Fine root biomass differs significantly across different forest types and soil depth in Central Himalaya, India

Harish Bahadur Chand[1,*], Ganesh Joshi[2], Roshan Prasad Bhatta[3], Sanjay Singh[4], Abhishek Kumar[1], Nabin Raj Joshi[5] and Ramesh Bohara[2]

[1]Forest Research Institute (Deemed to be University), Dehradun 248 001, India
[2]Department of Forestry and Environmental Science, Kumaun University, Nainital 263 001, India
[3]Institute of Forestry, Pokhara 33700, Nepal
[4]Indian Council of Forestry Research and Education, Dehradun 248 001, India
[5]Asia Network for Sustainable Agriculture and Bioresources, Kathmandu 44600, Nepal

Fine roots (diameter less than 2 mm) comprise a significant portion of the plant biomass. They are important for water absorption, cycling of nutrients and the carbon budget on a global scale. The aim of the present study was to quantify fine root biomass in the Nainital district, Central Himalaya, India, which has several dominant forest types. A total of 81 samples were collected from nine sample plots for each forest type in three distinct directions. The results showed that sal forest (1.11 ± 0.04 t ha^{-1}) had the largest fine root biomass, followed by oak forest (0.72 ± 0.06 t ha^{-1}) and pine forest (0.61 ± 0.06 t ha^{-1}). We observed that the trend in fine root biomass across different forest types was as follows: sal forest > oak forest > pine forest, significant at 0.05 level. Fine root biomass was also observed to decrease similarly with increasing soil depth in each forest type, following the trend: 0–20 cm > 20–40 cm > 40–60 cm, which was significant at 0.05 level. Researchers will benefit from this study since it will help them comprehend fine root biomass variation and offer baseline data for future research on nutrient cycling and the global carbon budget.

Keywords: Forest types, global carbon budget, nutrient cycling, plant biomass, soil depth.

FINE roots (diameter less than 2 mm) represent an essential part of the forest ecosystem. They are a minor but functionally essential component of the plant biomass. Fine roots are essential for water intake, nutrient cycling and the production of specific growth hormones[1–4]. They significantly influence soil profile development and contribute substantially to soil organic carbon through root death and rhizodeposition[5]. Despite accounting for only a small proportion of the overall plant biomass, fine roots are estimated to account for 30% of above-ground biomass[6] and one-third of yearly worldwide net primary output[7,8].

Fine roots have a lifespan of weeks to years, depending on the species and environmental conditions[9]. According to the site, the production of fine roots, their biomass and turnover might vary significantly over seasons and/or across years[10,11]. Fine root biomass is influenced by the tree species, site and structure of the soil, how compact or airy it is, how far the roots can spread horizontally and vertically and how deep they can grow, as well as the competition among trees of the same species[12]. In forests, the average yearly loss of the fine root system is estimated to range between 40% and 92%. Due to their high turnover, fine roots add 2–5 times more organic matter to the soil than the above-ground components[13].

The international scientific community has made studying the responses of the terrestrial ecosystem to global change a priority. Estimating the fine root biomass of forests is becoming more important because of its role in the carbon budget of ecosystems, biogeochemical cycling, and a possible role of fine root vitality as an indicator of the physical and chemical state of the soil and how it changes over time[14]. Furthermore, difficulty in obtaining valid estimates of fine root growth has restricted the accuracy of nutrient and energy estimates for forest ecosystems[15–17]. Despite their importance, sampling fine roots takes a longer time, and accurate estimates have been difficult to monitor by researchers. So, fine roots are one of the challenging and most useful features to study in terrestrial ecosystems.

The Himalayan region is expected to get warmer by 2.6°–4.6°C by the end of the 21st century, according to several CMIP5 models[18]. Climate change-related variations in fine root development might alter nutrient availability in forests, impacting the overall production. As a result, precise fine root biomass estimations are critical in enhancing carbon budgeting models[19]. Despite the valuable importance of fine roots in the growth of plants and the amount of tree biomass, there have been limited studies on fine roots biomass. The study aimed to quantify the fine root biomass across different selected forest types of the Nainital district, Central Himalaya, India.

