Variation in Tree Density, Biomass and Carbon Stock across an Altitudinal Gradient under Large Cardamom Agroforestry System of Darjeeling Himalaya

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Abstract

It has been reported that the large cardamom-based traditional agroforestry systems in the Darjeeling Himalaya of West Bengal, India represents a sustainable land use system with a high potential to store and sequester biomass carbon. Therefore, the present study was undertaken to evaluate the changes in biomass stock and carbon accumulation of this indigenous system along an altitudinal gradient. The study area was classified into three altitude classes as low (700–1200 m asl), mid (1200–1700 m asl) and high (> 1700 m asl). The biomass and carbon storage for low-, mid- and high-altitude classes was estimated at 630.17 and 296.18 Mg ha^{-1}, 397.05 and 186.61 Mg ha^{-1} and 315.78 and 148.42 Mg ha^{-1}, respectively. *Schima wallichi*, *Cryptomeria japonica* and *Cupressus cashmeriana* were the most dominant species in the low-, mid-, and high altitudinal classes, respectively. The IVI and total biomass of the five dominant species in low-, mid- and high altitudes ranged from 17.34–26.04, 18.15–37.56, 27.13–42.43 and 9.05-133.75 $Mgha^{-1}$, 1.38–37.43 $Mgha^{-1}$ and 19.0-72.1 $Mgha^{-1}$ respectively. *Schima wallichi* occurred in all the altitudinal classes among the top five dominant species. Across all the altitudinal gradients, the average ecosystem carbon storage was estimated at 295.02 Mg ha^{-1}. The contribution of SOC to the ecosystem carbon stock increased with the increasing altitude. In contrast, the contribution of biomass carbon to the ecosystem carbon stock decreased with the increase in altitude. The ecosystem carbon stock estimated for the low-altitude class was 36.43% and 45.30% higher than the mid- and high-altitude agroforestry systems. The large cardamom-based agroforestry systems in the Darjeeling Himalayas are thus a prospective carbon sink, both in vegetation and soil due to higher tree densities and natural resource conservation-based traditional farming practices.

Introduction

Traditional agroforestry systems are a viable option to increase land productivity while, reducing global climate change impacts (Nath *et al.*, 2021). Agroforestry systems sequester carbon more efficiently than monoculture farming (Bhusara et al., 2016; Brahma *et al.*, 2018; Besar et al., 2020; Hariah et al., 2020). In addition, continued accumulation of woody biomass escalate the ability of the system to capture more carbon (Prasad et al., 2016). While increasing sequestration, it also enhances the soil carbon storage (Smith et al., 2007), which overall increase the ecosystem carbon stock of the system. Agroforestry systems incorporating large cardamom are a time-tested sustainable land management practice in the eastern Himalayas, particularly in the Darjeeling hills, Sikkim, Bhutan and Nepal (Sharma et al., 2009). Large cardamom (*Amomum subulatum*) is grown under different species of shade trees, including *Alnus nepalensis, Schima wallichiana, Cryptomeria japonica and Cupressus cashmeriana*. These tree-based systems, thus harbour a multitude of ecosystem functions and services including carbon sequestration, conservation of watersheds and other socio-ecological benefits. The importance of tree-based systems in climate change mitigation and adaptation is already brought to the forefront of various discussions and international forums (Zomer et al., 2022). In this context, the biomass and carbon storage potential of large cardamom-based agroforestry systems need to be evaluated. The biomass storage and carbon dynamics in these tree-based systems found in the Sikkim Himalayan regions are already reported by

Singh et al (2018) and Lepcha and Devi (2020). However, the potentiality of these systems found in the Darjeeling Himalayas is not well understood.

The large cardamom-based agroforestry systems in the Darjeeling Himalayas are highly peculiar due to their diverse structure and functionality (Singh et al., 2018). They are often regarded as the shadow of natural forests and offer multiple benefits from ecological to livelihood, including restricting carbon emissions and ensuring socio-economic security (Yadav et al., 2021). Therefore, the present study aimed to evaluate the variation in tree density, biomass and carbon stock across an altitudinal gradient under large cardamom agroforestry systems of Darjeeling Himalaya. The study is found imperative since the outputs of the study would help in advancing our understanding of the efficiency and sustainability of the system to mitigate accelerated climate change phenomenon.

