

# Fine-root biomass, production, turnover of *Ulmus pumila*, *Populus sibirica*, *Hippophae rhamnoides* and soil organic carbon in Mongolian Semi-Arid Steppe

TSEEPIL AVIRMED<sup>1</sup> , SER-ODDAMBA BYAMBADORJ<sup>1,2</sup> , OTGONSAIKHAN BYAMBASUREN<sup>1</sup> , SARANGUA LKHAGVASUREN<sup>1</sup>, KHULAN SHARAVDORJ<sup>1</sup>  AND BATKHUU NYAM-OSOR<sup>1\*</sup> 

<sup>1</sup> Department of Environment and Forest Engineering, National University of Mongolia, Ikh Surguuliin gudamj 1, P.O. Box 46A/523, 210646 Ulaanbaatar, Mongolia  
<sup>2</sup> Department of Environment and Forest Resources, College of Agriculture and Life Science, Chungnam National University, 34134 Daejeon, South Korea

\* Correspondence:

Batkhuu Nyam-Osor  
[batkhuu@num.edu.mn](mailto:batkhuu@num.edu.mn)

**Avirmed, T., Byambadorj, S.-O., Byambasuren, O., Lkhagvasuren, S., Sharavdorj, K. and Nyam-Osor, B. 2026.**

Fine-root biomass, production, turnover of *Ulmus pumila*, *Populus sibirica*, *Hippophae rhamnoides* and soil organic carbon in Mongolian Semi-Arid Steppe. *Baltic Forestry* 32(1): id 795; <https://doi.org/10.46490/BF795>.

Received 29 March 2025

Revised 8 April 2026

Accepted 28 April 2026

## Abstract

Implementing reforestation and forest restoration measures is the most effective way to counter desertification and land degradation in low-precipitation steppe regions. The study area, situated in Argalant soum, Tuv aimag, is a grassland that is strongly affected by desertification in the steppe area. From a phytogeographic perspective, the area is described as a Middle Khalkha semi-arid steppe (dry steppe) region. Selecting tree species that can adapt to the local environment is crucial for successful afforestation efforts. Fine roots were measured in sequential soil layers 0–40 cm depth increments across a total of 216 samples in the afforestation site, and 60 soil samples were collected in sequential layers from 0 to 60 cm in depth at the afforestation and control sites. This study showed that *Hippophae rhamnoides* had higher fine root biomass accumulation (1.689 g m<sup>-2</sup>), renewal rate (1.071 yr) and productivity (0.949 g m<sup>-2</sup>). For *Populus sibirica* and *Ulmus pumila*, their fine root development showed similar results. However, three different tree species accumulated different amounts of soil organic carbon. *U. pumila* (51.16 Mg ha<sup>-1</sup>) increased the soil carbon stock by one time compared to the other two species. It is necessary to select and plant tree species that have a significant impact on increasing fine-root biomass, productivity, soil fertility and soil organic carbon stocks in the arid steppe regions of Mongolia.

**Keywords:** semi-arid; afforestation; fine root production; fine root turnover over-rate; soil organic carbon

## Introduction

Desertification and land degradation are major global challenges for continental ecosystems, especially in semi-arid and arid climate zones (Ye et al. 2018, Byambadorj et al. 2021, Zhang et al. 2021). Mongolia has an extreme climate in Central Asia and an ecosystem vulnerable to climate change and human activities (Bekei 2018, Bayasgalankhuu et al. 2022), and the average annual air temperature has increased by 2.49°C over the past 80 years. Recent studies have shown that due to the impacts of climate and human activities, desertification and land degradation currently affect 76.9% of Mongolia's territory (MNET 2020).

The Government of Mongolia has initiated the “Billion Tree” National Movement and begun implementing it nationwide, with the main goal to increase forest cover to 9.0% of the territory (“Billion Tree” National Movement 2023). Reforestation is considered a very important terrestrial carbon sink and increases carbon sequestration capacity; thus, it mitigates the influence of excessive industrial carbon

emissions and global climate change (Silver et al. 2000, Smith et al. 2000, Fitzsimmons 2003, Zhou et al. 2006). Mongolia covers 1,564 thousand km<sup>2</sup>, which is 1.05% of the world's dryland area, and soil organic carbon stocks are directly related to its territory size and soil types. Therefore, the organic carbon reserves in our country's soil have a significant impact on processes such as global climate change, carbon sequestration, and emissions. Mongolia ranks 14<sup>th</sup> in terms of soil organic carbon stocks in the world and accounts for 0.94% of carbon stocks (FAO and ITPS 2020, Batkhisig and Dorjgotov 2021).

Quantifying above-ground biomass (AGB) and carbon stocks of trees is essential for assessing the relationship between growth and biomass (Chave et al. 2005). Among the many methods in this field, the allometric equation is the most reliable for estimating tree biomass (Gower et al. 1999) and carbon stocks (Chave et al. 2005). This is why it is used to estimate forest carbon emissions and sequestration to mitigate global warming under the UN-REDD+ Programme (Reducing Emissions

from Deforestation and forest Degradation; Picard et al. 2012).

In forest ecosystems, the belowground biomass accounts for 13–25%, of which 2–15% are fine roots (Helmisaari et al. 2002). Fine roots account for a small fraction of the total biomass of trees but have a significant impact on terrestrial ecosystems, particularly on soil carbon cycling (Nadelhoffer and Raich 1992, Hendrick and Pregitzer 1993, Jackson et al. 1997, Röderstein et al. 2005). Fine roots are effective degraders and are the primary source of soil organic carbon, contributing 30–80% of total soil organic carbon (Steele et al. 1997, Brown 2002, Howard et al. 2004). Fine roots are typically less than 2 mm in diameter, and it is important to consider seasonal changes, root growth, and development of newly grown fine roots within a given year (Cannon 1949, Böhm 1979, Zobel and Waisel 2010, McCormack et al. 2015, Laliberté 2017). The process of fine root formation, followed by drying and death, is crucial for the accumulation of organic matter in the soil and plays a vital role in seedling viability, health, and growth intensity (Montagnoli et al. 2018). It has been noted that soil carbon accumulation is highly dependent on soil depth (Jobbagy and Jackson 2000, Li et al. 2010, Wang X. et al. 2010, Wu et al. 2010, Perez-Quezada et

al. 2011, Qian et al. 2011, Zhang et al. 2011, Zhu et al. 2011).

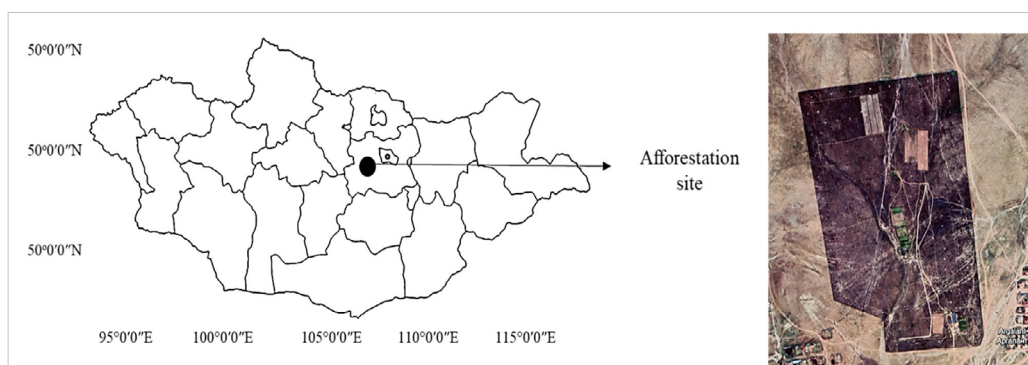
These studies demonstrate that tree and shrub communities in arid regions play a significant role in the global carbon cycle (Li et al. 2010, Wang Y.G. et al. 2010). The hypothesis of the study is (i) SOC could be increased under various tree species; (ii) fine roots of tree species could be increased during the growing season. The purpose of our study was to estimate the fine-root seasonal turnover rate, production, and soil organic carbon (C) stock of relatively young *U. pumila*, *P. sibirica* and *H. rhamnoides* planted in semi-arid regions of Mongolia.

## Material and methods

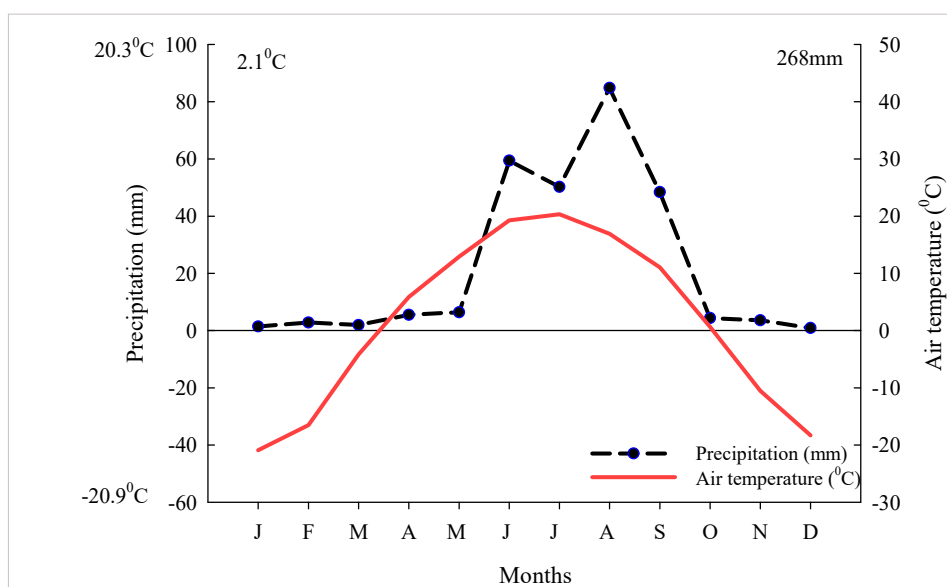
### Study site description

The study was conducted at the “Green Asia network” INGO site, located in the afforested areas established in 2017 in the territory of Argalant soum, Tuv aimag (Figure 1). It is a grassland region strongly affected by desertification in the steppe area (MNET 2020). In terms of phytogeography, the site is described as the Middle Khalkha semi-arid steppe (dry steppe) region, dominated by *Agropyron cristatum*, *Artemisia adamsii*, *Artemisia*

**Figure 1.** The location of the study site (Argalant soum, Tuv Aimag [province])



**Figure 2.** Monthly mean temperature (solid line) and monthly rainfall (broken, dotted line) in 2017 and between 2020



**Table 1.** Biometric characteristics of the forest at each plantation site and morphological traits of the three tree species planted

Site	Biometric characteristics	Property		
		Tree species		
		<i>U. pumila</i>	<i>P. sibirica</i>	<i>H. rhamnoides</i>
Afforestation	North latitude	47°57'10.5"	47°57'18.8"	47°57'10.3"
	East longitude	105°53'09.7"	105°53'08.0"	105°53'10.7"
	Altitude (m)	1234	1245	1293
	Average age	4	4	4
	Average RCD (mm)	27.1 ± 4.9	51.4 ± 3.9	33.1 ± 4.6
	Average height H (cm)	136.2 ± 9.8	312.0 ± 10.6	151.4 ± 6.1
	Density (trees ha <sup>-1</sup> )	1050	1050	1050
	Soil type	Kastanozems (leptic, Sceleptic) FAO		
	Land use	Grassland		

Note: H – shoot height; RCD – root collar diameter. The values are means with SE = standard error.

*frigida*, *Bassia prostrata*, *Elymus sibiricus*, *Heteropappus hispidus*, *Oxytropis myriophylla*, and *Poa attenuata* (Uli-ziykhutag 1989).

Mongolia is a country with extreme weather, averaging 268 mm of annual precipitation and 2.1°C of annual temperature, with a mean monthly temperature of -20.9°C in January and +20.3°C in July (NAMEM 2020; Figure 2).

The plantation was established in 2017 using two-year-old seedlings of three different woody species, namely, *Ulmus pumila* L., *Populus sibirica* Hort. ex Tausch., and *Hippophae rhamnoides* L. (Table 1). Seedlings were planted in holes (60–70 cm deep, 50–60 cm in diameter) with a 2.5-m distance between the trees and a 4-m distance between the rows. All seedlings were equipped with a hose irrigation system and were continuously watered three times a month during the growing seasons.