*For correspondence. (e-mail: charish0136@gmail.com)

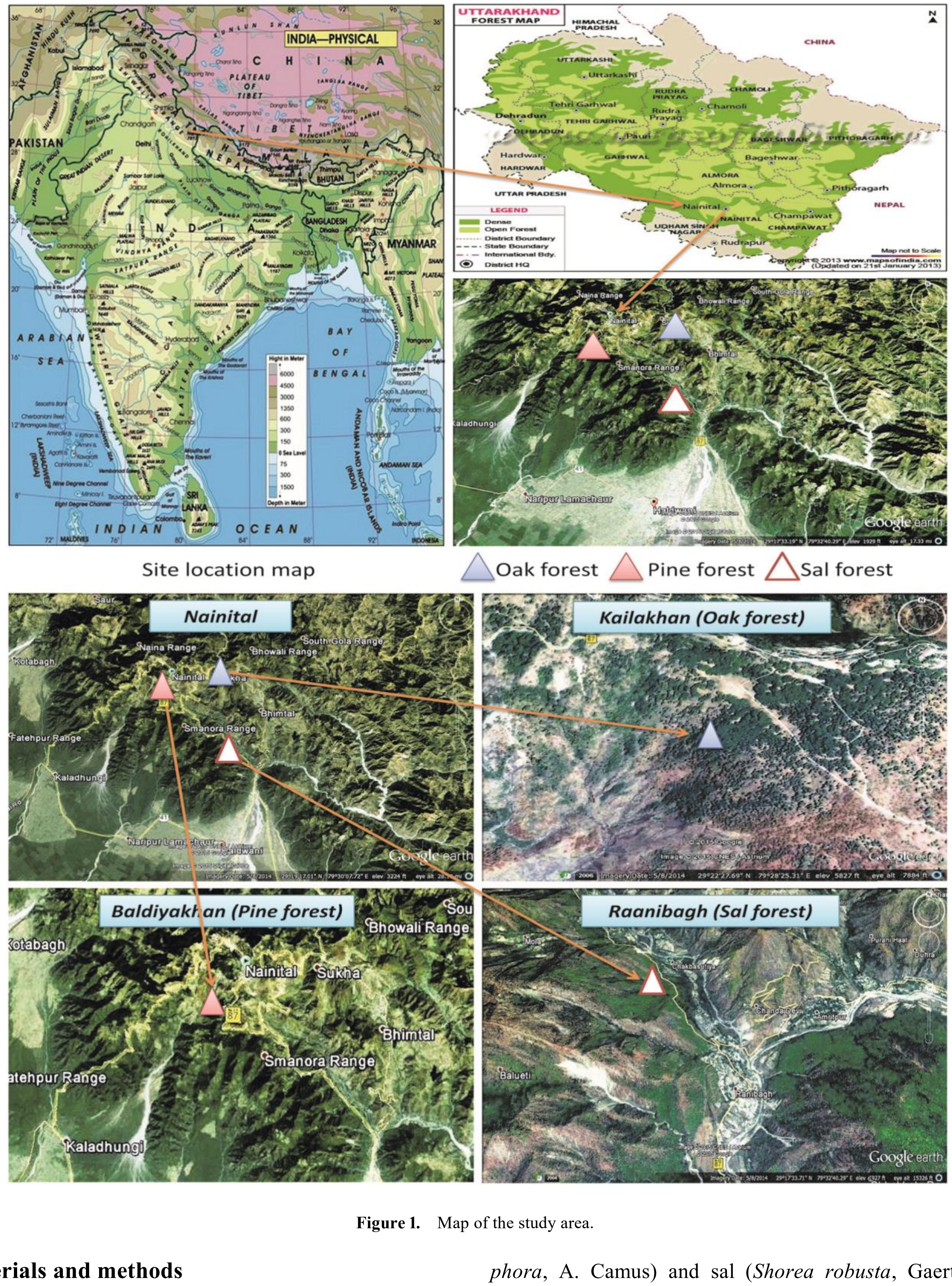

Figure 1. Map of the study area.

Materials and methods

Study site

This study was undertaken in three major dominant forests: pine (*Pinus roxburghii*, Sarg.), oak (*Quercus leucotrichophora*, A. Camus) and sal (*Shorea robusta*, Gaertn. F) (Figure 1). These are located in Kailakhan (29°24′N; 79°28′E), Baldiyakhan (29°22′N; 79°26′E) and Ranibagh (29°17′N; 79°32′E) respectively, at different altitudes ranging from 500 to 2100 m amsl. All the sites fall in the Reserved Forest category of the Nainital Forest Division.

Each forest represents varied species composition and structure. These forests have a diverse terrain, soil characteristics and climatic conditions from a lower to a higher elevation, representing sal followed by pine and oak forests in Central Himalaya.