Material And Methods

Site Description

The present study was conducted in the Darjeeling Himalayan region of West Bengal, India from, January 2019 to April 2021. The study site extends between 26° 27' 05"-27° 13' 10" N latitude and 87° 59' 30"-88° 53' E longitude with an altitude of 132–3660 m. The region is humid and sub-tropical to sub-alpine where the average temperature varies between 3 to 22°C (Saxena, 2005). The average annual rainfall is between 270–310 cm and the soils of the region are acidic, yellow to red-brown in color and silty loam to sandy loam textured (Froehlich and Sarkar, 2000). Tropical (below 800 m), subtropical (800–1600 m), temperate (1600–2400 m), cold-temperate (2400–3200 m) and sub-alpine (3200–4000 m) types of vegetation are found in the Darjeeling Himalayas (Cajee, 2018). The forests in the region are mostly reserved and protected.

Sampling Design

The traditional large cardamom-based agroforestry farming in Darjeeling Himalayas was reported as the system where large cardamom is cultivated under the canopy of reserved or protected forest leased out to the growers by the State Forest Department with no rights to cut the trees (Sharma et al., 2009). A reconnaissance survey was conducted in the study area to explore the carbon storage potential of the large cardamom based traditional agroforestry systems. A total of 25 traditional large cardamom-based agroforestry holdings were purposively selected based on their accessibility, covering altitudes from 700–2000 m. The study area was classified into three altitude classes as low (700–1200 m asl), mid (1200–1700 m asl) and high (> 1700 m asl) with eleven, nine and five holdings, respectively. The geographical coordinates of the holdings were recorded with Garmin 72.

Estimation Of Biomass Carbon

An indirect or non-destructive method was adopted for estimating the above ground biomass (AGB) of trees following an allometric model suggested by Nath et al. (2019) (Eq. 1).

AGB = $0.18D^{2.16} \times 1.32$; where D is diameter at breast height (Eq. 1)

The below ground biomass (BGB) was estimated by multiplying the AGB by a factor of 0.25 as per IPCC guideline (1996) and Huang et al. (2020). The total trees biomass obtained by the summation of AGB and BGB and the tree biomass carbon was estimated as 47% of the biomass in the tree (IPCC, 2006).

Estimation Of Soil Organic Carbon

For the determination of soil organic carbon stock, soil samples were collected from each homegarden at different depths, viz., 0–20, 20–40 and 40–60 cm. Walkley and Black's rapid titration method was adopted for estimating the organic carbon content in the soil and the carbon stock in the soil was calculated by multiplying the organic carbon with the weight of the soil (depth x bulk density) for a particular depth and expressed in megagrams (Mg) per ha (Joao Carlos et al., 2001).

Statistical Tools

Statistical analysis was performed using IBM SPSS version 2020. The data were subjected to two-way analysis of variance (ANOVA) to compare the significance of two factors viz., traditional agroforestry systems and altitude.

Results And Discussion

Tree density

Tree density estimated for the system ranged from 5.0-210.0 trees ha^{-1} (*Litsea glutinosa*-*Cryptomeria japonica*). The prominent tree species with higher population density documented in the system were *Schima wallichii* (205 trees ha^{-1}), *Ficus auriculata* (190 trees ha^{-1}) and *Alnus nepalensis* (155 trees ha^{-1}). Tree density estimated at low-altitude class was in the range of 30–205 trees ha^{-1} (*Cryptomeria japonica*-*Schima wallichi*). *Ficus auriculata* (190 trees ha^{-1}), *Litsea monopetela* (130 trees ha^{-1}) and *Ficus colorata* (120 trees ha^{-1}) were the other denser tree species reported from low altitude class. In the mid-altitude, *Cryptomeria japonica* (210 trees ha^{-1}) followed by *Alnus nepalensis* (155 trees ha^{-1}) and *Schima wallichii* (95 trees ha^{-1}) were the denser tree species. While at high altitude class, the maximum tree population density was found for *Cupressus cashmeriana* (145 trees ha^{-1}) followed by *Alnus nepalensis* (120 trees ha^{-1}) and *Cryptomeria japonica* (110 trees ha^{-1}).