### Fine root sampling, processing and measuring

The experimental treatment started in 2020 (May, July, September) and is still ongoing. A total of 216 samples were taken by coring (4 cm diameter, 30 cm deep) three times (May, July and September) from the soil of the sub-field where three tree species are growing (adapted from Ponder and Alley 1997). For processing, each sample was placed in a nylon bag (300-µm mesh) contained in a plastic cylinder (6-mm mesh) and washed automatically using a washing machine (adapted by Benjamin and Nielsen 2004). The fine roots were examined under a microscope and divided into two groups: the three species were classified as 'live' (hereinafter termed as fine-root biomass, FRB) or 'dead' (fine-root necromass, FRN) depending on their colour, texture and shape (Vogt and Persson 1991). After selection, root fragments of each species were first roughly grouped by the calliper method into half-millimetre diameter classes and scanned at a resolution of 400 dpi using a calibrated flatbed scanner coupled to a lighting system for image acquisition (Epson Expression 10000 XL). Subsequently, images were analysed using a WinRhizo Pro V 2007d (Regent Instruments, Inc., Quebec, Canada) to classify different fine-root fragments into four

diameter classes (< 0.5, 0.5–1.0, 1.0–1.5, and 1.5–2.0 mm). After measuring fine-root length (FRL), the live and dead fine-root samples were oven-dried separately by the diameter classes and weighed. Understory fine roots were also dried and weighed.

### Fine-root product

The production ( $P$ ) between two sampling dates is calculated either by adding the differences in biomass ( $\Delta B$ ) and necromass ( $\Delta N$ ), by adding only the differences in biomass ( $\Delta B$ ), or by equating  $P$  to zero (Fairley and Alexander 1985). The conditions under which the  $P$  formulas are to be used are as follows:

$$P = \Delta B + \Delta N \quad (\text{Eq. 1})$$

- a) if biomass and necromass have increased;  
b) if biomass has decreased and necromass has increased; but ( $\Delta B$ ) lower than ( $\Delta N$ ):

$$P = \Delta B \quad (\text{Eq. 2})$$

If biomass has increased and necromass has decreased:

$$P = 0 \quad (\text{Eq. 3})$$

- a) if biomass and necromass have decreased;  
b) if biomass has decreased and necromass has increased; but ( $\Delta B$ ) higher than ( $\Delta N$ ).

### Fine-root turnover rates

The turnover rate of fine-roots  $T_{Bmax}$  was calculated by dividing the annual fine-root production  $P_a$  by the highest biomass value (maximum biomass,  $B_{max}$ ) according to Gill and Jackson (2000):

$$T_{Bmax} = P_a / B_{max} \quad (\text{Eq. 4})$$

Alternatively, the turnover rate  $T_{Bmean}$  was calculated by dividing the annual fine-root production  $P_a$  by the mean biomass  $B_{mean}$  according to the method of McClaugherty et al. (1982).

$$B_{mean} = \sum \frac{B}{n}, \quad (\text{Eq. 5})$$

where  $n$  – number of samples per year.

$$T_{Bmean} = \frac{P_a}{B_{mean}} \quad (\text{Eq. 6.})$$

### Soil sampling, processing and measuring

We collected soil samples from areas under three species and non-vegetated patches of bare ground. All soil samples were taken in three replicates within the afforestation and control sites (Figure 1). A total of 48 soil samples (0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, three replications) were collected from each sampling and control plot. Soil bulk density (BD) and soil moisture (SM) were determined in accordance with Walter et al. (2016), and soil particle analyses were carried out by the procedure of Kilmer and Mullins (1954). Soil temperature was measured at each depth of the soil profile using Checktemp® Digital Thermometer HI98501 (Hanna Instruments, Inc., USA) with an accuracy of  $\pm 0.2^\circ\text{C}$ . Soil samples were air-dried, sieved through a 2 mm sieve and stored at room temperature. The samples were subjected to the following physical and chemical analyses (ISO 11464:2006): particle size was determined by sieve/pipette technique (Kilmer and Mullins 1954), pH was determined on a 1:2.5 air-dried soil/distilled water mixture using a glass electrode pH meter (MNS ISO 10390:2001), electrical conductivity (EC) was determined for a 1:5 air-dried soil/distilled water mixture using a platinum electrode. Soil organic carbon was measured according to Walkley and Black (1934), and organic carbon stock was determined as described by Batjes (1996). Calcium carbonate content was determined by the volumetric method (ASTM D4373-96; ASTM 1996). Available phosphorus ( $\text{P}_2\text{O}_5$ ) was measured by molybdenum blue colorimetry, after  $(\text{NH}_4)_2\text{CO}_3$  digestion (MNS 3310:1991). Nitrate-nitrogen ( $\text{NO}_2\text{-N}$ ) was determined using a  $\text{CH}_3\text{COONa}$  digestion and spectrophotometry. Potassium ( $\text{K}_2\text{O}$ ) was analysed by flame spectrometry (Soil Survey Staff 2014).

The soil organic carbon stocks were calculated according to the IPCC (2003):

$$\text{SOC stock (Mg ha}^{-1}\text{)} = \sum_{i=1}^n \left[ \text{SOC} \cdot \text{BD} \cdot \text{Depth} \cdot \left(1 - \frac{\text{frag}}{100}\right) \right], \quad (\text{Eq. 7})$$

where

*SOC* (soil organic carbon) – the C concentration in soil sample (kilograms of C per 1 kilogram of soil),

*BD* – the soil bulk density, i.e. soil density of the fine earth (mega grams per 1 cubic meter),

*Depth* – the thickness of the horizon within the considered section (centimeters), and

*frag* – the percent of rock fragments.

### Statistical analysis

Two-way analysis of variance (ANOVA) with Duncan's multiple range test (DMRT) were used for multiple comparisons among the data obtained from the one site and three species. All statistical analyses were performed using the SAS software package, version 9.4 (SAS Institute, Inc. 2023). Principal component analysis (PCA) was performed using the Paleontological Statistics (PAST, version 4.12(b)) software package (Hammer et al. 2001).

Analysis was carried out using R (Wickham 2016, R Core Team 2023). The graphs were produced using the Sigma Plot for Windows software suite, version 12.5 (Systat Software, Inc. 2013).

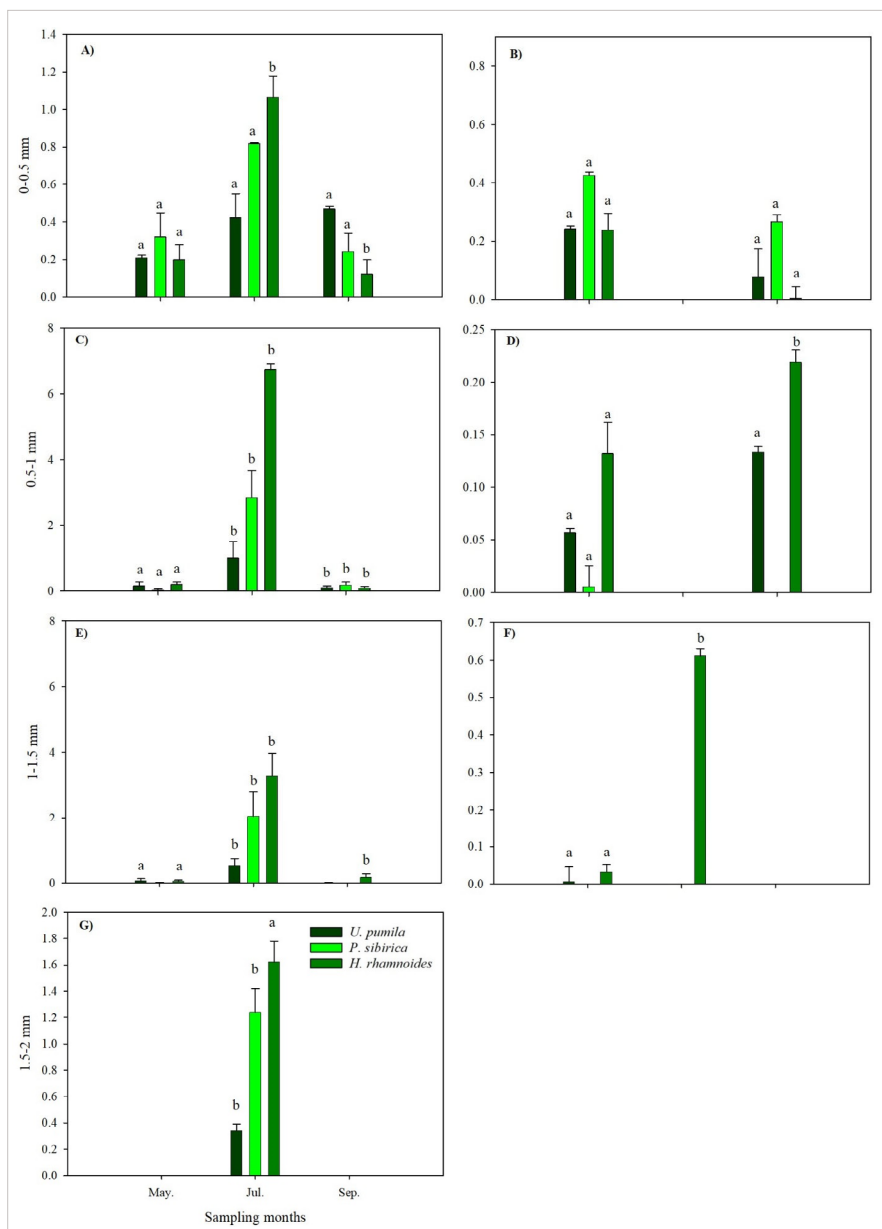
## Results

### Fine root analysis

The development of the tree fine-roots varied by species type and timeline at the afforestation site. Monthly differences in the results for the fine-root diameter categories showed that the 0–0.5 mm category was more prevalent in May and September, while the 0–2 mm category was more prevalent in July (Figure 3). The highest fine-root biomass accumulated in the 0–20 cm soil depth, with the 0–1 mm diameter category having the highest amount of fine-roots. For *U. pumila*, the measurement was similar in  $\text{May} < \text{July} < \text{September}$  for the thinnest fine-root diameter category of 0–0.5 mm. For *P. sibirica* and *H. rhamnoides*, the 0–0.5 mm fine-root category was the highest in July. In that month, the fine-root biomass was the highest across all diameter categories with *H. rhamnoides* showing the highest amount. Additionally, the fine-root necromass varied across diameter categories, except 1.5–2.0 mm category, were not observed necromass in this category. The fine roots of *U. pumila* and *P. sibirica* were measured at 0–0.5 mm (Figure 3A), while those of *H. rhamnoides* were measured at 0–1.5 mm (Figure 3A, C, E, G). The 0.5–1.5 mm diameter category dominated fine-root necromass measurements (Figure 3B, D, F).

As shown in Table 2, the fine-root diameters varied by category for each tree species during the measurement periods. Most of the fine root diameters for each of the three tree species were measured at the beginning (May) and end (September) of the plant growth period. Live fine roots belonged to the 0–0.5 mm diameter category. Fine roots in the 0.0–0.5 mm diameter category comprised *P. sibirica* (88.46%) in May, *U. pumila* (79.98%) in September, and *H. rhamnoides* (53.09%) in the 0.5–1.0 mm diameter fine root category was measured in June. The highest amount of necromass of fine roots was recorded in May and September for *P. sibirica* (Table 2).