Method

The sequential soil core method was used in the present study[12,20–22]. The method is based on volume metric samples excavated with a sharp-edged metallic tube called a soil core with a diameter of 7.62 cm (internal) and length of 90 cm (30 cm extra length kept to avoid hammering damage to the core). The soil core was divided into three depthwise sections: 0–20, 20–40 and 40–60 cm for each forest site. Altogether 81 samples were collected from nine plots for each forest type in three distinct directions during 2014–2015. Soil samples with roots were collected from each forest type at different depth intervals (0–20, 20–40 and 40–60 cm) using a 50 cm metallic rod with clear marked points at 20 and 40 cm. Soil coring was carried out randomly at 1, 2 and 4 m distances from a centrally chosen tree (reference point) in three distinct directions. The samples were tagged with unique identifiers and sent to the laboratory for additional processing.

Using a succession of sieves ranging from 1 to 5 mm, fine roots from each sample were sorted and separated from organic components contained in the soil. The fine roots were manually sifted and separated using forceps. The acquired roots were cleaned with flowing tap water. Next, fine roots (dead or alive) of 2 mm were air-dried for a few minutes before being separated individually using a ruler based on their colour and texture. For each sample, the fresh weight of the sorted fine root was determined (depthwise), packed in paper bags and oven-dried up to 60°C until it attained a constant temperature. Finally, the biomass was estimated by weighing the oven-dried fine roots using a volumetric sample size. The impact of soil depth and forest type on fine root biomass was studied using a one-way ANOVA.

Results

Descriptive analysis

Oak forest biomass for fine roots was estimated to be 0.72 ± 0.06 t ha^{-1} on average. As shown in Figure 2, the mean biomass for fine roots in pine and sal forests was 0.61 ± 0.06 t ha^{-1} and 1.11 ± 0.04 t ha^{-1} respectively. Table 1 provides the descriptive statistics of fine root biomass in different forest types.

Fine root biomass

Fine root biomass was measured at three separate sites (hilltop, hill mid and hill base) at three different soil depth intervals for each of the three forest types (oak, pine and sal-dominated forests) at 0–20, 20–40 and 40–60 cm.

Oak forest

Table 2 shows that the hilltop (2.494 ± 0.533 t ha^{-1}) had the highest total fine root biomass, followed by the hill base (2.048 ± 0.437 t ha^{-1}) and hill mid (1.960 ± 0.493 t ha^{-1}). The depthwise share of this total fine root biomass on the hilltop was 0.921 (36.9%), 1.185 (47.5%) and 0.388 t ha^{-1} (15.6%) along 0–20, 20–40 and 40–60 cm respectively. Similarly, the depthwise share of total fine root biomass in the hill base was 0.709 (34.6%), 0.958 (46.8%) and 0.380 t ha^{-1} (18.6%) and in hill mid was 1.002 (51.1%), 0.570 (29.1%) and 0.388 t ha^{-1} (19.8%) along the same depth intervals respectively. The trend of root mass in different soil depth intervals showed that most of the roots were in 20–40 cm in the oak-dominated forest; however, for the hill mid, most of the roots were located at 0–20 cm depth. Majority of roots were found in the upper area of the soil, according to observations at 0–40 cm soil depth. Table 2 depicts the fine root biomass in oak forest estimated in each sample plot at different soil depth intervals.

Pine forest

Hill base (1.894 ± 0.502 t ha^{-1}) had the highest total fine root biomass, followed by hilltop (1.894 ± 0.502 t ha^{-1}) and hill mid (1.499 ± 0.350 t ha^{-1}) in the pine-dominated forest (Table 3). Depthwise share of this total fine root biomass at the hilltop was 0.980 (51.7%), 0.490 (24.9%) and 0.424 t ha^{-1} (22.4%), along with 0–20, 20–40 and 40–60 cm respectively. Moreover, the depthwise share of total fine root biomass in the hill mid was 0.797 (53.2%), 0.395 (26.3%) and 0.307 t ha^{-1} (20.5%) and in the hill base was

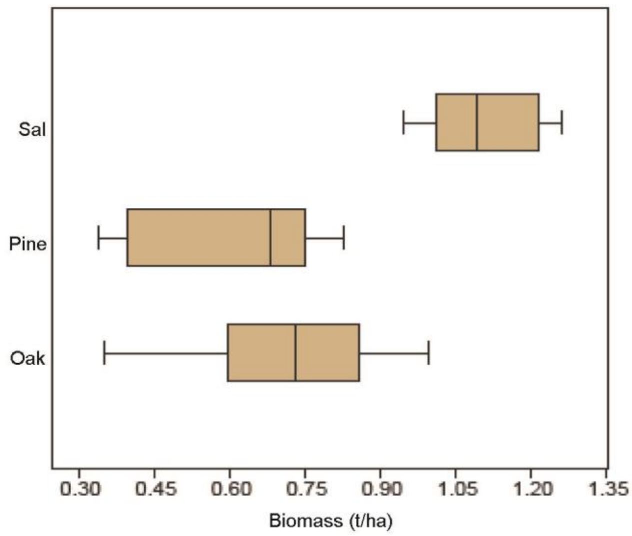

Figure 2. Box plot showing fine root biomass (t ha^{-1}) in different forest types.

