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FINE ROOT BIOMASS OF ERICA *TRIMERA* (ENGL.) ALONG AN ALTITUDINAL GRADIENT ON BALE MOUNTAINS, ETHIOPIA

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Abstract

Fine roots biomass of *Erica trimera* was investigated at three altitudinal levels, i.e. 3000, 3300, and 3500 masl across three depth classes (0-10, 10-20, and 20-40 cm) for each of the four seasons of Bale Mountains by using sequential soil coring. Soil chemical characteristics and moisture were analyzed for all of the three altitudinal levels and depth classes. The annual fine root production of the species was calculated based on min-max method. Fine root production increased markedly from 3270 kg. ha^{-1}. yr^{-1} at 3000 masl and 2850 kg. ha^{-1}. yr^{-1} at 3300 masl to 9987 kg. ha^{-1}. yr^{-1} at 3500 masl. Total nitrogen, available phosphorous, organic carbon, moisture content and PH of the soil increased significantly as altitude increased. In the two lower altitudinal levels, 3000 and 3300masl, fine root mass and biomass decreased as depth increased, but at the higher altitude (3500 masl) fine root tended to more concentrated at the deeper depths while the availability of soil nutrient and soil acidity showed a tendency to decreased as depth increased at all of the three sites. The highest fine root mass and biomass was recorded at the major rainy season followed by the transition period, the small rainy and dry period, in that order. The highest fine root mass during the major rainy season and lowest fine root mass in the dry season indicated that soil moisture was critical factor in governing the pattern of root growth in this ecosystem.

Keywords: Bale Mountains; Treeline Ecosystems; Fine Root; Erica Trimera, Altitude.

1. Introduction

In tropical mountains the Lower Montane Forest (LMF) which are composed of trees with a maximum height of 25–35m (at the most 40 m) are replaced by the Upper Montane Forest (UMF) in which the trees are not taller than 18–22m, and decrease in height from their lower limit toward the tree line where less than 10m are reached [53]. Tree lines are the transition zones between the

upper limit of the closed montane forest and the beginning of the tree less alpine zone [30]. Similarly [19], identified three distinctive belts of vegetation along altitudinal gradients of tropical east African mountains namely; montane forest, ericaceous, and the alpine belt. In general above the closed montane forest the height of trees decreases with increasing altitude [20, 52]. The height and diameter at breast height (DBH) of *Erica trimera* decrease significantly as altitude increases [53, 35]. The species has a potential to grow to a tree height of 8 – 12 m when the condition is favorable but at higher altitudes it exhibits shrub life-form even lower than 2 m height [36].

For several decades, there has been an intensive debate among plant ecologists on the causes of this altitudinal reduction in tree size in tropical mountains. Currently, there are at least four contrasting arguments to explain the situation. The most popular idea is the one which considers the low temperature at higher elevation as a severe stress that limits the growth and development of trees due to frost injury [31, 34]. According to these authors the replacement of trees by non-trees as altitude increased in the tree line ecotone is because tree species lack either the avoidance or tolerance adaptation to the low temperature. For instance, the giant roset plant (*Lobelia rhynchopetalum*) that builds tree like life-form at Senate platu of Bale Mountains shows adaptation mechanisms to coldness, such as having an arborecent habit, the formation of night bud, or controlled extra cellular freezing to escape the pronounced diurnal fluctuations of temperature [33, 34].

The second school of thought suggests the retarded photosynthetic rate by the low temperature as a possible reason for the limited tree growth at higher altitude. According to [16] the rate of photosynthesis of high elevation trees is 30 – 50 % lower than that of low elevation trees. Moreover, the low temperature decreased the quantum yield of photosystem II because turnover of the protein electron acceptor Qb is limited in cold environment, which results in photo-inhibition. Or indirectly, low soil temperature can limit enzymically driven root processes such as root growth, nutrient uptake and respiration, decreasing the demand for carbon that results in accumulation of non-structural carbohydrate in the leaves which ultimately reduces the rate of photosynthesis [41, 8].

The third group of reports are based on the sink limitation theory i.e., new tissue development is limited not by carbon availability rather by the low temperature which limits cell division [28, 29, 47, 43]. Tree line species are unable to use the carbon gained from day time photosynthesis in growth because of the low temperature.

The last but not least assumptions relate the phenomenon to the response of fine roots of plants to different environmental factors. The low temperature at higher elevations affect the soil condition negatively, reduces nutrient availability that force the plants to partition more biomass to their belowground part by hindering the above ground growth in order to maximize below ground resource capture [51, 49, 44].

Below ground parts of plants consist of buttress roots (> 5 mm diameter), coarse roots (2 – 5 mm diameter), and fine roots (< 2 mm diameter) [53, 14]. The two former classes of roots are relatively persistent throughout the life history of the plants while the fine roots are deciduous. In spite of the fact that the fine roots consist of small fraction (< 5%) of the total biomass of standing crop their turnover represent large proportion (30 – 60%) of annual net primary production [14].