In contrast to the Sikkim Himalayan large cardamom based traditional agroforestry systems, where *Alnus nepalensis* reported as the prominent shade tree with density of 80.13 tree ha^{-1} (Lepcha and Devi, 2020), the prominent trees found in the Darjeeling Himalayan systems were *Schima wallichi* (205.0 trees ha^{-1}), *Cryptemoria japonica* (210 trees ha^{-1}) and *Cupressus cashmeriana* (145 trees ha^{-1}) at low-, mid- and high-altitude class respectively. In this study *Alnus nepalensis* was found with density of only 35 trees ha^{-1} at low altitude class while, at mid- and high-altitude class the species followed *Cryptemoria japonica* and *Cupressus cashmeriana* with density of 155 and 120 trees ha^{-1}, respectively. However, the density of *Alnus nepalensis* estimated at mid- and high-altitude classes in the present study is 39.87–74.87 trees ha^{-1} than estimated at Sikkim Himalayas (80.13 trees ha^{-1}) in the altitude of 1350 to 1619 m above mean sea level. This was because the studied systems at Sikkim Himalayas were in the agricultural landscape planted 20 years ago where the growers preferred *Alnus nepalensis* to maintain soil fertility and productivity as it can fix atmospheric nitrogen (Sharma et al., 1994). In contrast, the Darjeeling systems were cultivated under the canopy of leased out forest land by the growers with no rights to change the natural species composition of the forest. However, total tree density estimated in this study (105.33 trees ha^{-1}) was lesser than the Sikkim Himalayan studies (124.19 trees ha^{-1}) because the Darjeeling Himalayan systems were forest-based (Sharma et al., 2007) where the dominance of the species was distributed as compared to the Sikkim Himalayan system which was planted at an agricultural landscape where preferred species were planted and allowed to grow.

The tree density of the Darjeeling Himalayan system was also either comparable or higher than the poplar agroforestry system of North-western India (Rizvi et al., 2011), jhum fallow agroforestry of Tripura (Chaudhary et al., 2016), homegardens of Terai region and Darjeeling Himalayas of West Bengal (Subba et al., 2017), poplar agroforestry systems of China (Fang et al., 2010) and coffee agroforestry of Guatemala (Schmitt-Harsh et al., 2012). This indicates that the under-canopy forest-based traditional large cardamom agroforestry systems have the potential to promote, harbour and maintain diverse tree species with higher overall population due to their retained structure and composition as of the original forest. This also results in higher tree growth and thus acts in a way very similar to a natural forest (Sharma et al., 2007). However, the basal area of the systems estimated in the range of 4.46–18.27 m^2 ha^{-1} with an average of 13.31 m^2 ha^{-1} was found lesser than the Sikkim systems (Lepcha and Devi, 2020), tea agroforestry of Assam (Kalita et al., 2016), managed plantation and jhum fallow agroforestry of Tripura (Chaudhary et al., 2016) and homegardens of terai region and Darjeeling Himalayas of West Bengal. This might be due to the predominance of trees of young age (Subba et al., 2017) and the higher heterogeneity of the Darjeeling systems in terms of its structure and composition where dominance by the species was determined by higher inter- and intra-specific competition (Odum, 1983).

Tree Biomass And Carbon Stock

The biomass and carbon stock estimated for low, mid and high-altitude classes of large cardamom based traditional agroforestry systems of Darjeeling Himalaya is presented in Tables 1 and 2.

Table 1

Tree biomass and biomass carbon (Mg ha^{-1}) of large cardamom based traditional agroforestry systems at different altitude classes

AC	AGB	BGB	TB	AGC	BGC	TC
Low	504.14	126.03	630.17	236.94	59.24	296.18
Medium	317.64	79.41	397.05	149.29	37.32	186.61
High	252.63	63.16	315.78	118.73	29.68	148.42
Mean	**358.14**	**89.53**	**447.67**	**168.32**	**42.08**	**210.40**
$LSD_{0.05}$	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**

AC- Altitude class (Low- 700–1200 m asl; Mid- 1200–1700 m asl; High- > 1700 m asl); AGB- Above ground biomass; BGB- Below ground biomass; TB- Total biomass; AGC- Above ground carbon; BGC- Below ground carbon; TC- Total carbon

The biomass storage decreased gradually with the increasing altitude classes. Biomass stock decreased by 36.99% from low- to mid-altitude, 20.47% from mid- to high-altitude and 49.89% from low- to high-altitude classes due to variation in tree population, species richness and diameter at breast height (DBH) (Table 2).