Table 1. Descriptive statistics for fine root biomass in different forest types

Particulars	Forest type	Descriptive analysis	Statistic	Standard error
Biomass	Oak	Mean	0.722	0.06
		95% Confidence interval for mean		
		Lower bound	0.57	
		Upper bound	0.87	
		5% Trimmed mean	0.73	
		Median	0.73	
		Variance	0.04	
		Standard deviation	0.19	
		Minimum	0.35	
		Maximum	1.00	
		Range	0.64	
		Interquartile range	0.26	
		Skewness	–0.74	0.72
		Kurtosis	0.55	1.40
	Pine	Mean	0.61	0.06
		95% Confidence interval for mean		
		Lower bound	0.46	
		Upper bound	0.75	
		5% Trimmed mean	0.61	
		Median	0.68	
		Variance	0.03	
		Standard deviation	0.18	
		Minimum	0.34	
		Maximum	0.83	
		Range	0.49	
		Interquartile range	0.35	
		Skewness	–0.55	0.72
		Kurtosis	–1.48	1.40
	Sal	Mean	1.11	0.04
		95% Confidence interval for mean		
		Lower bound	1.02	
		Upper bound	1.20	
		5% Trimmed mean	1.11	
		Median	1.09	
		Variance	0.013	
		Standard deviation	0.11	
		Minimum	0.94	
		Maximum	1.26	
		Range	0.32	
		Interquartile range	0.20	
		Skewness	–0.23	0.72
		Kurtosis	–1.48	1.40

0.790 (38.3%), 0.863 (41.8%) and 0.410 t ha^{-1} (19.9%), along the same depth intervals respectively. The maximum share of root mass was at 0–20 cm soil depth interval for most of the sample plots, except at the hill base, where root mass was maximum at 20–40 cm soil depth interval. Table 3 shows the fine root biomass measured in each sample plot at various depth intervals in the pine forest.

Sal forest

As indicated in Table 4, the overall fine root biomass in sal-dominated forest was highest at the hill base (3.496 ± 0.475 t ha^{-1}), followed by hill mid (3.408 ± 0.518 t ha^{-1}) and hill top (3.108 ± 0.349 t ha^{-1}). The depthwise share in total biomass of fine roots in different soil depth intervals, i.e. 0–20, 20–40 and 40–60 cm was 1.338 (43.1%), 1.309 (42.1%) and 0.461 t ha^{-1} (14.8%) at the hilltop, 1.755 (51.5%), 1.112 (32.6%) and 0.541 t ha^{-1} (15.9%) in the hill mid, and 1.580 (45.2%), 1.338 (38.3%) and 0.483 t ha^{-1} (16.5%) at the hill base respectively. The largest root biomass in this forest was found in the top layer of the soil depth range, i.e. 0–20 cm in each study plot. Table 4 shows the fine root biomass measured in each sample plot at various depth intervals in the sal forest.

Statistical analysis

Before conducting ANOVA, the assumptions of normality of the data were tested. The kurtosis values and biomass skewness were within the range –1.96 to +1.96, indicating that the data are normally distributed. The test of normality for skewness and kurtosis is given in Supplementary

Table 2. Fine root biomass in oak forest (values inside parenthesis are percentage of contribution)

Forest	Forest site	Tree girth (cm)	Soil depth (cm)	Fine root biomass ($t\ ha^{-1}$) in each sample plot			Mean value ± SE ($t\ ha^{-1}$)
				I	II	III	
Oak	Hilltop	151	0–20	0.483	1.624	0.658	0.921 (36.9) ± 0.355
			20–40	1.053	1.141	1.360	1.185 (47.5) ± 0.091
			40–60	0.505	0.219	0.439	0.388 (15.6) ± 0.086
			Total	2.040	2.984	2.457	2.494 (100.0) ± 0.533
			Mean	0.680	0.995	0.819	0.831 (33.3) ± 0.091
	Hill mid	85	0–20	1.097	0.548	1.360	1.002 (51.1) ± 0.239
			20–40	0.702	0.307	0.702	0.570 (29.1) ± 0.132
			40–60	0.351	0.197	0.614	0.388 (19.8) ± 0.122
			Total	2.150	1.053	2.677	1.960 (100.0) ± 0.493
			Mean	0.717	0.351	0.892	0.653 (33.3) ± 0.160
	Hill base	182	0–20	0.702	1.251	0.176	0.709 (34.6) ± 0.311
			20–40	1.141	0.812	0.921	0.958 (46.8) ± 0.097
			40–60	0.351	0.351	0.439	0.380 (18.6) ± 0.029
			Total	2.194	2.413	1.536	2.048 (100.0) ± 0.437
			Mean	0.731	0.804	0.512	0.683 (33.3) ± 0.088