Moreover, they constitute 60 – 90 % of the total belowground net primary production [49]. Therefore, investigation on the relationship between tree fine root dynamics and environmental gradients along elevational transects could provide insight into the response of tree root system and also the change in allocation pattern that entails. The present study aims to investigate the fine root production of *Erica trimera* along an elevation gradient in Bale Mountains. The study also aims to investigate the correlation between the soil nutrients and fine root biomass of *Erica trimera* along the elevation gradient.

2. Materials and Methods

2.1. Study Site Description

The study was conducted in the Bale Mountains National Park (BMNP), at the ericaceous vegetation of the eastern escarpment. The park is located in the south eastern Ethiopia 400 km by road from Addis Ababa. The Bale Mountains form the south eastern limit of the eastern Ethiopian highlands along the eastern edge of the great east African rift valley. The area is located between $6^0$29'and$7^0$10'N and 39^{0}28' and 39^{0}57'E. The study area mainly consists of teritiary (Oligocene) trapean lavas which cover the Mesozoic marine sediments and underlying pre-cambrian rocks after the Eocene uplifting of the Ethiopian highlands [36]. The soils are mainly derived from the basaltic and trachytic parent rock and are young, fairly fertile, silty loams of redish brown, to black colored alfisols [36].

The rainfall of the Bale Mountains is highly influenced by southeasterly winds from the Indian Ocean. The Inter Tropical Convergent Zone (ITCZ) and local altitudinal and topographic influences affect the distribution of the precipitations in the area. The mean annual rainfall based on the data between 1997 and 2007 from the Rira Station is 633.11 mm. Mean maximum monthly precipitations is 181 mm in April and mean minimum monthly precipitation is 13 mm in May. The mean annual minimum and maximum temperatures are 3.85 and 17.17 ^{0}C, respectively. The mean monthly maximum temperature, 19 ^{0}C, recorded in March, and the mean minimum temperature, 2.25^{0}C, recorded in January. The diurnal amplitude of the temperature is widest (15.58 ^{0}C) during the dry season and smallest (11.33 ^{0}C) during the major rainy season. Night frosts have been reported from the area. For instance, [22] recorded a minimum temperature reading of -15 ^{0}C and [36] has reported a nocturnal minimum temperature -3 ^{0}C from the study area. Frosts never penetrate deeply into the soil for example -12 ^{o}C, -7 ^{o}C, and 0 ^{o}C, have been registered at 0 cm, 1cm, and 5 cm soil depths respectively [36]. The annual mean temperature decreases with lapse rates of 0.75 ^{o}C and 0.5 ^{o}C per 100 m altitude during the dry and the rainy season, respectively [36].
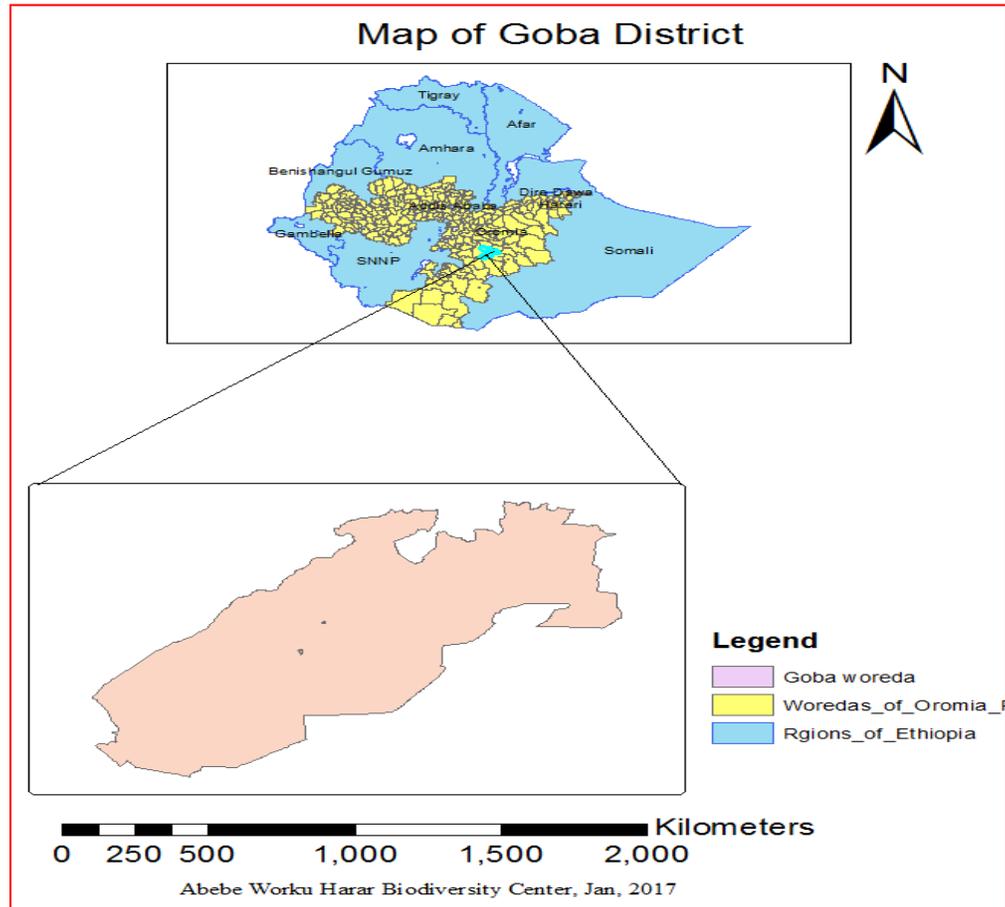
2.2. Study Area Map