A comparison of surface areas at the species level showed that *U. pumila* measured  $5.92 \pm 0.44 \text{ cm}^2$  in July and  $5.13 \pm 0.38 \text{ cm}^2$  in September. *P. sibirica* exhibited similar measurements across all months, while *H. rhamnoides* had the highest measurements in July at  $5.25 \pm 0.36 \text{ cm}^2$  (Table 3). When compared at the species level, fine-root length of *U. pumila* was consistent across all measurement months. The fine-root growth of *P. sibirica* was longer in September ( $25.50 \pm 4.01 \text{ cm}$ ), while that of *H. rhamnoides* was longer in July ( $31.11 \pm 4.29 \text{ cm}$ ). Fine-root necromass length was measured in May and September for all three tree species (Table 3). Regarding the total volume of living fine roots of trees, the highest values were noted in *P. sibirica* ( $0.14 \pm 0.04 \text{ cm}^3$ ) and *H. rhamnoides* ( $0.10 \pm 0.02 \text{ cm}^3$ )



**Figure 3.** Live fine root biomass and fine root necromass of trees in the afforestation sites by root size and diameter: A) 0–0.5 mm live fine root biomass, B) 0–0.5 mm dead fine root mass, C) 0.5–1 mm live fine root biomass, D) 0.5–1 mm dead fine root mass, E) 1–1.5 mm live fine root biomass, F) 1–1.5 mm dead fine root mass, G) 1.5–2 mm live fine root biomass, H) 1.5–2 mm dead fine root mass

**Table 2.** The live tree fine root biomass and dead tree fine root necromass by percentage and by diameter

Species	Diameter (mm)	Live fine-root			Necromass		
		May (%)	Jul (%)	Sep (%)	May (%)	Jul (%)	Sep (%)
<i>U. pumila</i>	0.0–0.5	48.07	18.47	79.98	78.95	-	36.67
	0.5–1.0	36.32	43.46	17.35	18.55	-	63.32
	1.0–1.5	15.61	23.25	2.67	2.50	-	-
	1.5–2.0	-	14.82	-	-	-	-
<i>P. sibirica</i>	0.0–0.5	88.46	11.78	57.06	98.65	-	100.0
	0.5–1.0	9.87	40.82	42.94	1.35	-	-
	1.0–1.5	1.67	29.55	-	-	-	-
<i>H. rhamnoides</i>	1.5–2.0	-	17.85	-	-	-	-
	0.0–0.5	47.29	8.37	38.60	59.11	-	2.06
	0.5–1.0	10.48	53.09	27.19	32.70	-	97.94
	1.0–1.5	26.49	25.78	18.85	8.18	-	-
	1.5–2.0	15.74	12.76	15.36	0.00	-	-

**Table 3.** Fine-root: Surface area, length, volume

Month	<i>U. pumila</i> (live)	<i>P. sibirica</i> (live)	<i>H. rhamnoides</i> (live)	<i>U. pumila</i> (necromass)	<i>P. sibirica</i> (necromass)	<i>H. rhamnoides</i> (necromass)
Surface area (cm <sup>2</sup> )						
May	4.96 ± 0.44 <sup>a</sup>	4.37 ± 0.35 <sup>a</sup>	4.99 ± 0.37 <sup>a</sup>	3.74 ± 0.94 <sup>a</sup>	4.15 ± 0.25 <sup>a</sup>	3.90 ± 0.36 <sup>a</sup>
Jul	5.92 ± 0.45 <sup>a</sup>	4.41 ± 0.34 <sup>a</sup>	5.25 ± 0.36 <sup>a</sup>	-	-	-
Sep	5.13 ± 0.38 <sup>a</sup>	4.88 ± 0.54 <sup>a</sup>	4.80 ± 0.58 <sup>a</sup>	9.05 ± 0.00 <sup>a</sup>	2.96 ± 0.51 <sup>a</sup>	3.89 ± 1.15 <sup>a</sup>
Length (cm)						
May	26.54 ± 5.36 <sup>a</sup>	22.82 ± 2.29 <sup>a</sup>	24.33 ± 3.49 <sup>a</sup>	14.39 ± 3.69 <sup>a</sup>	17.67 ± 2.18 <sup>a</sup>	18.26 ± 3.70 <sup>a</sup>
Jul	24.80 ± 3.37 <sup>a</sup>	20.83 ± 3.74 <sup>a</sup>	31.11 ± 4.29 <sup>a</sup>	-	-	-
Sep	25.41 ± 3.01 <sup>a</sup>	25.51 ± 4.02 <sup>a</sup>	20.86 ± 3.92 <sup>a</sup>	3.56 ± 0.00 <sup>a</sup>	11.16 ± 1.80 <sup>a</sup>	12.54 ± 4.54 <sup>a</sup>
Total volume (cm <sup>3</sup> )						
May	0.04 ± 0.01 <sup>a</sup>	0.02 ± 0.01 <sup>a</sup>	0.04 ± 0.01 <sup>a</sup>	0.02 ± 0.01 <sup>a</sup>	-	0.02 ± 0.01 <sup>a</sup>
Jul	0.05 ± 0.01 <sup>a</sup>	0.14 ± 0.05 <sup>a</sup>	0.10 ± 0.02 <sup>ab</sup>	-	-	-
Sep	0.03 ± 0.01 <sup>a</sup>	0.02 ± 0.01 <sup>a</sup>	0.04 ± 0.01 <sup>b</sup>	0.02 ± 0.00 <sup>a</sup>	-	0.01 ± 0.01 <sup>a</sup>

in July, and similar results were observed in the examined tree species in May and September (Table 3).

A comparison of surface areas at the species level showed that *U. pumila* measured  $5.92 \pm 0.45$  cm<sup>2</sup> in July and  $5.13 \pm 0.38$  cm<sup>2</sup> in September. *P. sibirica* exhibited similar values across all months, while *H. rhamnoides* showed the highest values in July at  $5.25 \pm 0.36$  cm<sup>2</sup> (Table 3). When compared at the species level, fine-root length of *U. pumila* was consistent across all measurement months. The fine-root growth of *P. sibirica* was longer in September ( $25.51 \pm 4.02$  cm), while *H. rhamnoides* had higher length in July ( $31.11 \pm 4.29$  cm). Fine-root necromass length (dead fine root length) was measured in May and September for all three tree species (Table 3). Regarding the total volume of living fine roots of trees, the highest values were noted in *P. sibirica* ( $0.14 \pm 0.05$  cm<sup>3</sup>) and *H. rhamnoides* ( $0.10 \pm 0.02$  cm<sup>3</sup>) in July, and similar results were observed for the examined tree species in May and September (Table 3).

The fine-root system of the young trees of the three species was more abundant in the soil surface layer. The highest total biomass of fine roots during the entire growing season was produced by *H. rhamnoides*, 0.489 g (May 16.6%, Jul 52.2%, Sep 31%), while *P. sibirica*, 0.366 g (May 12%, Jul 50.7%, Sep 37.3%), and *U. pumila*, 0.359 g (May 25.5%, Jun 42%, Sep 32.6%), demonstrated similar values. The three tree species accumulated the highest fine-root biomass in the middle of the growing season (July; Figure 4A, C, E).

The proportion of total fine-root mass in each soil layer also decreased with soil depth. Figure 4 shows fine-root biomass accumulation for three tree species at soil depths of 0–40 cm. The fine-root biomass of *U. pumila* began to increase in May and reached its maximum in September ( $0.067 \pm 0.052$  g) at the 0–10 cm soil depth. However, in May, the fine-root biomass increased the most ( $0.071 \pm 0.040$  g) and subsequently decreased in July at the soil depth of 10–20 cm. This pattern was observed at the soil depth of 20–40 cm. Furthermore, the greatest reduction in fine roots in *U. pumila* was observed in most soil layers in May (Figure 4A). For *P. sibirica*, the highest

fine-root biomass was observed at the 0–10 cm soil depth in July ( $0.081 \pm 0.008$  g) and at the 10–20 cm soil depth in September ( $0.097 \pm 0.067$  g) (Figure 4C). Along with the high accumulation of fine-root biomass, the fine-root necromass was measured in all soil layers in May (Figure 4B, D, F). For *H. rhamnoides*, the highest fine-root biomass accumulation occurred at the 0–30 cm soil depth in all measured months, related to the biological characteristics of the tree species.

The 74.5% of the total fine-root biomass is distributed within the 0–20 cm soil depth. The decrease in fine root biomass was observed with increasing soil depth. Additionally, the fine-root biomass of *H. rhamnoides* showed a better distribution in the 20–40 cm soil depth compared to the other two species (Figure 4).

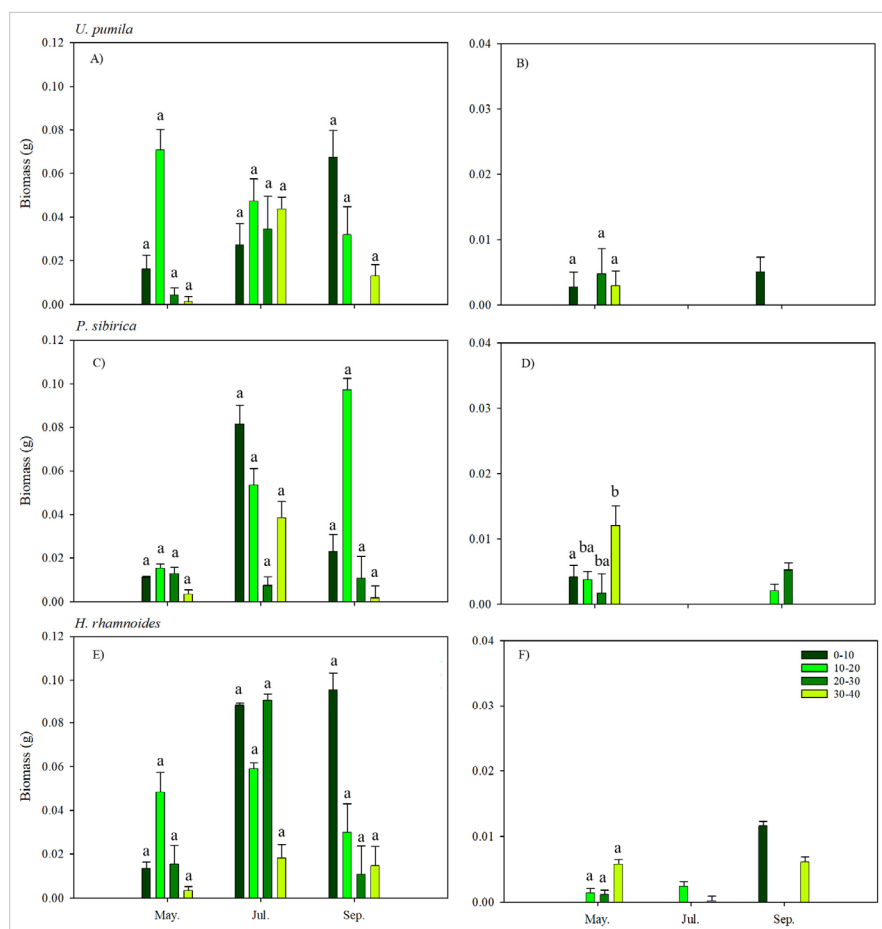
### Fine-root production

Based on the fine root biomass (g), total biomass accumulation per unit area was calculated. According to the results, the highest total biomass accumulation per unit area occurred in the middle of the growth period (July). In terms of species, *H. rhamnoides* ( $1.689$  g m<sup>-2</sup>) had the highest fine root biomass accumulation per unit area (Table 4).

The measurement results showed *H. rhamnoides* ( $0.586$  g m<sup>-2</sup>) had the highest fine-root production in July, while *U. pumila* ( $0.118$  g m<sup>-2</sup>) had the lowest production in September. When comparing species, *H. rhamnoides* had the highest production ( $0.949$  g m<sup>-2</sup>) and its fine root system sufficiently increases soil moisture and nutrition increment, reduces soil compaction, boosts soil microorganism and activates the nutrient cycling (Table 4). Fine root turnover rate (higher turnover rate indicates higher microbial activity and soil nutrient cycling) per unit area varied among these three tree species during the annual growth period. The highest turnover rate was observed in *H. rhamnoides*, 1.071 (year), while the lowest was in *U. pumila* at 0.547 (year; Table 4).