Table 2
Biomass and carbon accumulation by tree species in large cardamom based traditional agroforestry systems

Species	D	H	Dy	AGB	BGB	TB	AGC	BGC	TC
Low-altitude class									
Alnus nepalensis	39.5	39.3	35	23.3	5.8	29.2	11.0	2.7	13.7
Oroxylum indicum	20.7	32.6	70	11.6	2.9	14.5	5.4	1.4	6.8
Celtis tetrandra	16.9	22.9	35	3.7	0.9	4.6	1.7	0.4	2.2
Terminalia myriocarpa	23.9	35.0	105	23.6	5.9	29.6	11.1	2.8	13.9
Cupressus cashmeriana	18.8	41.1	60	8.	2.0	10.1	3.8	0.9	4.7
Juniperus indica	24.8	29.9	95	23.3	5.8	29.1	10.9	2.7	13.7
Cryptomeria japonica	54.8	44.5	30	40.6	10.1	50.7	19.1	4.8	23.8
Macaranga denticulata	26.7	15.8	65	18.7	4.7	23.4	8.8	2.2	11.0
Ostodes paniculata	19.7	30.5	35	5.2	1.3	6.5	2.5	0.6	3.1
Albizia odoratissima	28.7	18.3	110	36.7	9.2	45.9	17.3	4.3	21.6
Erythrina variegate	31.2	27.4	50	20.1	5.0	25.1	9.4	2.4	11.8
Albizia procera	23.2	18.3	70	14.9	3.7	18.6	7.0	1.7	8.7
Castanopsis indica	18.1	26.8	60	7.5	1.9	9.3	3.5	0.9	4.4
Litsea monopetala	24.8	27.1	130	31.9	8.0	39.8	15.0	3.7	18.7
Toona ciliata	24.5	27.4	105	25.0	6.3	31.3	11.8	2.9	14.7
Ficus auriculata	19.7	36.6	190	28.4	7.1	35.5	13.3	3.3	16.7
Ficus lacor	16.6	27.1	115	11.7	2.9	14.7	5.5	1.4	6.9
Ficus semicordata	29.9	27.4	110	40.3	10.1	50.4	19.0	4.7	23.7
Citrus spp	12.7	23.4	45	2.6	0.6	3.3	1.2	0.3	1.5
Firmiana colorata	24.8	27.4	120	29.4	7.3	36.8	13.8	3.5	17.3
Schima wallichii	33.7	29.9	205	97.5	24.4	121.8	45.8	11.45	57.3
Mean	**25.4**	**29.0**	**88**	**24.0**	**6.0**	**30.0**	**11.3**	**2.8**	**14.1**
Mid-altitude class									
Alnus nepalensis	29.9	39.3	155	56.8	14.2	71.2	26.7	6.7	33.4
Bischofia javanica	22.9	33.5	40	8.2	2.1	10.3	3.9	1.0	4.8