Figure 1: Map of Goba district where the permanent study sites were established.

2.3. Sampling Method

Three permanent sites were established along an elevation gradient on the Harrena (south eastern part of BMNP) escarpment site 1 at 3000 masl, site 2 at 3300 masl, and site 3 at 3500 masl. One permanent plot size of 30 m X 30 m has been established at each of the three sites. Plots were laid based on the homogeneity of vegetation and minimal human interference [37]. From each plots 5 healthy and good looking *Erica trimera* trees were selected for sampling fine roots. Four points were randomly identified at 1 m radiuses' around the selected trees. Using a modified Auger (3 cm diameter and 80 cm long) core samples were extracted to a depth of 40 cm. Three depth classes were considered: d1= 0 – 10 cm, d2= 10 – 20 cm, d3 = 20 – 40 cm. Core samples of similar depth classes from different points around the same selected tree were mixed. In general there are four seasons i.e., three main seasons and one transition period in the study area. Sampling has been taking place at the end of each season. A total of 45 core samples have been collected and taken to the ecophysiology laboratory at Addis Ababa University at each of the four sampling seasons. The core samples were processed immediately after collection to differentiate the live and dead roots as well as to record the dry weight.

2.4. Fine Root Processing

Core samples were washed and sieved on a series of mesh sieves of decreasing diameter (2.8 mm, 2.0 mm, and 1.0 mm). The fine roots (< 2 mm diameter) of *Erica trimera* were separated from fine roots of other tree species on the basis of color and texture. Roots of *Erica trimera* are dark black in color and rough surface. Washed fine roots were sorted into live and dead fine root fractions on the basis of visual, mechanical, and/or microscopic techniques [22, 52]. Live roots are much more elastic than dead ones and don't break down easily when bent. Dead roots have poor cohesion between their cortex and periderm while live roots have good cohesion. Dry weight was determined after drying the roots at 70 ℃ to a constant temperature.

2.5. Calculation of Fine Root Production

Estimates of fine root production from sequential soil cores often differ depending on the method of calculation used [51, 52, 22]. In the present study fine root production was estimated by the simple and widely used, Min-Max method, in which subtracting the minimum from the maximum fine root standing crop within the sampling period [21].

$P = Max_{FRM} - Min_{FRM}$, where P is the annual fine root production in $gm.m^{-2}yr^{-1}$, Max_{FRM} and Min_{FRM} are the maximum and minimum fine root mass in the sampling period, respectively.

2.6. Soil Chemical Analysis

Soil samples were collected at the same time of root sampling for dry season from each of the three sites by using modified auger the same as to that of root sampling. Soil samples were collected for each of the depth classes that were considered for the fine root sampling. Soil nitrogen, available phosphorous, organic carbon, PH, and soil moisture content were analyzed at the national soil Laboratory, Ethiopian Agricultural Research Organization.

2.7. Data Analysis

All the collected data were subjected to analysis of variance (ANOVA) test of SPSS statistical package. Multiple comparisons of means were carried out using Tukey's Honestly Significant Difference (HSD). Mean difference were considered significant at $P < 0.05$.

3. Results

3.1. Total Fine Root Mass, Biomass, and Necromass Along an Elevation Gradient

In all of the sampling times total fine root mass (the sum of biomass and necromass) increased significantly ($P < 0.05$) as altitude increased (fig. 2). The mean fine root mass at site 3 (3,500 masl) was greater than at site 1 (3000 masl) and 2 (3300 masl) by 305.6% and 74.4 %, respectively. The mean total fine root masses of site 1, 2, and 3 were 328.97, 781.69, and 1524.43 g/m^2, respectively. Fine root biomass also increased significantly as altitude increased. The mean fine root biomasses of sites 1, 2, and 3 were 285.52, 643.78, and 1350.09 g/m^2, respectively (fig. 3). Fine root