### Soil properties

The study aimed to determine the impact of 4-year-old trees on the soil by planting and growing trees in de-



**Figure 4.** Fine-root dry biomass in the plantation site: *U. pumila* A) live fine-root, B) necromass; *P. sibirica* C) live fine-root, D) necromass; *H. rhamnoides* E) live fine-root, F) necromass. Monthly dynamics of live fine-root biomass and dead fine root necromass (2 mm) biomass (mean SE, n=3) at soil layer of 0–10, 10–20, 20–30, 30–40 cm depth

**Table 4.** Fine root biomass, production, turn-over rate

Month	Fine-root biomass (g m <sup>-2</sup> )			Fine-root production (g m <sup>-2</sup> )			Fine-root turn-over rate (year)		
	<i>U. pumila</i>	<i>P. sibirica</i>	<i>H. rhamnoides</i>	<i>U. pumila</i>	<i>P. sibirica</i>	<i>H. rhamnoides</i>	<i>U. pumila</i>	<i>P. sibirica</i>	<i>H. rhamnoides</i>
May	0.320	0.149	0.280	-	-	-	-	-	-
Jul	0.528	0.626	0.886	0.171	0.402	0.586	-	-	-
Sep	0.409	0.460	0.523	0.118	0.166	0.363	-	-	-
Total	1.257	1.234	1.689	0.289	0.568	0.949	0.547	0.907	1.071

**Table 5.** Comparison of soil properties in the afforestation site

Property	Soil depth (cm)	N	Property									
			pH	BD (g cm <sup>-3</sup> )	SM (%)	Sand (2–0.05 mm)	Silt (2–0.05 mm)	Clay (2–0.05 mm)	AN (mg kg <sup>-1</sup> )	AP (mg kg <sup>-1</sup> )	AK (mg kg <sup>-1</sup> )	SOCs (Mg ha <sup>-1</sup> )
<i>U. pumila</i>	0–20	45	7.75±0.06 <sup>a</sup>	1.20±0.02 <sup>a</sup>	8.24±0.82 <sup>a</sup>	66.08±2.48 <sup>a</sup>	23.67±2.29 <sup>a</sup>	9.81±0.48 <sup>a</sup>	1.11±0.25 <sup>a</sup>	1.74±0.37 <sup>a</sup>	53.40±5.73 <sup>a</sup>	8.01±0.97 <sup>a</sup>
	20–60	45	7.83±0.28 <sup>a</sup>	1.30±0.07 <sup>a</sup>	3.90±0.71 <sup>a</sup>	64.39±0.49 <sup>a</sup>	24.85±0.12 <sup>a</sup>	9.76±0.63 <sup>a</sup>	0.75±0.18 <sup>a</sup>	0.83±0.00 <sup>a</sup>	39.88±8.20 <sup>a</sup>	10.91±4.17 <sup>a</sup>
<i>P. sibirica</i>	0–20	45	7.65±0.03 <sup>a</sup>	1.18±0.05 <sup>a</sup>	10.24±1.03 <sup>a</sup>	65.36±0.55 <sup>a</sup>	23.13±0.34 <sup>a</sup>	11.50±0.23 <sup>a</sup>	0.96±0.26 <sup>a</sup>	1.31±0.07 <sup>a</sup>	20.77±6.16 <sup>ab</sup>	7.05±0.60 <sup>a</sup>
	20–60	45	7.74±0.10 <sup>a</sup>	1.24±0.03 <sup>a</sup>	4.84±0.08 <sup>a</sup>	70.70±0.90 <sup>a</sup>	19.75±0.20 <sup>a</sup>	9.54±0.71 <sup>a</sup>	0.50±0.09 <sup>a</sup>	0.92±0.11 <sup>a</sup>	12.29±1.21 <sup>ab</sup>	7.92±4.36 <sup>ab</sup>
<i>H. rhamnoides</i>	0–20	45	7.46±0.10 <sup>a</sup>	1.28±0.04 <sup>a</sup>	10.64±0.30 <sup>a</sup>	65.67±1.25 <sup>a</sup>	23.88±0.72 <sup>ab</sup>	10.45±0.54 <sup>a</sup>	1.12±0.38 <sup>a</sup>	1.20±0.21 <sup>a</sup>	32.99±7.63 <sup>ab</sup>	8.49±1.25 <sup>a</sup>
	20–60	45	7.58±0.20 <sup>a</sup>	1.26±0.01 <sup>a</sup>	5.25±0.70 <sup>a</sup>	65.58±2.22 <sup>a</sup>	23.95±1.71 <sup>a</sup>	10.47±0.51 <sup>a</sup>	0.52±0.09 <sup>a</sup>	0.96±0.03 <sup>a</sup>	14.46±1.96 <sup>ab</sup>	7.41±1.77 <sup>ab</sup>
Control	0–20	45	7.77±0.23 <sup>a</sup>	1.42±0.03 <sup>a</sup>	7.63±0.47 <sup>a</sup>	66.07±0.66 <sup>a</sup>	20.47±2.16 <sup>b</sup>	11.13±0.24 <sup>a</sup>	0.86±0.16 <sup>a</sup>	1.53±0.62 <sup>a</sup>	51.90±20.88 <sup>b</sup>	6.36±1.34 <sup>a</sup>
	20–60	45	7.78±0.08 <sup>a</sup>	1.41±0.07 <sup>a</sup>	8.09±1.67 <sup>a</sup>	73.26±2.19 <sup>a</sup>	13.31±0.85 <sup>b</sup>	8.92±0.84 <sup>a</sup>	0.40±0.13 <sup>a</sup>	1.55±0.79 <sup>a</sup>	14.74±0.22 <sup>b</sup>	4.19±2.91 <sup>b</sup>

Note: BD = Bulk density; SM = soil moisture; AN = available nitrogen; AP = available phosphorus; AK = available potassium.

graded areas. The results of physicochemical soil analysis showed that soil properties varied across the forest plantation site. Soil pH ranged from slightly alkaline (pH: 7.46–7.83). Soil bulk density (BD) was lower at the forest plantation site (1.18–1.30 g cm<sup>-3</sup>) compared to the control site (1.42 ± 0.03 g cm<sup>-3</sup>). Soil moisture was higher at the forest plantation site, and the moisture content decreased

with soil depth. The afforestation site soil had a sandy texture. The mechanical composition of the soil at the control and afforestation areas was similar: the sandy texture at the afforestation site ranged from 64.39–70.70 mm, and the control site soil sand was 73.26 ± 0.47 mm.

On the other hand, the soil silt of the afforestation site was 19.75–24.85 mm, and clay was 20.47 ± 2.16 mm,

while the control site soil silt was 9.54–11.50 mm, and clay was  $11.13 \pm 0.24$  mm (Table 5). The key indicators of soil fertility, including available nitrogen (AN), available phosphorus (AP), available potassium (AK) and SOC, were compared between soils of the afforestation site and the control site. The results showed that AN, AP and AK are highest in the soil at a depth of 0–20 cm. In the soil, where *U. pumila* trees have been planted, the levels of AN, AP and AK were the highest, with the AN value being particularly elevated in association with *H. rhamnoides*. The highest SOC values were found in the soil samples collected at the depth of 20–60 cm in the afforestation area, where *U. pumila* was growing. The SOC values in the control soil samples were consistently lower compared to those in the soil from the afforestation site (Table 5).

### Soil organic carbon stock

To determine the impact of fine-root biomass for three tree species on SOC stock. A positive correlation was observed between tree fine-root biomass and the increase in the SOC stock by 55% (Figure 5A, B). Regarding the differences between species, the SOC stock of *U. pumila* ( $51.16 \pm 0.57$  Mg ha<sup>-1</sup>) was high during all measurement periods. *P. sibirica* ( $30.30 \pm 0.45$  Mg ha<sup>-1</sup>) and *H. rhamnoides* ( $34.61 \pm 1.76$  Mg ha<sup>-1</sup>) showed similar results (Figure 5A). In general, as soil depth increased, significant changes in SOC stock were noted. In all soil layers, *U. pumila* was rich in SOC stock, with the greatest increase occurring at a depth of 20–40 cm, while SOC stock decreased at 40–60 cm. Additionally, at all measurement depths, the SOC stock in the control site was significantly lower than that in the afforestation site (Figure 5B).

### The relationship between fine root traits and soil properties

A principal component analysis (PCA) was conducted to determine the relationships between environmental conditions, soil chemical and physical properties, soil organic carbon stocks, air temperature and air humidity on fine root biomass accumulation in three tree species.

The impact of soil growth environment and climate on the fine root biomass of three tree species at the afforestation site was projected onto a two-dimensional plot using

PCA. Together, PCA components accounted for 46.3% of the variation in fine-root biomass accumulation in the planted *U. pumila* (PCA 1: 27.1%, PCA 2: 19.2%). The fine-root biomass of *U. pumila* was highly affected by climate, soil moisture, and soil fertility indicators at the afforestation site. In contrast, the fine-root biomass of *P. sibirica* PCA 52.9% (PCA 1: 32.7%, PCA 2: 20.2%) and *H. rhamnoides* PCA 50.9% (PCA 1: 29.3%, PCA 2: 21.6%) was significantly influenced by climate factors, as well as by increasing soil fertility, and the mechanical components of soil (Figure 6A, B, C).

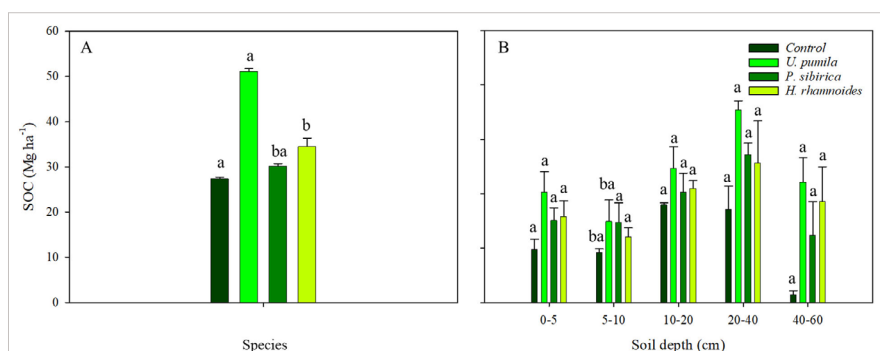
The impact of soil growth environment and climate on the fine root biomass of the three tree species at the afforestation site was projected onto a two-dimensional plot using PCA. Together, PCA components accounted for 46.3% of the variation in fine-root biomass accumulation in the planted *U. pumila* (PCA 1: 27.1%, PCA 2: 19.2%). The fine-root biomass of *U. pumila* was highly affected by climate, soil moisture, and soil fertility indicators at the afforestation site. In contrast, the fine-root biomass of *P. sibirica* PCA 52.9% (PCA 1: 32.7%, PCA 2: 20.2%) and *H. rhamnoides* PCA 50.9% (PCA 1: 29.3%, PCA 2: 21.6%) was significantly influenced by climate factors, as well as by increasing soil fertility, and the mechanical components of soil (Figure 6A, B, C).

## Discussion

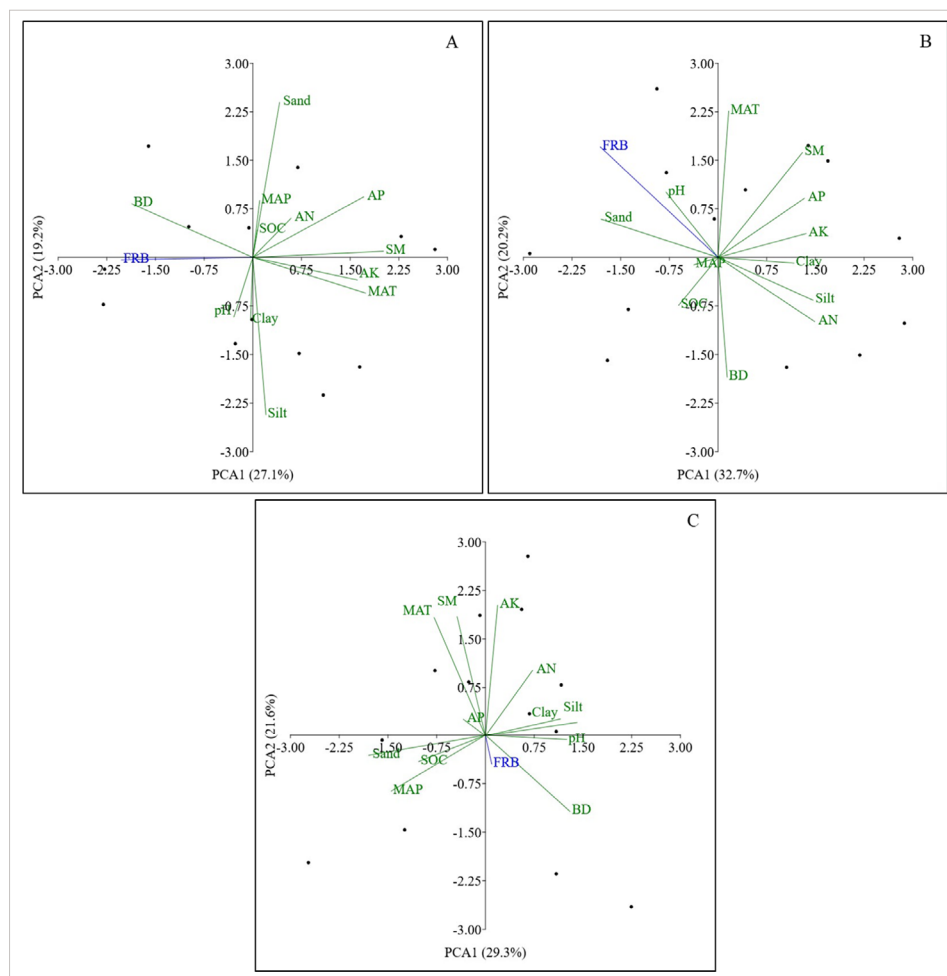
For afforestation and reforestation activities, selecting the appropriate tree species in regions with extreme climates is crucial. Previous studies have confirmed that *U. pumila*, *P. sibirica*, and *H. rhamnoides* are well-adapted and capable of thriving in the Mongolian dry steppe region with low rainfall (Cho et al. 2019, Byambadorj et al. 2020, 2021, Nyam-Osor et al. 2021, Montagnoli et al. 2022, Avirmed et al. 2023). In the scope of the National Programme to enhance afforestation and reforestation efforts aimed at combating desertification and land degradation, these tree species are expected to be planted in significant quantities in the future (“Billion Tree” National Movement 2023).