Table 3. Fine root biomass in pine forest

Forest	Forest site	Tree girth (cm)	Soil depth (cm)	Fine root biomass ($t\ ha^{-1}$) in each sample plot			Mean value ± SE ($t\ ha^{-1}$)
				I	II	III	
Pine	Hilltop	155	0–20	1.316	0.483	1.141	0.980 (51.7) ± 0.254
			20–40	0.548	0.351	0.570	0.490 (25.9) ± 0.070
			40–60	0.329	0.176	0.768	0.424 (22.4) ± 0.178
			Total	2.194	1.009	2.479	1.894 (100.0) ± 0.502
			Mean	0.731	0.336	0.826	0.631 (33.3) ± 0.150
	Hill mid	76	0–20	0.548	1.141	0.702	0.797 (53.2) ± 0.178
			20–40	0.395	0.527	0.263	0.395 (26.3) ± 0.076
			40–60	0.329	0.461	0.132	0.307 (20.5) ± 0.096
			Total	1.272	2.128	1.097	1.499 (100.0) ± 0.350
			Mean	0.424	0.709	0.366	0.500 (33.3) ± 0.106
	Hill base	65	0–20	1.009	0.570	0.790	0.790 (38.3) ± 0.127
			20–40	0.592	1.426	0.570	0.863 (41.8) ± 0.282
			40–60	0.439	0.307	0.483	0.410 (19.9) ± 0.053
			Total	2.040	2.304	1.843	2.062 (100.0) ± 0.462
			Mean	0.680	0.768	0.614	0.687 (33.3) ± 0.045

Table 1. As shown in Supplementary Table 2, the Shapiro–Wilk test also suggests that the data are normally distributed when the significance value is less than 0.05.

Fine root biomass across different forest types

The one-way ANOVA revealed that the fine root biomass differed significantly between forest types. Multiple comparisons were analysed using a post-hoc test (Tukey HSD test). The findings revealed that fine root biomass varied significantly depending on forest type. The highest fine root biomass was found in the sal forest, followed by oak and pine forests. Thus, fine root biomass followed the pattern: sal forest > oak forest > pine forest, which was significant at 0.05 level. Table 5 presents ANOVA and Tukey HSD test for fine root biomass across different forest types.

Fine root biomass across different soil depth intervals

Fine root biomass was found to decrease with increasing soil depth. The highest fine root biomass was concentrated at a soil depth of 0–20 cm (1.10 $t\ ha^{-1}$), followed by 20–40 (0.91 $t\ ha^{-1}$) and 40–60 cm (0.43 $t\ ha^{-1}$) as shown in Supplementary Table 3. The decrease in fine root biomass with increase in soil depth was not the same for all plots of different forest types. However, statistical analysis showed that fine root biomass was maximum at 0–20 cm and decreased with increasing soil depth interval. The trend in fine root biomass was as follows: 0–20 > 20–40 > 40–60 cm, significant at 0.05 level. Table 6 presents the one-way ANOVA and Tukey HSD test for fine root biomass across different soil depth intervals.

Table 4. Fine root biomass in sal forest

Forest	Forest sites	Tree girth (cm)	Soil depth (cm)	Fine root biomass (t ha^{-1}) in each sample plot			Mean value ± SE (t ha^{-1})
				I	II	III	
Sal	Hilltop	82	0–20	1.492	1.053	1.470	1.338 (43.1) ± 0.143
			20–40	1.141	1.558	1.229	1.309 (42.1) ± 0.127
			40–60	0.505	0.307	0.570	0.461 (14.8) ± 0.079
			Total	3.137	2.918	3.269	3.108 (100.0) ± 0.349
			Mean	1.046	0.973	1.090	1.036 (33.3) ± 0.034
	Hill mid	165	0–20	1.931	1.251	2.084	1.755 (51.5) ± 0.256
			20–40	1.448	0.878	1.009	1.112 (32.6) ± 0.173
			40–60	0.395	0.702	0.527	0.541 (15.9) ± 0.089
			Total	3.774	2.830	3.620	3.408 (100.0) ± 0.518
			Mean	1.258	0.943	1.207	1.136 (33.3) ± 0.098
	Hill base	65	0–20	1.667	1.755	1.316	1.580 (45.2) ± 0.134
			20–40	1.294	0.856	1.865	1.338 (38.3) ± 0.293
			40–60	0.636	0.614	0.483	0.578 (16.5) ± 0.048
			Total	3.598	3.225	3.664	3.496 (100.0) ± 0.475
			Mean	1.199	1.075	1.221	1.165 (33.3) ± 0.046