necromass didn't show altitudinal pattern during November and February on the other hand it increased as altitude increased during May and July (fig. 4).
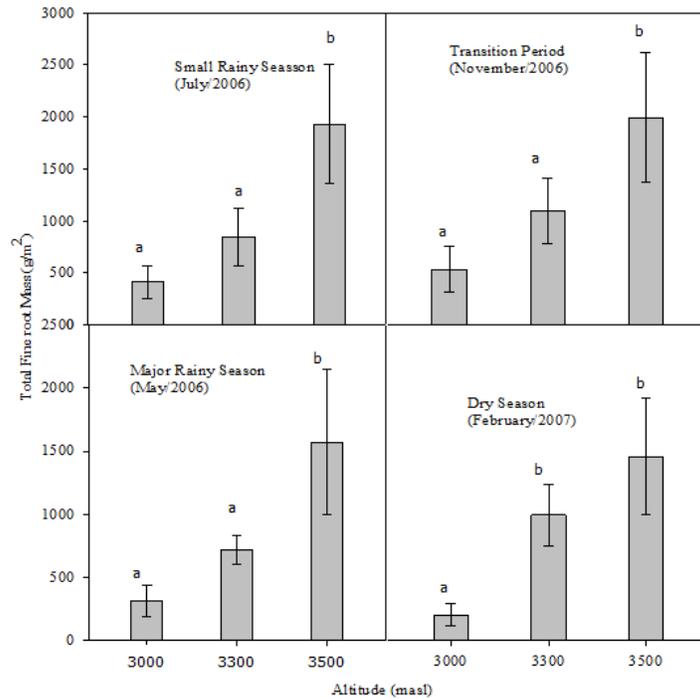

Figure 2: Total fine root masses (biomass + necromass) of Erica trimera along an elevation gradient sampled on May, July, November of 2006 and February of 2007 G.C. Within a block (sampling time) different letteres at the top of a bar indicate significant mean differences (P<0.05).
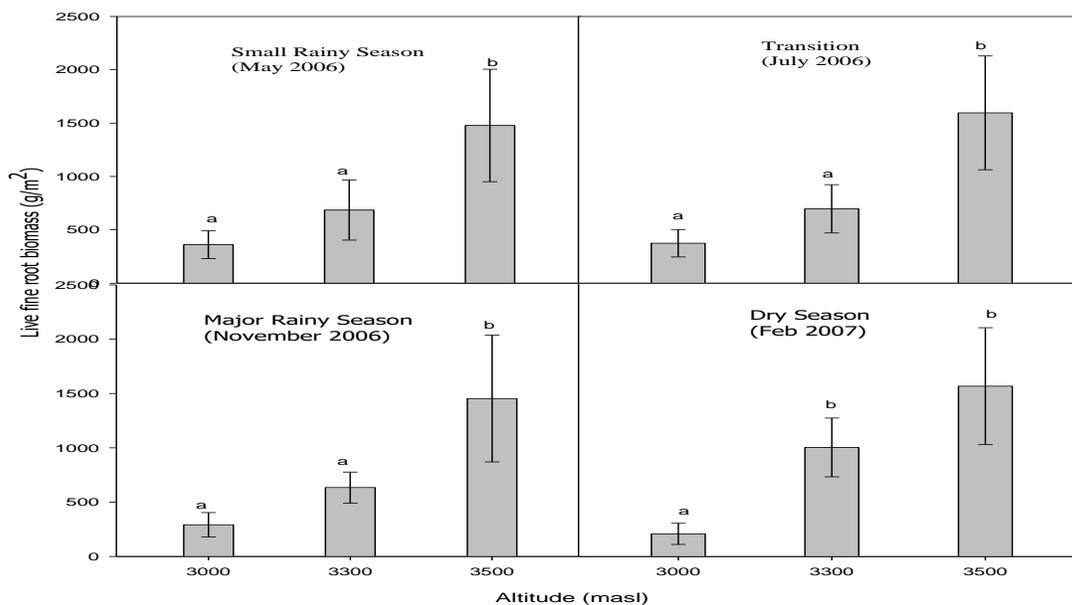