Species	D	H	Dy	AGB	BGB	TB	AGC	BGC	TC
Low-altitude class									
Brassaiopsis mitis	21.7	10.4	80	14.6	3.6	18.2	6.8	1.7	8.6
Cryptomeria japonica	32.5	44.5	210	91.9	23.0	114.9	43.2	10.8	54.0
Cupressus cashmeriana	17.5	41.1	35	4.0	1.0	5.0	1.9	0.5	2.4
Erythrina variegate	24.2	27.4	50	11.6	2.9	14.5	5.4	1.4	6.8
Exbucklandia populnea	22.3	15.2	20	3.9	1.0	4.8	1.8	0.5	2.3
Ficus semicordata	21.7	27.4	85	15.5	3.9	19.4	7.3	1.8	9.1
Ficus spp.	23.6	23.5	40	8.7	2.2	11.0	4.1	1.0	5.1
Firmiana colorata	16.9	27.4	55	5.8	1.5	7.3	2.7	0.7	3.4
Gynocardia odorata	22.3	19.8	45	8.7	2.2	10.9	4.1	1.0	5.1
Leucosceptrum canum	8.0	29.9	50	1.0	0.3	1.3	0.5	0.1	0.6
Macaranga denticulata	28.0	15.8	75	23.9	6.0	29.8	11.2	2.8	14.0
Mallotus tetracoccus	24.8	37.8	30	7.3	1.8	9.2	3.5	0.9	4.3
Prunus cerasoides	21.3	9.7	35	6.2	1.5	7.7	2.9	0.7	3.6
Schima wallichii	28.7	29.9	95	31.7	7.9	39.6	14.9	3.7	18.6
Terminalia myriocarpa	12.7	35.0	50	2.9	0.7	3.6	1.4	0.3	1.7
Toona ciliata	31.8	27.4	35	14.7	3.7	18.3	6.9	1.7	8.6
Mean	**43.2**	**52.1**	**124.7**	**25.1**	**8.4**	**41.8**	**15.7**	**3.9**	**19.6**
High-altitude class									
Alnus nepalensis	27.1	39.3	120	35.4	8.8	44.3	16.6	4.2	20.8
Cryptomeria japonica	28.7	44.50	110	36.7	9.2	45.9	17.3	4.3	21.6
Cupressus cashmeriana	33.1	41.1	145	66.2	16.5	82.7	31.1	7.8	38.9
Euonymus attenuatus	28.0	10.7	80	25.4	6.4	31.8	12.0	3.0	15.0
Litsea glutinosa	21.3	33.5	5	0.9	0.2	1.1	0.4	0.1	0.5
Machilus edulis	21.0	17.1	35	6.0	1.5	7.5	2.8	0.7	3.5
Magnolia doltsopa	22.3	15.8	15	2.9	0.7	3.6	1.4	0.3	1.7
Magnolia grandiflora	18.1	23.8	15	1.9	0.5	2.3	0.9	0.2	1.1

Species	D	H	Dy	AGB	BGB	TB	AGC	BGC	TC
Low-altitude class									
Magnolia lanuginosa	22.9	15.8	45	9.3	2.3	11.6	4.4	1.1	5.4
Pinus wallichiana	14.0	36.0	55	3.9	1.0	4.9	1.8	0.5	2.3
Rhododendron griffithianum	20.4	33.8	35	5.6	1.4	7.0	2.6	0.7	3.3
Schima wallichii	38.2	29.9	75	46.6	11.6	58.3	21.9	5.5	27.4
Terminalia myriocarpa	26.4	35.0	35	9.8	2.4	12.3	4.6	1.1	5.8
Thuja plicata plicata	22.6	10.7	10	2.0	0.5	2.5	0.9	0.2	1.2
Mean	**45.9**	**51.6**	**104.0**	**33.7**	**8.4**	**42.1**	**15.8**	**4.0**	**19.8**

D- Diameter at breast height (cm); H- height (m); Dy- Density (trees ha $^{-1}$); AGB- Above ground biomass (Mg ha $^{-1}$); BGB- Below ground biomass (Mg ha $^{-1}$); TB- Total biomass (Mg ha $^{-1}$); AGC- Above ground carbon (Mg ha $^{-1}$); BGC- below ground carbon (Mg ha $^{-1}$); TC- Total carbon (Mg ha $^{-1}$)

The changes in tree biomass storage along the altitude classes were inversely related ($r = -0.255^{*}$). A non-significant effect of altitude on forest biomass and carbon was earlier reported (Wondimu et al., 2021), while, on the contrary, either direct or inverse relationships between elevation and biomass or carbon stock also exist (Zhang et al., 2018). The varied relationship of altitude classes with biomass storage is attributed to site specific changes in tree population and their structure. The large cardamom based traditional agroforestry systems at low altitude-class accumulated the highest biomass and carbon due to the highest number of trees per unit area than the mid- and high-altitude classes. A significant and positive influence of tree species richness on forest biomass and biomass carbon storage along an elevational gradient has also been reported by Wu et al (2017) and Wondimu et al (2021).