Table 5. Statistical tests to determine the difference in fine root biomass among different forest types

	Sum of square	*df*	Mean square	*F*	Sigma
One-way ANOVA (dependent variable = biomass)					
Between groups	1.267	2	0.633	22.448	0.0000003
Within groups	0.677	24	0.028		
Total	1.944	26			

Forest type		Mean difference	Standard error	Sigma	95% Confidence interval	
					Lower bound	Upper bound
Multiple comparison (Tukey HSD)						
Oak	Pine	0.11633	0.07918	0.323	–0.0814	0.3141
	Sal	–0.39011*	0.07918	0.000	–0.5878	–0.1924
Pine	Oak	–0.11633	0.07918	0.323	–0.3141	0.0814
	Sal	–0.50644*	0.07918	0.000	–0.7042	–0.3087
Sal	Oak	0.39011*	0.07918	0.000	0.1924	0.5878
	Pine	0.50644*	0.07918	0.000	0.3087	0.7042

*Mean difference is significant at 0.05 level.

Discussion

In oak, pine and sal forests, cumulative fine root biomass varied from 1.960 to 2.494, 1.499 to 2.062 and 3.108 to 3.496 t ha^{-1} respectively. Fine root biomass estimations for oak and pine forests were greater than the reported values of 1.475 t ha^{-1} for oak and 0.960 t ha^{-1} for pine forests[21]. The present values are higher due to the marked difference in fine root diameter ≤1 mm. The fine root biomass of sal forests, on the other hand, was close to the values observed in sal forests of Nepal (3.200 and 3.700 t ha^{-1})[23,24]. Variation in fine root biomass was also observed for each forest at different sites (hilltop, hill mid and hill base). Comparatively, fine root biomass was higher in the hill base than in the other sites for each forest. This could be due to more fresh litter on the surface soil near the hill base. This provides the surface roots shelter and adds nutrients to the soil. It also creates a humid environment for new roots to grow and develop. In the study area, sal forest had substantially finer root biomass than oak and pine forests. Since sal and oak trees are deciduous, their fine root biomass is larger. According to studies, deciduous plants have more fine root organic matter than conifers[2,24,25]. The concentration of nitrogen on the forest floor, varied soil types, and varying climate patterns in these diverse forest types could influence the fine root biomass.

The results of this study reveal considerable variance in fine root biomass across the soil at different depths. In each forest type, fine root biomass decreased as soil depth increased. These findings are consistent with those from studies across different forests of the world[7,26,27]. Since the soil is porous and offers more nutrients at this depth, high fine root biomass in the upper soil layer is especially more frequent in Indian Himalayan forests[28,29]. Fine root biomass was found to be concentrated in soil layers deeper

Table 6. Statistical tests to determine the difference in fine root biomass for different soil depths intervals

		Sum of squares	d*f*	Mean square	*F*	Sigma	
One way ANOVA (dependent variable = biomass)							
Between Groups		2.131	2	1.065	11.675	0.00028	
Within Groups		2.190	24	0.091			
Total		4.321	26				

Soil depth (cm)		Mean difference	Standard error	Sigma	95% Confidence interval: Lower bound	95% Confidence interval: Upper bound
Multiple comparisons (Tukey HSD)						
0–20	20–40	0.18356	0.14240	0.415	–0.1721	0.5392
	40–60	0.66611*	0.14240	0.000	0.3105	1.0217
20–40	0–20	–0.18356	0.14240	0.415	–0.5392	0.1721
	40–60	0.48256*	0.14240	0.007	0.1269	0.8382
40–60	0–20	–0.66611*	0.14240	0.000	–1.0217	–0.3105
	20–40	–0.48256*	0.14240	0.007	–0.8382	–0.1269

*Mean difference is significant at 0.05 level.

than 30 cm in various studies[30–32]. This occurs when precipitation is higher in the study area and mostly depends upon the season of data collection. When nutrients are well accumulated and leached from the surface to deeper soil layers, fine root biomass is more concentrated in the deeper soil layers[30].