Figure 3: Live fine root biomass along an elevation gradient sampled on May, July, November of 2006 and February of 2007 which represent ends of Small rainy Season, Transition period, Major Rainy Season, and Dry Season, Respectively. Within a block (sampling time) different letters at the top of bars indicate significant mean differences (P< 0.05).
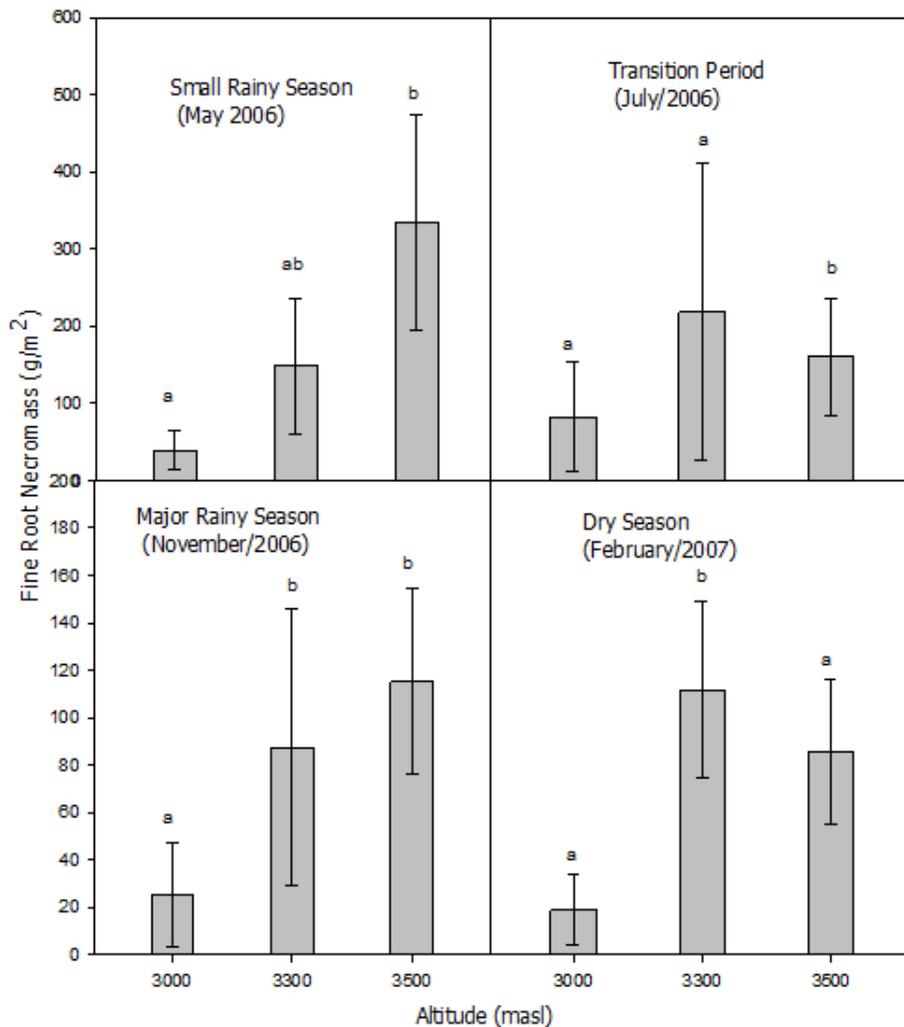
Figure 4: Fine root necromass (dry weight of dead fine roots) along an elevation gradient
sampled on May, July, November of 2006 and February of 2007 which are the ends of the small
rainy season, transition Period, major rainy season, and dry season of the study area. Within the
block (sampling time) different letters at the top of a bar indicates significant mean differences
(P< 0.05).

3.2. Depth Wise Distribution of Fine Roots

The vertical distributions of fine roots were more or less similar during all of the sampling periods.
In the two site of the lower altitudes total fine root mass decreased as depth increased but at the
site with the highest altitude fine roots are found to be more concentrated in the deeper depths than
at the surface. On the average more than 75% of the roots from Site 1 and 71% of the roots from
Site 2 were found on the depths of $0 - 20$ cm. In contrast $60 - 74\%$ of fine roots were found in the
two lower depth classes i.e., $10 - 40$ cm in Site 3. Table 1 and table 2 depicts the results observed
on total fine root mass (dry weights of live + dead fine roots) and live fine root dry weight recorded
per square meter.

Table 1: Depth with distributions of total fine root mass (live + dead) in the three sites. The values are mean ± SE, n=20.

Sites	Altitude (masl)	Total fine root mass (g/m^2) across depth classes		
		0 – 10 cm	10 – 20 cm	20 – 40 cm
1	3000	129.53±22.78	94.255±14.04	105.19±13.97
2	3300	308.86±38.30	267.05±30.72	210.28±35.89
3	3500	407.12±42.76	558.45±61.97	558.86±64.10

Table 2: Depth with distributions of fine root biomass (only live roots) in the three sites. The values are mean ± SE, n=20.

Sites	Altitude (masl)	Fine root biomass (g/m^2) across depth classes		
		0 – 10 cm	10 – 20 cm	20 – 40 cm
1	3000	111.47±19.22	79.99±9.84	94.08±14.20
2	3300	240±26.47	230.08±28.27	173.70±27.53
3	3500	367.44±42.61	497.47±55.70	485.18±56.78

3.3. Seasonal Dynamics of Fine Root

The three major seasons and one transition season of the study area were considered to collect samples. Dry season extends from November to February, a small rainy season between March and April and a major rain season from August to October. The months from May to July represent a transition period between the small rain seasons the major rain season. Fine root samples were collected at the end of each season. Fine root samples were collected in first week of May (small rain season), end of July (transition period), beginning of November (major rain season), and end of February (dry season).