Total tree biomass and carbon storage in this study was found much higher than that quantified for Sikkim Himalayan systems (Lepcha and Devi, 2020), homegardens of the Terai zone and Darjeeling Himalayas of West Bengal (Pala *et al.*, 2020) and elsewhere (Kalita et al., 2016). However, it is comparable to different subtropical forest ecosystems of Indian eastern Himalayas (Borah et al., 2015; Chaudhary et al., 2016). The variation in biomass and carbon accumulation amongst these studies is due to variation in geographical location (site quality, topography, climate and edaphic conditions), plant species and species diversity (stem density, stem size distribution, age, density, diameter, canopy height and wood density), management practices and disturbance history (Kalita et al., 2016; Devi and Yadava, 2016; Tamang et al., 2021).

Ivi And Total Biomass Of Dominant Species

The Importance Value Index (IVI) of the species found in each altitudinal class is determined by the summation of relative density, relative dominance, and relative frequency (Brower et al., 1997). The IVI value indicates the ecological significance of a species in a particular area, accordingly, species having a higher IVI value have higher relative dominance than other species in the study area (Zafriakama *et al.*, 2020). In the present study, five species with top IVI values were selected from each of the altitudinal classes and evaluated their potential contribution toward total biomass (Fig. 1, 2, 3, 4, 5, and 6). *Schima wallichii*, *Cryptomeria japonica*, and *Cupressus cashmeriana* were the dominant species reported from the low-, mid-, and high altitudinal classes respectively. In addition, *Schima wallichi* was one of the top five dominant species in all the altitudinal classes. It is also evident that the total biomass carbon was significantly higher for the most dominant species in each of the altitude classes, even though there is no direct relation observed between dominance and biomass during the study. While comparing the total biomass of the most dominant species among the three altitudinal classes, maximum biomass was observed with the dominant species in the lowest altitudinal class (*Schima wallichii*, 133.75 Mg ha^{-1}) followed by the high- (*Cupressus cashmeriana*, 72.1 Mg ha^{-1}) and mid-altitudinal classes (*Cryptomeria japonica* (37.43 Mg ha^{-1}).

The potential biomass and carbon storage varied from species to species and also with altitude class due to variations in tree density and DBH (Table 2). At the low-altitude class, the most prominent tree species in terms of biomass accumulation was *Schima wallichii* with an estimated biomass of 121.8 Mg ha^{-1} and average DBH and density of 33.7 cm and 205 trees ha^{-1} respectively. It was followed by *Cryptomeria japonica* (estimated biomass of 50.7 Mg ha^{-1}, DBH 54.8 cm and density 30 trees ha^{-1}) and *Ficus semicordata* (biomass of 50.4 Mg ha^{-1}, DBH 29.9 cm and density 110 trees ha^{-1}). In the mid-altitudinal class, the major tree found was *Cryptomeria japonica* with biomass of 114.9 Mg ha^{-1}, DBH 32.5 cm and density of 210 trees ha^{-1}, followed by *Alnus nepalensis* (biomass of 71.2 Mg ha^{-1} with DBH 29.9 cm and density 155 trees ha^{-1}) and *Schima wallichii* (biomass of 39.6 Mg ha^{-1} with DBH 28.7 cm and density 95 trees ha^{-1}). *Cupressus cashmeriana*, *Schima wallichii*, *Cryptomeria japonica* and *Alnus nepalensis* were the dominant tree species found at high-altitude class with biomass accumulation of 82.7, 58.3, 45.9 and 44.3 Mg ha^{-1} with a DBH of 33.1, 38.2, 28.7 and 27.1 cm and density of 145, 75, 110 and 120 trees ha^{-1}, respectively.