### Fine-root analysis

This study aimed to determine the biomass accumulation, production, and turnover rate of fine-root for tree



**Figure 5.** SOC in different tree species: A) SOC in the presence of different tree species, B) Comparison of SOC at varying depths



**Figure 6.** Principal component analysis (PCA) of fine-root biomass: A) *U. pumila*, B) *P. sibirica*, C) *H. rhamnoides*

species. All fine-root measurements are presented separately for live fine root and fine-root necromass. The planted tree species demonstrated high productivity, owing to the significant biomass of fine roots, developed mainly due to fertile soil and regular watering. Fine-root biomass is dependent on several factors, including species type, age, BD, soil properties, and environmental conditions such as temperature, precipitation, topography, and elevation (Finér et al. 2007, 2011). However, 74.5% of the total live fine-roots were distributed within the 0–20 cm soil depth (Wang et al. 2012). Previous research has shown that the maximum accumulation of plant roots occurs in the topsoil (Bonger et al. 2008, Himmelbauer et al. 2010).

Overall, fine-root biomass increased in spring, peaked in summer and then declined in autumn, consistent with findings from other studies (Brassard et al. 2009, 2011). Also, 74.5% of the fine-root necromass was measured at the 0–20 cm soil depth. Fine-root necromass, often found on the soil surface, is a crucial factor in enhancing soil fertility. These results align with other research suggesting that fine-root necromass decreases with soil depth (Lai et al. 2016, Du et al. 2019). *H. rhamnoides* benefits from regular drip watering, which helps increase harvest yield and makes it less susceptible to water shortages compared to

the other two species. However, significant fine-root loss for *H. rhamnoides* was observed in July and September (Figure 4). This loss can be attributed to several factors, including sandy texture (Huang et al. 2012), low soil moisture content (Olesinski et al. 2011, Ma et al. 2021), and high air temperature (Dress and Boerner 2001, Phillips et al. 2006).

Conversely, the necromass for *U. pumila* and *P. sibirica* was higher due to limited watering in May. Low rainfall in 2020 likely adversely affected fine-root biomass accumulation compared with previous years (2017–2019) (NAMEM 2020). In the afforestation site, droughts typically occur annually from April to May. During drought years, trees often experienced water deficits, leading to a decline in belowground biomass (Joslin et al. 2000, Chiantante et al. 2005, 2006, Di Iorio et al. 2011). Fine-root production tends to decrease during the driest periods, suggesting a potential adaptation to water scarcity (Montagnoli et al. 2012). However, we did not collect samples during winter due to very low soil temperatures, reaching from  $-30^{\circ}\text{C}$  to  $-40^{\circ}\text{C}$ , which limited both the formation and decomposition of fine roots. Regarding the characteristics of fine roots, 76% of the live mass and 95% of the necromass of fine roots in the three tree species fell into the 0–1 mm

diameter category. These findings align with previous research (Bauhus and Messier 1999, King et al. 2002, Pinno et al. 2010).

Furthermore, the surface area of fine roots in the three studied tree species was low in May but increased in July and September. This pattern is explained by low air humidity during the spring months, which emphasises the need for increased watering in this season. The results also showed that fine-root length decreased with depth from the soil surface, consistent with previous research findings (Tracy et al. 2013). Topsoil contains higher nutrient levels that support root growth in the upper layers. As soil depth increases, nutrient availability gradually decreases, restricting root development. In contrast, root length tends to show the opposite trend: in nutrient-rich upper soils, roots can easily access resources, whereas in deeper, nutrient-poor layers, roots must extend further to reach nutrient-rich zones (Tang et al. 2023).

According to our results, the fine-root production of the three tree species ranged from 0.29 to 0.95 g m<sup>-2</sup>, with turnover rates varying between 0.55 and 1.07 year<sup>-1</sup> (Table 4). These findings can be compared to studies conducted by Chinese researchers in regions with similar climate and orography. For instance, the fine-root turnover rate of 20-year-old *U. pumila* planted in the Gurbantunggut Desert was reported to be 2.08 year<sup>-1</sup> (Pei et al. 2011). Additionally, the fine-root production of 15-year-old *Salix psammophila* grown in Yanchi sandy soil was measured at 310.22 g m<sup>-2</sup> (Lai et al. 2016). The studies mentioned above suggested that the production of fine roots by trees increases with age. In Mongolia, research on tree fine roots is still in its initial stages. Therefore, future studies should focus on the detailed seasonal dynamics of tree fine-roots.

### Soil properties

Most of the soils in Mongolia are alkaline, with soil pH significantly influenced by BD, tree species, and soil depth. In the afforestation area, soil pH decreased with increasing soil depth. In contrast, all soil depths in the control site showed similar pH levels. Planting trees in alkaline soils can lead to shifts in soil pH (Hong et al. 2018). The contents of essential nutrients, like N, P, and K, in the soil are significantly influenced by both soil depth and tree species (Table 5). In general, *H. rhamnoides* thrives in sandy, stony, light-textured soils with a pH of 6.5–7.5 (Mohit et al. 2018). This species is rich in N and contributes positively to soil fertility (Mohit et al. 2018). *U. pumila* is considered more suitable for planting in sandy and degraded areas as it enhances soil nutrient levels (Wang et al. 2021). Additionally, some studies found that N content can negatively affect soil BD during the restoration of degraded lands (Wang et al. 2011, Singh et al. 2012). It has been shown that planting *U. pumila* on sandy soils in northern China, where the climate is similar, resulted in a significant increase in SOC, N and P levels in soil (Zhao et al. 2008, 2010,

Zhou et al. 2017). Our study corroborates these findings, showing that both *H. rhamnoides* and *U. pumila* accumulate higher levels of N.

However, the soil P content in the afforestation site is lower compared to the control area, and no significant differences were observed in BD. The observed decrease in soil moisture depth in the study area is attributed to low rainfall and drought during the spring (Table 5). Previous studies have shown that afforestation activities in decertified and land-degraded areas enhance soil fertility (Zhang et al. 2018) and significantly increase SOC stock (Chen et al. 2013, Wang et al. 2022, Avirmed et al. 2023, Shuai et al. 2024). Furthermore, afforestation leads to increased plant species diversity, enhances microbial activity (Zhao and Li 2017), and positively influences SOC cycling (Zhang et al. 2019).

Tree roots play a crucial role in SOC dynamics (Wang et al. 2019). Fine-root necromass contributes to the accumulation of SOC stock (Wang et al. 2014). Interestingly, as the fine-root biomass of planted trees increases, the SOC stock initially rises and then subsequently decreases (Tian et al. 2022). Our previous research results showed that in a dry-steppe zone, the SOC stocks accumulated by 10-year-old *U. pumila* (69.49 Mg ha<sup>-1</sup>), *H. rhamnoides* (52.58 Mg ha<sup>-1</sup>), and *P. sibirica* (47.10 Mg ha<sup>-1</sup>) were significantly higher as against the control plots (Avirmed et al. 2023). In this study, the effects of *U. pumila* (51.16 Mg ha<sup>-1</sup>), *H. rhamnoides* (34.61 Mg ha<sup>-1</sup>), and *P. sibirica* (30.30 Mg ha<sup>-1</sup>) on SOC stock were reaffirmed (Figure 5). Also, 8-year-old *P. sibirica* and 13-year-old *U. pumila* cultivated in the Horching area of northern China, which shares similar climatic conditions, accumulated SOC stock of 75.17 Mg ha<sup>-1</sup> and 68.41 Mg ha<sup>-1</sup>, respectively (Yuan et al. 2021). These studies show that *U. pumila*, *P. sibirica*, and *H. rhamnoides* are well-suited for planting in regions with low rainfall (Wang et al. 2021). The impact on SOC stock may vary depending on the type of afforestation and timing of planting (Xu et al. 2023).

Therefore, to increase the SOC stock, it is advisable to select and plant *U. pumila* and *P. sibirica* for reforestation and afforestation efforts, as these species are more ecophysiologicaly adaptable to the conditions in the areas with low precipitation, like Mongolia (Byambadorj et al. 2020, Nyam-Osor et al. 2021, Montagnoli et al. 2022). In general, SOC is abundant at depths of 0–40 cm (IPCC 2003) and 0–50 cm (Yuan et al. 2021) below the soil surface. For instance, in a 13-year-old tree-planted field, SOC stock decreased with depth but showed a tendency to increase over the years (Li et al. 2015). Due to the young age of the trees planted in this study, soil samples were collected at a depth of 0–60 cm. This study serves as a baseline, and future research should focus on the dynamics of fine-root biomass and SOC stock studies over time.

### The relationship between fine-root analysis and soil properties

To confirm the accuracy of the study results, principal component analysis (PCA) was conducted. The accumulation of fine-root biomass for the three tree species is significantly influenced by climate, particularly soil fertility, and soil mechanical composition. The factors affecting fine root growth are generally similar across the three species. In *U. pumila*, strong correlations were observed with MAT, SM, P, and SOC. In *P. sibirica*, high correlations were noted with MAT, MAP, SM, N, P, K, silt, and clay. In *H. rhamnoides*, pH, K, silt, clay, BD, SM, SOC, and MAT showed high correlations. As the tree age increases, the amount of silt and clay in the soil tends to increase (Jia et al. 2019). A well-developed root system can negatively impact sand formation while promoting the development of silt and clay (Liu et al. 2019), which is considered an important factor for reducing desertification and curbing sand migration. Similar findings by Staszal et al. (2022) showed that fine roots play a significant role in increasing SOC accumulation. In particular, fine-root biomass capable of absorbing nutrients, whilst necromass contributes to 58–96% of total C in soil through decay (Shahzad et al. 2015). SOC stock showed a positive correlation with N, P, K, MAT, SM, sand, silt, and BD (Zhang et al. 2019a,b). These factors significantly influence plant photosynthesis and SOC stock by enhancing the amount of plant residues in the soil (Zhang et al. 2019a,b). However, MAP and fine-root (FR) biomass showed weaker correlations with SOC stock. Previous studies have indicated that SOC stock tends to decrease with increasing sandy texture while it increases with greater silt and clay content (Schimel et al. 1994, Chang et al. 2019, Zhang et al. 2019a,b, Shuai et al. 2024). Silt and clay support the accumulation of SOC, whereas sand has a large specific surface area, leading to a weak association with SOC and negative correlation (Balesdent et al. 1998). In addition, multiple linear regression models interpreted the correlation as strong when the site value exceeded 0.30.