In all of the three sites fine roots showed seasonal variation with the highest peak at November, the end of major rainy season and lowest in February, end of dry season (table 3).

Table 3: Seasonal variations of fine root biomass across the three sites. Different superscript letter within rows indicate significant mean difference ($P<0.05$). The values are mean ±SE, n=20

Site	Altitude (masl)	Fine root biomass at the four seasons (g/m^2)			
		Small rain	Transition	Major rain	Dry
1	3000	1214.2±214.0[a]	316.61±56.56[b]	456.643±82.09[a]	129.36±25.38[c]
2	3300	845.55±125.78 [a]	721.82±50.97 [a]	922.25±115.13 [a]	637.16±69,09[b]
3	3500	1931.41±257.50 [a]	1568.61±257.32 [a]	1665.03±231.24 [ab]	932.69±131.65[b]

3.4. Fine Root Production Along an Altitudinal Gradient

The annual fine root production of *Erica trimera* in the 40 cm soil profile was estimated based on the Min-Max method in the three sites. Fine root production increased markedly from 3270 kg. ha^{-1}. yr^{-1} at 3000 masl and 2850 kg. ha^{-1}. yr^{-1} at 3300 masl to 9987 kg. ha^{-1}. yr^{-1} at 3500 masl.

3.5. Soil Chemical Characteristics and Moisture Along an Altitudinal Gradient

In general soil fertility was found to increase as altitude increase. Total nitrogen, available phosphorous, and organic carbon increased significantly ($P<0.05$) as altitude increased. Soil acidity decreased as altitude increased. Moisture content increased as altitude increased.

Table 4: The average soil chemical charachteristics and moisture along an altitudinal gradient. Different superscript letters within a column indicate significant mean differences ($p<0.05$). Values are mean ±SE, n=20

Site	Altitude (masl)	Soil Characteristics					
		PH (H$_2$O 1:2.5)	Soil Nutrient				Soil moisture content (%)
			Total nitrogen (%)	Available phosphorous (ppm)	Organic carbon (%)	C/N ratio	
1	3000	5.00±0.02[a]	0.71±0.02[a]	8.68±0.32[a]	8.30±0.11[a]	11.75±0.14[a]	11.91±0.57[a]
2	3300	5.08±0.05[b]	1.09±0.06[b]	11.60±0.69[b]	13.85±1.0[b]	12.67±0.33[b]	21.15±1.09[b]
3	3500	5.22±0.13[b]	1.31±0.08[c]	14.94±2.01[c]	20.52±1.6[c]	15.58±0.46[c]	32.06±1.34[c]

3.6. Depth Wise Variation of Soil Chemical Characteristics and Moisture

In all of the three sites soil fertility and soil acidity decreased as the soil depth increased. Available phosphorus, total nitrogen and organic carbon showed a significant decrease as the soil depth increased in all of the three sites ($P < 0.05$). On the other hand, there is no significant difference in soil moisture between the three depths in the two higher sites.

Table 5: Depth wise variation of soil chemical charachteristics and moisture in the three sites. Within a row different superscript letters indicate significant mean differences ($P < 0.05$). Values are mean ± SE, n=4.

Site	Altitude (masl)	Chemical characteristics and moisture	Depth Classes (cm)		
			0 -10	10 - 20	20 - 40
1	3000	PH (H2O 1:2.5)	4.99±0.03[a]	5.00±0.00[a]	5.05±0.03[b]
		Total nitrogen (%)	0.75±0.01[a]	0.69±0.02[b]	0.68±0.01[b]
		Available phosphorous (ppm)	9.25±0.29[a]	8.66±0.1[b]	8.13±0.17[c]
		Organic carbon (%)	8.53±0.29[a]	8.23±0.09[b]	8.15±0.20[b]
		C/N ratio	11.5±0.65[a]	12.00±0.00[a]	11.75±0.25[b]
		Soil moisture content (%)	11.87±0.74[a]	11.29±1.50[a]	12.57±0.55[b]
2	3300	PH (H2O 1:2.5)	5.00±0.00[a]	5.05±0.03[b]	5.16±0.03[c]
		Total nitrogen (%)	1.20±0.01[a]	1.07±0.01[b]	1.02±0.01[c]