Fine root biomass contribution varied between 75% and 85% of total biomass within 0–40 cm soil depth for each forest in the study, which was lower than the contribution (90%) in pine and oak forests of Central Himalayas[33]. The values observed in this study are higher, with Rawat[34] reporting 70.8% of total biomass within 0–40 cm soil depth and Noguchi *et al.*[26] reporting 74–93% fine root distribution within 0–40 cm soil depth along different elevation gradients in tropical moist forests of the Amazon. The reason for variation could be the seasonal changes in the soil profile, its physical and chemical composition, topography, forest types, species composition and forest floor conditions. Forest type, soil condition, stand age and sample method influence fine root organic matter, production, turnover and nutrients[35].

Conclusion

Fine roots are an essential component of forest carbon flow, contributing a considerable amount of net primary production of the forest ecosystem. They also play an important part in the nutrient cycle and carbon budgeting of the soil system. The aim of this study was to assess the fine root biomass in various forest types in Central Himalaya. The fine root biomass varied significantly across three dominant forest types, i.e. sal forest > oak forest > pine forest. Fine root biomass was also shown to decrease as soil depth increased, i.e. 0–20 > 20–40 > 40–60 cm. These findings provide baseline information that may aid future studies on nutrient availability as well as the global carbon budget.

1. Sayer, E. J., Tanner, E. V. J. and Cheesman, A. W., Increased litterfall changes fine root distribution in a moist tropical forest. *Plant Soil*, 2006, **281**, 5–13.
2. Vogt, K. A., Vogt, D. J., Palmiotto, P. A., Boon, P., Ohara, J. and Asbjornsen, H., Review of root dynamics in forest ecosystems grouped by climate, climatic forest type and species. *Plant Soil*, 1996, **187**, 159–219.
3. Gill, A. R. and Jackson, B. R., Global patterns of root turnover for terrestrial ecosystems. *New Phytol*., 2000, **147**, 13–31.
4. Vogt, K. A., Grier, C. C. and Vogt, D. J., Production, turnover, and nutrient dynamics of above- and belowground detritus of world forests. *Adv. Ecol. Res*., 1986, **15**, 303–378.
5. Persson, H., The distribution and productivity of fine roots in boreal forests. *Plant Soil*, 1982, **71**, 87–101.
6. Noordwijik, M., Lawson, G., Soumare, A., Groot, J. J. R. and Hairiah, K., Root distribution of trees and crops: competition and/or complementarit. In *Tree-Crop Interactions: A Physiological Approach* (eds On, C. K. and Huxley, P.), CAB International, Washington, Oxon, UK, 1996, pp. 319–364.
7. Jackson, R. B., Mooney, H. A. and Schulze, E. D., A global budget for fine roots biomass, surface area, and nutrient contents. *Proc. Natl. Acad. Sci. USA*, 1997, **94**, 7362–7366.
8. Jones, R. H., Mitchell, R. J., Stevens, G. N. and Pecot, S. D., Controls of fine root dynamics across a gradient of gap sizes in a pine woodland. *Oecologia*, 2003, **134**, 132–143.
9. Hendrick, R. L. and Pregitzer, K. S., Patterns of fine root mortality in 2 sugar maple forests. *Nature*, 1993, **361**, 59–61.
10. Wang, Z. Q. and Guo, D. L., Root ecology. *J. Plant Ecol*., 2008, **32**, 1213–1216.
11. Barbhuiya, A. R., Arunachalam, A., Pandey, H. N., Khan, M. L. and Arunachalam, K., Fine root dynamics in undisturbed and disturbed stands of a tropical wet evergreen forest in northeast India. *Trop. Ecol.*, 2012, **53**(1), 69–79.
12. Pant, H. and Tewari, A., Fine root biomass, productivity and turnover in two contrasting aspects in natural chir pine (*Pinus roxburghii* Sarg.) forests of Central Himalaya. *Russ. J. Ecol*., 2015, **46**(6), 511–517.
13. Welke, S. E., Hope, G. D. and Hunt, G. A., Effects of harvesting on fine root biomass and decomposition in an Engelmann spruce subalpine fir forest. *Can. J. For. Res*., 2003, **33**(5), 847–853.
14. Polomski, O. and Kuhn, N., Wurzelsysteme Forschungsanstalt für Wald. In *Schnee und Landschaft (WSL/FNP) Birmensdorf* (ed. Haupt, P.), Bern, Switzerland, 1998.
15. Steen, E., Root and rhizome dynamics in a perennial grass crop during an annual growth cycle. *Swed. J. Agric. Res*., 1985, **156**, 25–30.