### Conclusions

The fine-root biomass of planted deciduous trees is highly dependent on climatic conditions and soil properties. Concerning the species studied, the fine-root biomass, production, and the turnover rate of *H. rhamnoides* were the highest. Planting trees on degraded land increased soil fertility and increased SOC stock by 1-fold. Regarding the three examined tree species, the *U. pumila* had the greatest impact on SOC stocks. To summarise this study, planting *U. pumila*, *P. sibirica*, and *H. rhamnoides* for afforestation activities in the dry-steppe showed that for four years, the tree species adapted to the harsh environment and increased soil fertility. For decreasing desertification, choosing the right species for the environment

is key to successful afforestation. Our study suggests that these species could be the right fit, but further study is much needed.

### Acknowledgements

The authors gratefully thank the staff of the “Green Asia network” INGO and members of the Laboratory of Forest Genetics and Ecophysiology, the National University of Mongolia, for their inestimable assistance and valuable technical help in the laboratory and field work.

### References

- ASTM International. 1996. Standard Test Method for Calcium Carbonate Content of Soils (ASTM D4373-96). West Conshohocken, PA: Author, 3 pp.
- Avirmed, Ts., Byambadorj, S.-O., Chiantante, D., Sharavdorj, Kh., Ganbat, B., Sukhbaatar, G. and Nyam-Osor, B. 2023. Afforestation of semi-arid regions of Mongolia: Carbon sequestration in trees and increase of soil organic carbon. *Plant Biosystems – An International Journal Dealing with all Aspects of Plant Biology* 157(4): 1–21; <https://doi.org/10.1080/11263504.2023.2200781>.
- Balesdent, J., Besnard, E., Arrouays, D. and Chenu, C. 1998. The dynamics of carbon in particle-size fractions of soil in a forest-cultivation sequence. *Plant and Soil* 201(1): 49–57; <https://doi.org/10.1023/A:1004337314970>.
- Batjes, N. H. 1996. Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science* 47: 151–163; <https://doi.org/10.1111/j.1365-2389.1996.tb01386.x>.
- Batkhishig, O. and Dorjgotov, D. 2021. Khörsnii organik нүүрстөрөгчийн өөрчлөлт ба түүнд нөлөөлөх хүчин зүйлс. Үндсэн судалгааны тайлан [Changes in soil organic carbon and factors affecting it. Basic Research Report]. Ulaanbaatar: p. 157–158 (in Mongolian).
- Bauhus, J. and Messier, C. 1999. Soil exploitation strategies of fine roots in different tree species of the southern boreal forest of eastern Canada. *Canadian Journal of Forest Research* 29: 260–273; <https://doi.org/10.1139/x98-206>.
- Bayasgalankhuu, L., Ilahi, S., Wei, W. and Wu, Y. 2022. Energy Analysis on Wheat Yield of Mongolian Agriculture. *Processes* 10: 190; <https://doi.org/10.3390/pr10020190>.
- Bekei, A. 2018. Mongolyn khödөө аж ахуйн едийн засаг [The Economic of Mongolian Agriculture]. Ulaanbaatar (Mongolia): MULS Press (in Mongolian).
- Benjamin, J. G. and Nielsen, D. C. 2004. A method to separate plant roots from soil and analyze root surface area. *Plant and Soil* 267: 225–234.
- Billion Tree National Movement. 2023. National Forest Agency. URL: <https://terbummod.mn>.
- Bogner, C., Wolf, B., Schlather, M. and Huwe, B. 2008. Analysing flow patterns from dye tracer experiments in a forest soil using extreme value statistics. *European Journal of Soil Science* 59(1): 103–113; <https://doi.org/10.1111/j.1365-2389.2007.00974.x>.
- Böhm, W. 1979. Methods of studying root systems. Berlin, Heidelberg: Springer, 188 pp.; <https://doi.org/10.1007/978-3-642-67282-8>.
- Brassard, B. W., Chen, H. Y. H. and Bergeron, Y. 2009. Influence of environmental variability on root dynamics in northern forests. *Critical Reviews in Plant Sciences* 28(3): 179–197; <https://doi.org/10.1080/07352680902776572>.
- Brassard, B. W., Chen, H. Y. H., Bergeron, Y. and Pare, D. 2011. Differences in fine root productivity between mixed-

- and single-species stands. *Functional Ecology* 25: 238–246; <https://doi.org/10.1111/j.1365-2435.2010.01769.x>.
- Brown, S.** 2002. Measuring carbon in forests: current status and future challenges. *Environmental Pollution* 116: 363–372.
- Byambadorj, S. O., Chiatante, D., Akhmadi, K., Luntén, J., Ochirbat, B., Park, B. B., Scippa, G. S., Montagnoli, A. and Nyam-Osor, B.** 2020. The effect of different watering regimes and fertilizer addition on the growth of tree species used to afforest the semi-arid steppe of Mongolia. *Plant Biosystems – An International Journal Dealing with all Aspects of Plant Biology* 155(4): 747–758; <https://doi.org/10.1080/11263504.2020.1779845>.
- Byambadorj, S.-O., Nyam-Osor, B., Park, B. B., Avirmed, Ts., Scippa, G. S. and Chiatante, D.** 2021. Afforestation of Mongolian steppe: patterns of biomass partitioning in *Populus sibirica* and *Ulmus pumila* trees in response to management supporting measures. *Plant Biosystems – An International Journal Dealing with all Aspects of Plant Biology* 156(4): 969–981; <https://doi.org/10.1080/11263504.2021.1985002>.
- Cannon, W. A.** 1949. A tentative classification of root systems. *Ecology* 30: 542–548.
- Chang, E., Li, P., Li, Z., Xiao, L., Zhao, B., Su, Y. and Feng, Z.** 2019. Using water isotopes to analyse water uptake during vegetation succession on abandoned cropland on the Loess Plateau, China. *Catena* 181: 104095; <https://doi.org/10.1016/j.catena.2019.104095>.
- Chave, J., Andalo, C., Brown, S., Cairns, M. A., Chambers, J. Q., Eamus, D., Folster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.-P., Nelson, B. W., Ogawa, H., Puig, H., Riéra, B. and Yamakura, T.** 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* 145: 87–99; <https://doi.org/10.1007/s00442-005-0100-x>.
- Chen, S., Huang, Y., Zou, J. and Shi, Y.** 2013. Mean residence time of global topsoil organic carbon depends on temperature, precipitation and soil nitrogen. *Global Planet Change* 100: 99–108; <https://doi.org/10.1016/j.gloplacha.2012.10.006>.
- Chiatante, D., Di Iorio, A., Sciandra, S., Scippa, G. S. and Mazzoleni, S.** 2006. Effect of drought and fire on root development in *Quercus pubescens* Willd. and *Fraxinus ornus* L. seedlings. *Environmental and Experimental Botany* 56: 190–197; <https://doi.org/10.1016/j.envexpbot.2005.01.014>.
- Chiatante, D., Di Iorio, A. and Scippa, G. S.** 2005. Root responses of *Quercus ilex* L. seedlings to drought and fire. *Plant Biosystems* 139: 198–208; <https://doi.org/10.1080/11263500500160591>.
- Cho, S., Ser-Oddamba, B., Batkhuu, N.-O. and Kim, H. S.** 2019. Comparison of water use efficiency and biomass production in 10-year-old *Populus sibirica* and *Ulmus pumila* plantations in Lun soum, Mongolia. *Forest Science and Technology* 15(3): 147–158; <https://doi.org/10.1080/21580103.2019.1634646>.
- Di Iorio, A., Montagnoli, A., Scippa, G. S. and Chiatante, D.** 2011. Fine root growth of *Quercus pubescens* seedlings after drought stress and fire disturbance. *Environmental and Experimental Botany* 74: 272–279; <https://doi.org/10.1016/j.envexpbot.2011.06.009>.
- Dress, W. J. and Boerner, R. E. J.** 2001. Methods of calculating fine root production in forests. In: Fitter, A. H. (Ed.) *Ecological interactions in the soil*. London (U.K.): Wiley, p. 37–41.
- Du, H., Lu, L., Liang, S., Zeng, F., Wang, K. and Peng, W.** 2019. Seasonal changes and vertical distribution of fine root biomass during vegetation restoration in a karst area, southwest China. *Frontiers in Plant Science* 9: 2001; <https://doi.org/10.3389/fpls.2018.02001>.
- Fairley, R. I. and Alexander, I. J.** 1985. Methods of calculating fine root production in forests. In: Fitter, A. H., Atkinson, D. and Read, D. J. (Eds.) *Ecological interactions in soil: plants, microbes and animals*. Oxford: Blackwell, p. 37–42.
- FAO and ITPS. 2020. Global Soil Organic Carbon Map, V. 1.5: Technical Report. Rome: FAO, 168 pp.; <https://doi.org/10.4060/ca7597en>.
- Finér, L., Helmisaari, H. S., Lohmus, K., Majdi, H., Brunner, I., Børja, I., Eldhuset, T., Godbold, D., Grebenc, T., Konopka, B., Kraigher, H., Mottonen, M. R., Ohashi, M., Oleksyn, J., Ostonen, I., Uri, V. and Vanguelova, E.** 2007. Variation in fine root biomass of three European tree species: Beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* L. Karst.), and Scots pine (*Pinus sylvestris* L.). *Plant Biosystems – An International Journal Dealing with all Aspects of Plant Biology* 141: 394–405; <https://doi.org/10.1080/11263500701625897>.
- Finér, L., Ohashi, M., Noguchi, K. and Hirano, Y.** 2011. Fine root production and turnover in forest ecosystems in relation to stand and environmental characteristics. *Forest Ecology and Management* 262: 2008–2023; <https://doi.org/10.1016/j.foreco.2011.08.042>.
- Fitzsimmons, M.** 2003. Effects of deforestation and reforestation on landscape spatial structure in boreal Saskatchewan, Canada. *Forest Ecology and Management* 174(3): 577–592; [https://doi.org/10.1016/S0378-1127\(02\)00067-1](https://doi.org/10.1016/S0378-1127(02)00067-1).
- Gill, A. R. and Jackson, R. B.** 2000. Global patterns of root turnover for terrestrial ecosystems. *New Phytologist* 147: 13–31; <https://doi.org/10.1046/j.1469-8137.2000.00681.x>.
- Gower, S. T., Kucharik, C. J. and Norman, J. M.** 1999. Direct and indirect estimation of leaf area index, fAPAR, and net primary production of terrestrial ecosystems. *Remote Sensing of Environment* 70: 29–51; [https://doi.org/10.1016/S0034-4257\(99\)00056-5](https://doi.org/10.1016/S0034-4257(99)00056-5).
- Hammer, Ø., Harper, D. A. T. and Ryan, P. D.** 2001. PAST: Paleontological Statistics Software Package for Education and Data Analysis, Version 4.03. *Palaeontologia Electronica* 4(1): 4, 9 pp., 178 kb. Available online at: [https://palaeo-electronica.org/2001\\_1/past/past.pdf](https://palaeo-electronica.org/2001_1/past/past.pdf).
- Helmisaari, H. S., Makkonen, K., Kellomäki, S., Valtonen, E. and Mäliköinen, E.** 2002. Below- and above-ground biomass, production and nitrogen use in Scots pine stands in eastern Finland. *Forest Ecology and Management* 165: 317–326; [https://doi.org/10.1016/S0378-1127\(01\)00648-X](https://doi.org/10.1016/S0378-1127(01)00648-X).
- Hendrick, R. L. and Pregitzer, K. S.** 1993. The dynamics of fine-root length, biomass, and nitrogen content in two northern hardwood ecosystems. *Canadian Journal of Forest Research* 23: 2507–2520; <https://doi.org/10.1139/x93-312>.
- Himmelbauer, M. L., Loiskandl, W. and Rouseva, S.** 2010. Spatial root distribution and water uptake of maize grown on field with subsoil compaction. *Journal of Hydrology and Hydromechanics* 58(3): 163–174; <https://doi.org/10.2478/v10098-010-0015-z>.
- Hong, S. B., Piao, Sh., Chen, A., Liu, Y., Liu, L., Shushi, P., Sardans, J., Yan, S., Peñuelas, J. and Zeng, H.** 2018. Afforestation neutralizes soil pH. *Nature Communications* 9: 520; <https://doi.org/10.1038/s41467-018-02970-1>.
- Howard, E. A., Gower, S. T., Foley, J. A. and Kucharik, C. J.** 2004. Effects of logging on carbon dynamics of a jack pine forest in Saskatchewan, Canada. *Global Change Biology* 10(8): 1267–1284; <https://doi.org/10.1111/j.1529-8817.2003.00804.x>.
- Huang, G., Zhao, X. Y., Li, Y. Q. and Cui, J. Y.** 2012. Restoration of shrub communities elevates organic carbon in arid soils of northwestern China. *Soil Biology and Biochemistry* 47: 123–132; <https://doi.org/10.1016/j.soilbio.2011.12.025>.