		Available phosphorous (ppm)	12.97±0.27[a]	11.02±0.27[b]	10.80±0.48[c]
		Organic carbon (%)	15.71±0.18[a]	13.72±0.11[a]	12.10±0.37[b]
		C/N ratio	13.00±0.00[a]	13.00±0.00[a]	12.00±0.40[b]
		Soil moisture content (%)	23.31±1.61[a]	20.67±1.69[a]	19.47±1.04[b]
3	3500	PH (H2O 1:2.5)	4.99±0.03[a]	5.25±0.09[b]	5.43±0.05[c]
		Total nitrogen (%)	1.44±0.00[a]	1.35±0.02[b]	1.16±0.01[c]
		Available phosphorous (ppm)	17.27±2.8[a]	16.61±2.01[b]	10.94±2.59[c]
		Organic carbon (%)	23.50±0.33[a]	20.05±0.38[a]	18.00±0.22[b]
		C/N ratio	16.50±0.29[a]	15.00±0.41[a]	15.25±0.25[b]
		Soil moisture content (%)	34.39±1.67[a]	31.86±2.12[a]	29.93±4.07[b]

3.7. Above Ground Parameters

At the time of plot establishment the above ground parameters of the vegetation height, DBH, number of stems were recorded at each of the three sites. The height and DBH of *Erica trimera* decrease significantly ($P < 0.05$) as altitude increased. According to the above ground biomass estimation model described in Chave el el., 2005 the estimated above ground biomass decrease as altitude increased.

Table 6: Above ground parameters of *Erica trimera* at the three sites

Site	Altitude (masl)	DBH (cm) Mean±SE	Hieght Mean±SE	Number of stems	Plot size (m^2)	Stem density (number of stems/ha)
1	3000	44.65±10.7	9.9±1.0	21	900	233
2	3300	25.81±2.44	8.1±0.45	81	900	900
4	3500	16.8±2.72	2.95±0.27	40	400	1000

4. Discussion

4.1. Fine Root Mass and Biomass Along an Elevation Gradient

Total fine root mass and biomass increase significantly ($P < 0.05$) as altitude increased during all of the seasons (Fig. 2). A similar pattern was reported by [48] from the Ecuadorian Andes forest. However, the result of the present study could not be explained as in [48] based on a functional equilibrium of carbon partitioning between the root and the shoot where plants in the nutrient limited sites allocate more carbon (biomass) to their belowground parts so as to maximize nutrient up take because the most important soil nutrients such as nitrogen and phosphorus were found to increase significantly as altitude increased (Table 4). Hence, the hypothesis that state plants at higher elevation allocate more carbon to their below ground part in response to low nutrient availability due to reduced mineralization rate was not supported by the result of the present study. In general the results contradict with the general rule that states plants in nutrient rich soils have increased above ground biomass than below ground biomass, as site 3 (3500 masl) had highest fine root mass (fig 2) and lowest aboveground biomass [34] (Table 6) while richest in soil nutrients (Table 4). Therefore, the observed scenario could be explained like the findings of [33] the low temperature acting as an environmental stress for the limited growth of trees at high elevations. As

long as the growth in the shoot of tree species at higher elevation is limited due to the low temperature, excess photosynthate is translocated to the root. According to [28] tree life-form is disadvantageous at higher elevations because the shoot apical meristems of trees cannot benefit from radiant canopy warming during the day or stored warmth in the topsoil during the night, whereas subsoil leaf meristems of many alpine graminoids and rosette forbs or dwarf shrubs do but experience convective cooling through tight atmospheric coupling. Therefore, tissue expansion may become blocked periodically, and trees lose a substantial fraction of the season and most nights for structural growth. Hence, the reduction of tree height and DBH as altitude increased is neither due to carbon shortage, nor due to allocation pattern change in response to resource limitation but probably might be created due to sink (growth) inhibition as a result of low temperature.

In fact it is worth mentioning that at high altitudes, reduced capture of below ground resources, which forces higher belowground biomass partitioning based on the functional equilibrium theory [12], may not only be due to less soil nutrient availability but also due to low nutrient uptake ability of roots due to low oxygen availability in the soil [3]. Therefore, the nutrient content of the fine roots of *Erica trimera* should be studied along an elevation gradient to understand to which extent do trees at higher elevation are using the relatively higher soil nutrients.

The finding of the present study i.e., increased fine root mass and biomass along an elevation gradient as the natural fertility increased agrees with the report of [1] which revealed the abundance and turnover rate of fine roots of 13 temperate wood and pine forests were positively related to nutrient availability. [28] also reported similar pattern to the present study in which fine root production increased as soil nutrient increased in the loblolly pine forests.

4.2. Depth Wise Variation of Fine Root Mass and Biomass

The decrease in total fine root mass and biomass with increase in depth at Site 1 (3000masl) and Site 2 (3300 masl) is in agreement with previous reports [18, 24] while, the concentration of fine roots on the deeper depths in Site 3 (3500 masl) is a deviation. For instance, 63% of the fine root biomass was in the upper 15 cm of a *Liriodendron tulpifera* (L.) forest soil sampled to 60 cm, and 71% of biomass in a 70 cm profile was concentrated in the upper 20 cm of a soil under *pinus taeda* (L) [19]. In addition half of the biomass of all fine roots was in the upper 22 cm of soil excavated to a depth of 100 cm in *Quercus alba* (L.) forest [24].