16. Eissenstat, D. M. and Yanai, R. D., The ecology of root life span. *Adv. Ecol. Res*., 1997, **27**, 1–62.
17. Vogt, K. A., Vogt, D. J. and Bloomfield, J., Analysis of some direct and indirect methods for estimating roots biomass and production of forests at an ecosystem level. *Plant Soil*, 1998, **200**, 71–89.
18. Sabin, T. P., Krishnan, R., Vellore, R., Priya, P., Borgaonkar, H. P., Singh, B. B. and Sagar, A., Climate change over the Himalayas. In *Assessment of Climate Change over the Indian Region* (eds Krishnan, R. *et al.*), Springer, Singapore, 2020, pp. 207–222.
19. Yuan, Z. Y. and Chen, H. Y. H., Fine root biomass, production, turnover rates, and nutrient contents in boreal forest ecosystems in relation to species, climate, fertility, and stand age: literature review and meta-analyses. *Crit. Rev. Plant Sci*., 2010, **29**, 204–221.
20. Persson, H., Root dynamics in a young Scots pine stand in Central Sweden. *Oikos*, 1978, **30**, 508–519.
21. Usman, S., Rawat, Y. S., Singh, S. P. and Gargoti, S. C., Fine root biomass production and turnover in evergreen forests of Central Himalaya, India. *Oecologia*, 1997, **6**, 4–8.
22. Ostonen, I., Lohmus, K. and Pajuste, K., Fine root biomass, production and its proportion of NPP in a fertile middle-aged Norway spruce forest: comparison of soil core and ingrowth core methods. *For. Ecol. Manage*., 2005, **212**, 264–277.
23. Bhattarai, P. K. and Mandal, N. T., Soil microbial biomass in relation to fine root in Kiteni hill Sal forest of Ilam, Eastern Nepal. *Nepal J. Biosci*., 2012, **2**, 80–87.
24. Gautam, P. G. and Mandal, N., Effects of disturbance on fine root biomass in tropical moist forest of eastern Nepal. *Nepal J. Biosci*., 2012, **21**, 10–16.
25. Leuschner, C. and Hertel, D., Fine root biomass of temperate forests in relation to soil acidity and fertility, climate, age and species. *Prog. Bot*., 2003, **64**, 405–438.
26. Noguchi, H. *et al.*, Fine root biomass in a tropical moist forest in the upper Negro River basin, Brazilian Amazon. *Tropics*, 2014, **22**(4), 179–183.
27. Helmisaari, H. S., John, D., Pekka, N. and Mikko, K., Fine root biomass in relation to site and stand characteristics in Norway spruce and Scots pine stands. *Tree Physiol*., 2007, **27**, 1493–1504.
28. Garkoti, S. C., Fine root dynamics in three central Himalayan high elevation forests ranging from closed canopied to open canopied tree line vegetation. *J. For. Res*., 2011, **16**(2), 136–143.
29. Verma, A. K., Garkoti, S. C., Singh, S., Kumar, S. and Kumar, M., Fine root production and nutrient dynamics in relation to stand characteristics of chir pine mixed banj oak forests in Central Himalaya. *Flora*, 2021, **279**, 151808.
30. Cordeiro, A. L. *et al.*, Fine-root dynamics vary with soil depth and precipitation in a low-nutrient tropical forest in the Central Amazonia. *Plant–Environ. Interact*., 2020, **1**(1), 3–16.
31. Melgar, R. J., Smyth, T. J., Sanchez, P. A. and Cravo, M. S., Fertilizer nitrogen movement in a Central Amazon Oxisol and Entisol cropped to corn. *Fert. Res*., 1992, **31**, 241–252.
32. Pathak, G. C., Joshi, H., Singh, R. D., Tewari, A., Pandey, R. and Singh, S. P., Vertical root distribution in Himalayan trees: about half of roots occur below 30 cm, the generally sampled depth. *Trop. Ecol*., 2021, **62**, 479–491.
33. Usman, S., Singh, S. P. and Rawat, Y. S., Fine root productivity and turnover in two evergreen Central Himalayan forests. *Ann. Bot*., 1999, **84**, 87–94.
34. Rawat, S. V., Fine root biomass and soil nutrient in Van Panchayat forest of Almora district. *Indian J. Plant Sci*., 2012, **1**(1), 101–108.
35. Nadelhoffer, K. J. and Raich, J. W., Fine root production estimates and belowground carbon allocation in forest ecosystems. *Ecology*, 1992, **73**, 1139–1147.

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