- IPCC. 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry. By: Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., and Wagner, F. (Eds.). Hayama, Kanagawa (Japan): Institute for Global Environmental Strategies (IGES) for the IPCC, 590 pp. Available online at: <https://www.ipcc-nggip.iges.or.jp/public/gpplulucf/gpplulucf.html>.
- ISO 11464. 2006. Soil Quality-Pretreatment of Samples for Physico-Chemical Analysis (International Standard ISO 11464:2006). Vernier, Geneva. URL: <https://www.iso.org/standard/37718.html>.
- Jackson, R. B., Mooney, H. A. and Schulze, E. D.** 1997. A global budget for fine-root biomass, surface area, and nutrient contents. *Proceedings of the National Academy of Sciences* 94: 7362–7366; <https://doi.org/10.1073/pnas.94.14.7362>.
- Jia, X., Wang, X., Hou, L., Wei, X., Zhang, Y., Shao, M. and Zhao, X.** 2019. Variable response of inorganic carbon and consistent increase of organic carbon as a consequence of afforestation in areas with semiarid soils. *Land Degradation and Development* 30: 1345–1356; <https://doi.org/10.1002/ldr.3320>.
- Jobbagy, E. and Jackson, R.** 2000. The Vertical Distribution of Soil Organic Carbon and its Relation to Climate and Vegetation. *Ecological Applications* 10: 423–436; <https://doi.org/10.2307/2641104>.
- Joslin, J. D., Wolfe, M. H. and Hanson, P. J.** 2000. Effects of altered water regimes on forest root systems. *New Phytologist* 147: 117–129; <https://doi.org/10.1046/j.1469-8137.2000.00692.x>.
- Kilmer, V. J. and Mullins, J. F.** 1954. Improved stirring and pipetting apparatus for mechanical analysis for soils. *Soil Science* 77: 437–441.
- King, J. S., Albaugh, T. J., Allen, H. L., Buford, M., Strain, B. R. and Dougherty, P.** 2002. Below-ground carbon input to soil is controlled by nutrient availability and fine root dynamics in loblolly pine. *New Phytologist* 154: 389–398; <https://doi.org/10.1046/j.1469-8137.2002.00393.x>.
- Lai, Z., Zhang, Y., Liu, J., Wu, B., Qin, S. and Fa, K.** 2016. Fine-root distribution, production, decomposition, and effect on soil organic carbon of three revegetation shrub species in northwest China. *Forest Ecology and Management* 359: 381–388; <https://doi.org/10.1016/j.foreco.2015.04.025>.
- Laliberté, E.** 2017. Below-ground frontiers in trait-based plant ecology. *New Phytologist* 213: 1597–1603; <https://doi.org/10.1111/nph.14247>.
- Li, C. H., Li, Y. and Tang, L. S.** 2010. Soil organic carbon stock and carbon efflux in deep soils of desert and oasis. *Environmental Earth Sciences* 60(3): 549–557; <https://doi.org/10.1007/s12665-009-0195-1>.
- Li, S., Su, J., Liu, W., Lang, X., Huang, X., Jia, C., Zhang, Z. and Tong, Q.** 2015. Changes in biomass carbon and soil organic carbon stocks following the conversion from a secondary coniferous forest to a pine plantation. *PLOS One* 10(9): e0135946; <https://doi.org/10.1371/journal.pone.0135946>.
- Liu, J. X., Liu, G. B., Flanagan, D. C., Wang, B., Wang, Z. Y. and Xiao, J.** 2019. Effects of soil-incorporated plant litter morphological characteristics on the soil detachment process in grassland on the Loess Plateau of China. *Science of The Total Environment* 705: 134651; <https://doi.org/10.1016/j.scitotenv.2019.134651>.
- Ma, X. Z., Wang, X. P., Jin, Y. X. and Zhang, Y. F.** 2021. Fine root production, turnover of *Reaumuria songarica* and soil carbon and nitrogen in Alxa steppe desert of NW China. *Society for Ecological Restoration* 29(6): e13362; <https://doi.org/10.1111/rec.13362>.
- McClougherty, C. A., Aber, J. D. and Melillo, J. M.** 1982. The role of fine roots in the organic matter and nitrogen budgets of two forested ecosystems. *Ecology* 63: 1481–1490.
- McCormack, M. L., Dickie, I. A., Eissenstat, D. M., Fahney, T. J., Fernandez, C. W., Guo, D., Helmisaari, H. S., Hobbie, E. A., Iversen, C. M., Jackson, R. B., Leppälammil-Kujansuu, J., Norby, R. J., Phillips, R. P., Pregitzer, K. S., Pritchard, S. G., Rewald, B. and Zadworny, M.** 2015. Redefining fine roots improves understanding of belowground contributions to terrestrial biosphere processes. *New Phytologist* 207: 505–518; <https://doi.org/10.1111/nph.13363>.
- MNET. 2020. Mongolyn tsöljiltiin atlas [Desertification atlas of Mongolia]. The Ministry for Nature, Environment and Tourism. Ulaanbaatar: Toonot, p. 15 (in Mongolian).
- MNS 3310. 1991. Khörs: Khörsnii agrokhimiiin shinj channaruud Shinjilgeenii arguud [Soil: Soil Agrochemical Properties Analysing Methods]. (Mongolian National Standard 3310:1991). Ulaanbaatar: MEMS. URL: <https://estandard.gov.mn/website/masm/standards.aspx?search=3310%3A1991>.
- MNS ISO 10390. 2001. Khörsnii chanar: rN-iig todorkhoilokh [Soil Quality: Determination of pH] (Mongolian National Standard ISO 10390:2001). Ulaanbaatar: MASM, URL: <https://estandard.gov.mn/website/masm/standards.aspx?search=10390%3A2001>.
- Mohit, H., Jagdeesh, P. R., Aatifa, R., Aafaq, A. P., Dinesh, K. V. and Kolagani, M.** 2018. Seabuckthorn: A multi-purpose shrubs species in Ladakh cold desert. *Journal of Entomology and Zoology Studies* 6(2): 1330–1337.
- Montagnoli, A., Di Iorio, A., Terzaghi, M., Scippa, G. S. and Chiatante, D.** 2018. Effect of tree density on root distribution in *Fagus sylvatica* stands: a semi-automatic digitizing device approach to trench wall method. *Trees* 27: 1503–1513; <https://doi.org/10.1007/s00468-013-0897-6>.
- Montagnoli, A., Lasserre, B., Terzaghi, M., Byambadorj, S.-O., Nyam-Osor, B., Scippa, G. S. and Chiatante, D.** 2022. Fertilization reduces root architecture plasticity in *Ulmus pumila* used for afforesting Mongolian semi-arid steppe. *Frontiers Plant Science* 13: 878299; <https://doi.org/10.3389/fpls.2022.878299>.
- Montagnoli, A., Terzaghi, M., Di Iorio, A., Scippa, G. S. and Chiatante, D.** 2012. Fine-root morphological and growth traits in a Turkey-oak stand in relation to seasonal changes in soil moisture in the Southern Apennines, Italy. *Ecological Research* 27: 1015–1025; <https://doi.org/10.1007/s11284-012-0981-1>.
- Nadelhoffer, K. J. and Raich, J. W.** 1992. Fine root production estimates and belowground carbon allocation in forest ecosystems. *Ecology* 73: 1139–1147.
- NAMEM. 2020. Weather data 2010–2020. The National Agency for Meteorology and Environmental Monitoring of Mongolia. Available online at: <http://namem.gov.mn/eng/?p=56> (retrieved on 20 October, 2020).
- Nyam-Osor, B., Byambadorj, S.-O., Byung, B. P., Terzaghi, M., Scippa, G., Chiatante, D. and Montagnoli, A.** 2021. Root Biomass Distribution of *Populus sibirica* and *Ulmus pumila* Afforestation Stands Is Affected by Watering Regimes and Fertilization in the Mongolian Semi-arid Steppe. *Frontiers in Plant Science* 12: 638828; <https://doi.org/10.3389/fpls.2021.638828>.
- Olesinski, J., Lavigne, M. B. and Krasowski, M. J.** 2011. Effects of soil moisture manipulations on fine root dynamics in a mature balsam fir (*Abies balsamea* L. Mill.) forest. *Tree Physiology* 31: 339–348; <https://doi.org/10.1093/treephys/tpr006>.