The concentration of more fine roots to the depth of 0 – 20 cm and the higher abundance of important soil nutrients at the same depth in site 1 and 2 might indicate higher turnover rate occurred in this layer at those sites. Whereas in site 3, higher fine root mass and biomass was recorded at lower depths (10 – 20 cm) than at the surface (0 – 10 cm) didn't agree with nutrient availability. This may be due to the frequent freezing and thawing in the upper 0 – 5 cm soil depth that occur at higher altitudes of Bale Mountains [36]. According to [36] the night frosts in the study area (Bale Mountains) never penetrate into the ground hence, the surface temperature fluctuation may be inhospitable for root growth.

4.3. Seasonal Dynamics of Fine Root

In all of the three sites the fine root mass and biomass of *Erica trimera* showed seasonal pattern with the highest peak in the major rainy season and lowest in the dry season (Table 3). Highest fine root mass following the rainy season agrees with much of the reports from tropical, subtropical, and temperate forests. For example [15] reported higher standing fine root biomass in the rainy season, and low fine root biomass in the dry season in a tropical rain forest of eastern Malaysia. Similarly, [50] also reported highest fine root biomass in the rainy season in Indian evergreen forest. Furthermore, in temperate forest ecosystems a burst of fine root production take place in spring and significant mortality in the fall [41]. The Highest fine root biomass in the rainy season in the tropics is mainly correlated to the improvement of soil moisture [15].

4.4. Fine Root Production and Turnover

Root production and turnover have important consequences for carbon and nutrient cycling, water and nutrient acquisition, competition between plants and the survival and reproduction of species under changing environmental conditions [9]. Root turnover has often been used synonymously with annual root production or annual root mortality [9]. In this respect the present study revealed increased fine root production and turnover as altitude increased. This could be associated with the increase of soil nutrient availability as altitude increased tin two ways. First the increased soil fertility as altitude increase may cause higher fine root production and faster fine root turnover [1, 37, 26]. On the other hand the increased fine root turnover and production as altitude increased may contribute to the increased soil fertility as altitude increased [7, 17, 45, 10]. The result contradicts with the conclusion made by [40] i.e., when temperature increased fine root turnover rate and production also increased if soil nutrient and moisture availability are adequate.

4.5. The Results in Relation to Climate Change

The decrease of fine root production and turnover rate down the slope of Bale Mountains imply that climate change may reduce the amount of carbon, nitrogen, and phosphorous flux to the soil through the decomposition of tree root systems. Global warming may reduce the low temperature induced sink limitation on *Erica trimera* at its upper altitudinal limit so that the ericaceous belt could have a chance to expand into the alpine vegetation provided that fire and grazing are controlled in the area. Since the soils of the highest altitude (Site 3) are not limited with nitrogen and phosphorous *Erica trimera* could grow to a greater height in the future as a result of global warming. The speculation made earlier, that the flux of carbon from leaves to the roots and into soil should increase with warming [41] is challenged by the results of the present study as fine root production and turnover, the main source of carbon flux to the soil, decreased down the slope (increasing temperature).

4.6. The Results in Relation to Carbon Sequestration

Considerable amount of terrestrial CO_2 are sequestered in forest ecosystems [51], approximately 20% of atmospheric CO_2 is being sequestered by forest ecosystems of the world [6]. Around 37% of the total atmospheric CO_2 sequestered worldwide was done by forest ecosystems in 1994 [32]. The amount of carbon and nutrients returned to soil from fine root turnover may equal or exceed

that from leaf litter [24, 42, 5]. Moreover, tree fine roots are believed to have turnover rate [12] and hence, fine root production of different forest ecosystems are being documented in terms of their implications to carbon sequestration. The annual fine root production estimates of different forest ecosystems ranges from 160 to 689 Kg.ha^{-1}.yr^{-1} [25, 46, 22]. The annual fine root production of *Erica trimera* (single species) which has been estimated to be 35 to 158 kgha^{-1}yr^{-1} indicates the important role of tropical tree line ecosystems in global carbon sequestration.

5. Conclusion

This study has shown that the increased biomass allocation to fine roots as altitude increase is not due to resource limitation at higher elevations because soil nitrogen, phosphorus, organic carbon and soil moisture increased as altitude increased. Higher fine root production and turnover at higher altitude could not be a strategy to tolerate resource limitation stress rather it might be due to the excess carbohydrate following limited growth by the relatively low temperature at higher altitudes. Therefore, the decrease in height and DBH of most of tree-line species like *Erica trimera* as altitude increase might be caused by the inhibition of growth (cell division and expansion) by the lower temperature at higher altitudes rather than due to resource limitations. However, to understand the extent to which the plants of higher elevations use the available soil nutrients, the nutrient content of the fine roots should be studied in the future.

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