<td>0.51</td>
</tr>
<tr>
<td>Silt content</td>
<td>-0.25</td>
<td>0.38</td>
</tr>
<tr>
<td>Clay content</td>
<td>0.66</td>
<td>-0.51</td>
</tr>
<tr>
<td>Soil water storage</td>
<td>0.55</td>
<td>-0.61</td>
</tr>
<tr>
<td>Soil organic carbon</td>
<td>-0.39</td>
<td>0.11</td>
</tr>
<tr>
<td>Total nitrogen</td>
<td>-0.39</td>
<td>0.21</td>
</tr>
<tr>
<td>Total phosphorus</td>
<td>-0.37</td>
<td>0.80*</td>
</tr>
<tr>
<td>C:N ratio</td>
<td>0.06</td>
<td>-0.46</td>
</tr>
</tbody>
</table>

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).
Table 5
Pearson coefficients for correlations between fine root area index (FRAI), the coefficient of rooting distribution ($\beta$) and influencing factors as well as principal components analysis (PCA) of the influencing factors along the precipitation gradient. Numbers in bold mark the variables with closest correlation to the respective axis. Pearson correlation coefficients between MAP and HI with other environmental factors were also shown in the table.

<table>
<thead>
<tr>
<th></th>
<th>MAP</th>
<th>HI</th>
<th>FRAI</th>
<th>$\beta$</th>
<th>principal components analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Axis 1</td>
</tr>
<tr>
<td>Elevation</td>
<td>−0.56</td>
<td>−0.44</td>
<td>−0.56</td>
<td>0.92*</td>
<td>−0.608</td>
</tr>
<tr>
<td>MAT</td>
<td>0.74</td>
<td>0.64</td>
<td>0.73</td>
<td>−0.80</td>
<td>0.770</td>
</tr>
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<td>MAP</td>
<td>1</td>
<td>0.99**</td>
<td>0.98**</td>
<td>−0.22</td>
<td><strong>0.976</strong></td>
</tr>
<tr>
<td>MPET</td>
<td>−0.88*</td>
<td>−0.94*</td>
<td>−0.84</td>
<td>−0.26</td>
<td>−0.817</td>
</tr>
<tr>
<td>HI</td>
<td>0.99**</td>
<td>1</td>
<td>0.97**</td>
<td>−0.09</td>
<td><strong>0.964</strong></td>
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<tr>
<td>MSD</td>
<td>−1.00***</td>
<td>−0.99***</td>
<td>−0.98***</td>
<td>0.20</td>
<td>−<strong>0.979</strong></td>
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<tr>
<td>Soil bulk density</td>
<td>0.92*</td>
<td>0.85</td>
<td>0.87</td>
<td>−0.54</td>
<td>0.897</td>
</tr>
<tr>
<td>Sand content</td>
<td>−0.87</td>
<td>−0.90*</td>
<td>−0.95*</td>
<td>0.17</td>
<td>−<strong>0.941</strong></td>
</tr>
<tr>
<td>Silt content</td>
<td>0.63</td>
<td>0.72</td>
<td>0.74</td>
<td>0.23</td>
<td>0.702</td>
</tr>
<tr>
<td>Clay content</td>
<td>0.90*</td>
<td>0.85</td>
<td>0.94*</td>
<td>−0.59</td>
<td><strong>0.956</strong></td>
</tr>
<tr>
<td>Soil water storage</td>
<td>0.83</td>
<td>0.77</td>
<td>0.89*</td>
<td>−0.67</td>
<td><strong>0.911</strong></td>
</tr>
<tr>
<td>Soil organic carbon</td>
<td>0.53</td>
<td>0.59</td>
<td>0.69</td>
<td>−0.01</td>
<td>0.663</td>
</tr>
<tr>
<td>Total nitrogen</td>
<td>0.89*</td>
<td>0.89*</td>
<td>0.97**</td>
<td>−0.39</td>
<td><strong>0.970</strong></td>
</tr>
<tr>
<td>Total phosphorus</td>
<td>0.87</td>
<td>0.92*</td>
<td>0.92*</td>
<td>0.05</td>
<td><strong>0.900</strong></td>
</tr>
<tr>
<td>C:N ratio</td>
<td>−0.93*</td>
<td>−0.87</td>
<td>−0.87</td>
<td>0.47</td>
<td>−0.888</td>
</tr>
<tr>
<td>Stand age</td>
<td>−0.36</td>
<td>−0.46</td>
<td>−0.25</td>
<td>−0.82</td>
<td>−0.212</td>
</tr>
</tbody>
</table>

MAT, mean annual temperature; MAP, mean annual precipitation; MPET, mean annual potential evapotranspiration; HI, humidity index; MSD, mean annual sunshine duration;
* Correlation is significant at the 0.05 level (2-tailed test).
** Correlation is significant at the 0.01 level (2-tailed test).
Fig. 1 The location of the four study sites along the precipitation gradient (a) and seven sampling locations along a hillslope at the Changwu site (b).

85x38mm (300 x 300 DPI)
Fig. 2 Vertical distribution of fine root area density (FRAD) with soil depth of the stands at different ages. Error bars represent the standard error (n = 3).

74x37mm (300 x 300 DPI)
Fig. 3 Fine root surface area at tree level (FRAT; a) and the coefficient of rooting distribution ($\beta$; b) of different stand ages at the Changwu site. FRAT represents the mean of three replicate samples.
Fig. 4 Vertical distribution of fine root area density (FRAD) with soil depth along the hillslope.

79x42mm (300 x 300 DPI)
Fig. 5 Vertical distribution of fine root area density (FRAD) with soil depth along the precipitation gradient. Error bars represent the standard error (n = 3).

74x37mm (300 x 300 DPI)