- Pei, Z. Q., Zhou, Y., Zheng, Y. R. and Xiao, C. W. 2011. Contribution of fine root turnover to the soil organic carbon cycling in a *Reaumuria soongorica* community in an arid ecosystem of Xinjiang Uygur autonomous region, China. *Chinese Journal of Plant Ecology* 35: 1182–1191; <https://doi.org/10.3724/SP.J.1258.2011.01182>.
- Perez-Quezada, J. F., Delpiano, C. A. and Snyder, K. A. 2011. Carbon pools in an arid shrubland in Chile under natural and afforested conditions. *Journal of Arid Environments* 75(1): 29–37; <https://doi.org/10.1016/j.jaridenv.2010.08.003>.
- Phillips, D. L., Johnson, M. G., Tingey, D. T., Catricala, C. E., Hoyman, T. L. and Nowak, R. S. 2006. Effects of elevated CO<sub>2</sub> on fine root dynamics in a Mojave Desert community: a FACE study. *Global Change Biology* 12: 61–73; <https://doi.org/10.1111/j.1365-2486.2005.01085.x>.
- Picard, N., Henry, M., Mortier, F., Trotta, C. and Saint-Andre, L. 2012. Using Bayesian Model Averaging to Predict Tree Aboveground Biomass in Tropical Moist Forests. *Forest Science* 58: 15–23; <https://doi.org/10.5849/forsci.10-083>.
- Pinno, B. D., Wilson, S. D., Steinaker, D. F., Van Rees, K. C. J. and McDonald, S. A. 2010. Fine root dynamics of trembling aspen in boreal forest and aspen parkland in central Canada. *Ann Forest Science* 67: 710–716; <https://doi.org/10.1051/forest/2010035>.
- Ponder, F. Jr. and Alley, D. E. 1997. Soil sampler for rocky soils. Research Note NC-371. St. Paul, MN: U.S. Dept. of Agriculture, Forest Service, North Central Forest Experiment Station, 5 pp.; <https://doi.org/10.2737/NC-RN-371>.
- Qian, Y. B., Zhang, H. Y. and Wu, Z. N. 2011. Vegetation composition and distribution on the northern slope of Karlik Mountain to Naomaohu basin, East Tianshan Mountains. *Journal of Arid Land* 3(1): 15–24; <https://doi.org/10.3724/SP.J.1227.2011.00015>.
- R Core Team 2023. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: <https://www.R-project.org>.
- Röderstein, M., Hertel, D. and Leuschner, C. 2005. Above- and below-ground litter production in three tropical montane forests in southern Ecuador. *Journal of Tropical Ecology* 21: 483–492; <https://doi.org/10.1017/S026646740500249X>.
- SAS Institute, Inc. 2023. SAS software, Version 9.4 [Computer software]. SAS Institute Inc., 100 SAS Campus Drive, Cary, North Carolina, 27513, USA. URL: <https://www.sas.com>.
- Schimel, D. S., Braswell, B. H., Holland, E. A., Mckeown, R., Ojima, D. S., Painter, T. H., Parton, W. J. and Townsend, A. R. 1994. Climatic, edaphic, and biotic controls over storage and turnover of carbon in soils. *Global Biogeochemical Cycles* 8(3): 279–293.
- Shahzad, T., Chenu, C., Genet, P., Barot, S., Perveen, N., Mougin, C. and Fontaine, S. 2015. Contribution of exudates, arbuscular mycorrhizal fungi and litter depositions to the rhizosphere priming effect induced by grassland species. *Soil Biology and Biochemistry* 80: 146–155; <https://doi.org/10.1016/j.soilbio.2014.09.023>.
- Shuai, Q., Xue, J., Dai, L., Huang, Y., Jin, D., Chen, Z., Li, M., Shi, Z. and Chen, S. 2024. The effects of land use change on soil organic carbon stock in China: A meta-analysis with the empirical modeling approach. *Geoderma Regional* 36: e00774; <https://doi.org/10.1016/j.geodrs.2024.e00774>.
- Silver, W. L., Ostertag, R. and Lugo, A. E. 2000. The potential for carbon sequestration through reforestation of abandoned tropical agricultural and pasture lands. *Restoration Ecology* 8(4): 394–407; <https://doi.org/10.1046/j.1526-100x.2000.80054.x>.
- Singh, K., Pandey, V. C., Singh, B. and Singh, R. R. 2012. Ecological restoration of degraded sodic lands through afforestation and cropping. *Ecological Engineering* 43: 70–80; <https://doi.org/10.1016/j.ecoleng.2012.02.029>.
- Smith, P., Powlson, D. S., Smith, J. U., Falloon, P. and Coleman, K. 2000. Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture. *Global Change Biology* 6: 525–539; <https://doi.org/10.1046/j.1365-2486.2000.00331.x>.
- Soil Survey Staff. 2014. Kellogg Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No. 42, Version 5.0. Burt, R. and Soil Survey Staff (Eds.) USDA and NRCS, p. 610–613, 674. Available online at: <https://www.nrcs.usda.gov/sites/default/files/2023-01/SSIR42.pdf>.
- Staszal, K., Blonska, E. and Lasota, J. 2022. Fine root morphology and soil properties under influence of different tree stands along an altitudinal climosequence in the Carpathian Mountains. *Forest Ecosystems* 9: 100066; <https://doi.org/10.1016/j.fecs.2022.100066>.
- Steele, S. J., Gower, S. T., Vogel, J. G. and Morman, J. M. 1997. Root mass, net primary production and turnover in aspen, jack pine and black spruce forests in Saskatchewan and Manitoba. *Tree Physiology* 17: 577–587; <https://doi.org/10.1093/treephys/17.8-9.577>.
- Systat Software, Inc. 2013. SigmaPlot for Windows. Version 12.5 [Computer software]. Systat Software, Inc., 1735 Technology Dr, Ste 430, San Jose, California 95110, USA. URL: [www.systatsoftware.com](http://www.systatsoftware.com).
- Tang, Y., Liu, X., Lian, J., Cheng, X., Wang, G. G. and Zhang, J. 2023. Soil Depth Can Modify the Contribution of Root System Architecture to the Root Decomposition Rate. *Forests* 14: 1092; <https://doi.org/10.3390/f14061092>.
- Tian, S., Liu, X., Jin, B. and Zhao, X. 2022. Contribution of Fine Roots to Soil Organic Carbon Accumulation in Different Desert Communities in the Sangong River Basin. *International Journal of Environmental Research and Public Health* 19: 10936; <https://doi.org/10.3390/ijerph191710936>.
- Tracy, S. R., Black, C. R., Roberts, J. A. and Mooney, S. J. 2013. Exploring the interacting effect of soil texture and bulk density on root system development in tomato (*Solanum lycopersicum* L.). *Environmental Experimental Botany* 91: 38–47; <https://doi.org/10.1016/j.envexpbot.2013.03.003>.
- Ulziikhutag, N. 1989. Mongolyn urgamlyn aimgiin toim [Outline of Mongolian Flora]. Ulaanbaatar: State Press Publishing House, 208 pp. (in Mongolian).
- Vogt, K. A. and Persson, H. 1991. Measuring growth and development of roots. In: Lassoie, J. P. and Hinkley, T. M. (Eds.) Techniques and approaches in forest tree ecophysiology. Boca Raton (FL, USA): CRC Press, p. 477–501.
- Walkley, A. and Black, I. A. 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science* 37(1): 29–38.
- Walter, K., Don, A., Tiemeyer, B. and Freibauer, A. 2016. Determining soil bulk density for carbon stock calculations: a systematic method comparison. *Soil Science Society of America Journal* 80(3): 579–591; <https://doi.org/10.2136/sssaj2015.11.0407>.
- Wang, C., Han, S., Zhou, Y., Yan, C., Cheng, X., Zheng, X. and Li, M. H. 2012. Responses of Fine Roots and Soil N Availability to Short-Term Nitrogen Fertilization in a Broad Leaved Korean Pine Mixed Forest in Northeastern China. *PLOS One* 7: e31042; <https://doi.org/10.1371/journal.pone.0031042>.
- Wang, J., Zhao, X. C., Lai, L. M., Zhu, L. H., Wang, Y. J. and Zhou, J. H. 2014. Contribution of fine root production and turnover to soil organic carbon in *Tamarix ramosissima*

- community in Sangong river basin of Xinjiang, China. *Forestry Research* 27(6): 809–814; <https://doi.org/10.13275/j.cnki.lykxyj.2014.06.016>.
- Wang, K., Zhang, R., Song, L., Yan, T. and Na, E.** 2021. Comparison of C:N:P Stoichiometry in the Plant-Litter-Soil System Between Poplar and Elm Plantations in the Horqin Sandy Land, China. *Front. Plant Science* 12: 655517; <https://doi.org/10.3389/fpls.2021.655517>.
- Wang, S., Zhuang, Q., Yang, Z., Yu, N., and Jin, X.** 2019. Temporal and Spatial Changes of Soil Organic Carbon Stocks in the Forest Area of Northeastern China. *Forest* 10(11): 1023; <https://doi.org/10.3390/f10111023>.
- Wang, X., Zhang, C., Hasi, E. and Dong, Z.** 2010. Has the three Norths Forest Shelterbelt Program solved the desertification and dust storm problems in arid and semiarid China? *Journal of Environmental and Science* 74: 13e22; <https://doi.org/10.1016/j.jaridenv.2009.08.001>.
- Wang, Y., Fu, B., Lü, Y. and Chen, L.** 2011. Effects of vegetation restoration on soil organic carbon sequestration at multiple scales in semi-arid Loess Plateau, China. *CATENA* 85(1): 58–66; <https://doi.org/10.1016/j.catena.2010.12.003>.
- Wang, Y.G., Li, Y. and Ye, X.H.** 2010. Profile storage of organic/inorganic carbon in soil: From forest to desert. *Science of the Total Environment* 408(8): 1925–1931; <https://doi.org/10.1016/j.scitotenv.2010.01.015>.
- Wang, Y., Lv, W., Xue, K., Wang, S., Zhang, L., Hu, R., Zeng, H., Xu, X., Li, Y., Jiang, L., Hao, Y., Du, J., Sun, J., Dorji, T., Piao, S., Wang, C., Luo, C., Zhang, Z., Chang, X., Zhang, M., Hu, Y., Wu, T., Wang, J., Li, B., Liu, P., Zhou, Y., Wang, A., Dong, S., Zhang, X., Gao, Q., Zhou, H., Shen, M., Wilkes, A., Miehe, G., Zhao, X. and Niu, H.** 2022. Grassland changes and adaptive management on the Qinghai-Tibetan plateau. *Nature Reviews Earth Environment* 3(10): 668–683; <https://doi.org/10.1038/s43017-022-00330-8>.
- Wickham, H.** 2016. *ggplot2: Elegant Graphics for Data Analysis*. Cham: Springer, 260 pp.; <https://doi.org/10.1007/978-3-319-24277-4>.
- Wu, G.L., Liu, Z.H. and Zhang, L.** 2010. Long-term fencing improved soil properties and soil organic carbon storage in an alpine swamp meadow of western China. *Plant and Soil* 332(1/2): 331–337; <https://doi.org/10.1007/s11104-010-0299-0>.
- Xu, H., Yue, C., Zhang, Y., Liu, D. and Piao, S.** 2023. Forestation at the right time with the right species can generate persistent carbon benefits in China. *Proceedings of the National Academy of Sciences* 120(41): e2304988120; <https://doi.org/10.1073/pnas.2304988120>.
- Ye, G., Ma, Y., Feng, Z. and Zhang, X.** 2018. Transcriptomic analysis of drought stress responses of sea buckthorn (*Hippophae rhamnoides* subsp. *sinensis*) by RNA-Seq. *PLOS One* 13: 1–19; <https://doi.org/10.1371/journal.pone.0202213>.
- Yuan, J., Ouyang, Z., Zheng, H. and Su, Y.** 2021. Ecosystem carbon storage following different approaches to grassland restoration in south-eastern Horqin Sandy Land, northern China. *Global Ecology and Conservation* 26: e01438; <https://doi.org/10.1016/j.gecco.2020.e01438>.
- Zang, C., Tang, Y., Xu, X. and Kiely, G.** 2011. Toward spatial geochemical modelling; Use of geographically weighted regression for mapping soil organic carbon contents in Ireland. *Applied Geochemistry* 26(7): 1239–1248; <https://doi.org/10.1016/j.apgeochem.2011.04.014>.
- Zhang, X., Xu, D., Wang, Z. and Zhang, Y.** 2021. Balance of water supply and consumption during ecological restoration in arid regions of Inner Mongolia, China. *Journal of Arid Environments* 186: 104406; <https://doi.org/10.1016/j.jaridenv.2020.104406>.
- Zhang, X., Zhang, F., Wang, D., Fan, J., Hu, Y., Kang, H., Chang, M., Pang, Y., Yang, Y. and Feng, Y.** 2018. Effects of vegetation, terrain and soil layer depth on eight soil chemical properties and soil fertility based on hybrid methods at urban forest scale in a typical loess hilly region of China. *PLOS One* 13(10): e0205661; <https://doi.org/10.1371/journal.pone.0205661>.
- Zhang, Y., Li, P., Liu, X., Xiao, L., Li, T. and Wang, D.** 2019a. The response of soil organic carbon to climate and soil texture in China. *Frontiers in Earth Science* 16: 835–845; <https://doi.org/10.1007/s11707-021-0940-7>.
- Zhang, Y., Li, P., Liu, X., Xiao, L., Shi, P. and Zhao, B.** 2019b. Effects of farmland conversion on the stoichiometry of carbon, nitrogen, and phosphorus in soil aggregates on the Loess Plateau of China. *Geoderma* 351: 188–196; <https://doi.org/10.1016/j.geoderma.2019.05.037>.
- Zhao, N. and Li, X.G.** 2017. Effects of aspect-vegetation complex on soil nitrogen mineralization and microbial activity on the Tibetan Plateau. *Catena* 155: 1–9; <https://doi.org/10.1016/j.catena.2017.02.025>.
- Zhao, Q., Zeng, D.H. and Fan, Z.P.** 2010. Nitrogen and phosphorus transformations in the rhizospheres of three tree species in a nutrient-poor sandy soil. *Applied Soil Ecology* 46: 341–346; <https://doi.org/10.1016/j.apsoil.2010.10.007>.
- Zhao, Q., Zeng, D.H., Fan, Z.P. and Lee, D.K.** 2008. Effect of land cover change on soil phosphorus fractions in Southeastern Horqin Sandy Land, Northern China. *Pedosphere* 18: 741–748; [https://doi.org/10.1016/S1002-0160\(08\)60069-7](https://doi.org/10.1016/S1002-0160(08)60069-7).
- Zhou, S., Yin, Y., Xu, W., Ji, Z., Caldwell, I. and Ren, J.** 2006. The costs and benefits of reforestation in Liping County, Guizhou Province, China. *Journal of Environmental Management* 85(3): 722–735; <https://doi.org/10.1016/j.jenvman.2006.08.014>.
- Zhou, X., Tian, L., Zhang, J.F., Ma, L.N., Li, X.J. and Tian, C.J.** 2017. Rhizospheric fungi and their link with the nitrogen-fixing *Frankia* harbored in host plant *Hippophae rhamnoides* L. *Journal of Basic Microbiology* 57: 1055–1064; <https://doi.org/10.1002/jobm.201700312>.
- Zhu, W.B., Lv, A. and Jia, S.F.** 2011. Spatial distribution of vegetation and the influencing factors in Qaidam Basin based on NDVI. *Journal of Arid Land* 3(2): 85–93; <https://doi.org/10.3724/SP.J.1227.2011.00085>.
- Zobel, R.W. and Waisel, Y.** 2010. A plant root system architectural taxonomy: a framework for root nomenclature. *Plant Biosystems – An International Journal Dealing with all Aspects of Plant Biology* 144(2): 507–512; <https://doi.org/10.1080/11263501003764483>.