In contrast to maximum biomass and carbon stock by *Alnus nepalensis* at Sikkim Himalayan systems, *Schima wallichii, Cryptomeria japonica* and *Cupressus cashmeriana* reported the maximum biomass and carbon at low-, middle-and high-altitude classes respectively. However, similar to the Sikkim systems, the highest biomass and carbon accumulation in this study was also found to correspond with the highest tree density and DBH or basal area (Lepcha and Devi, 2020). The tree biomass and carbon storage estimated for different species in the present study were found inconsistent with the DBH of the trees but largely consistent with the tree density, similar to the studies reported for large cardamom systems of Sikkim Himalayas (Lepcha and Devi, 2020), and tea agroforestry system of Assam (Kalita et al., 2016) while, contrasted to *Dipterocarpus* forest of Manipur (Devi and Yadava, 2016). Similarly, above and below-ground biomass allocation of many individual tree species was reported with a major contribution by above-ground biomass (Justine et al., 2015; Singh and Singh, 2017).

Ecosystem Carbon Stock

The ecosystem carbon stock of large cardamom based traditional agroforestry system in Darjeeling Himalaya is given in Fig. 7.

The ecosystem carbon stock across all the elevation gradients was estimated at 295.02 Mg ha^{-1}. The contribution of tree biomass carbon and soil carbon to the total carbon stock was 71.32% and 28.68% respectively. The ecosystem carbon stock at low-, mid- and high-altitude classes were 363.10 Mg ha^{-1}, 272.06 Mg ha^{-1} and 249.90 Mg ha^{-1}, respectively. The contribution of SOC to ecosystem carbon stock increased with increasing altitude.

Ecosystem carbon stock under large cardamom traditional agroforestry systems estimated was higher than the stock estimated for traditional homegardens, farm forestry and plantation forests (Tamang et al., 2021). The carbon sequestration potential of tree-based land use systems varies with geographical location, nature of species, species richness and age of the tree (Liu et al., 2015). Moreover, the amount of carbon stored in large cardamom based traditional agroforestry system was reported to be predominantly dependent on its structure and function, which in turn were influenced by the community and culture of the region (Singh et al., 2018; Lepcha and Devi, 2020). Higher biomass and SOC stock can efficiently and permanently manage the ecosystem carbon pool in large cardamom based traditional agroforestry systems (Mathew et al., 2016). Large cardamom-based agroforestry systems are practised in leased forest areas where tree felling is prohibited. Such agroforestry development and management systems help in the conservation and improvement of SOC. The traditional large cardamom farming systems are diverse, structurally and compositionally, making the system permanent, stable, resilient and productive (Shukla et al., 2017; Subba et al., 2018).

Conclusion

The traditional large cardamom farming systems are diverse, structurally and compositionally, thus making the system resilient and productive. Therefore, identifying dominant tree species will help sustainable management of the system since the dominant species mainly regulate the magnitude and pattern of energy flow and material cycle between biotic and abiotic components of the system. The density of trees in the system was in the range of 5.0-210.0 trees ha^{-1} with *Schima wallichii* (205 trees ha^{-1}), *Ficus auriculata* (190 trees ha^{-1}) and *Alnus nepalensis* (155 trees ha^{-1}) as prominent tree species. In addition, biomass carbon data presented along an altitudinal gradient will enhance our understanding of the life history, nutrient cycling, carbon stocks, and potential to offset carbon dioxide emissions of the system. The tree biomass storage gradually decreased with the increasing altitude classes with as was evidenced from significant inverse relationship between tree biomass accumulation and altitude. The tree biomass and ecosystem carbon accumulated in the system quantified was 447.67 & 295.02 Mg ha^{-1} while, at low-, mid- and high-altitude class the biomass estimated was 630.17 & 363.1 Mg ha^{-1}, 397.05 & 272.06 Mg ha^{-1} and 315.78 & 249.09 Mg ha^{-1}, respectively. *Schima wallichii*, *Cryptomeria japonica*, and *Cupressus cashmeriana* were the dominant species in terms of their highest IVI values in low-, mid-, and high altitudinal classes respectively. Moreover, most of the dominant species in each altitude classes were also quantified with significantly higher total biomass carbon though no direct relationship between dominance and biomass was established during the study. The high ecosystem carbon storage under the large cardamom agroforestry systems indicates that management and promotion of such systems can be an efficient adaptation option in Darjeeling Himalayas to mitigate climate change locally and regionally in addition to the provision of livelihood and other ecological benefits.

Declarations

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Data availability: All data generated or analysed during this study are included in this paper.

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Figures

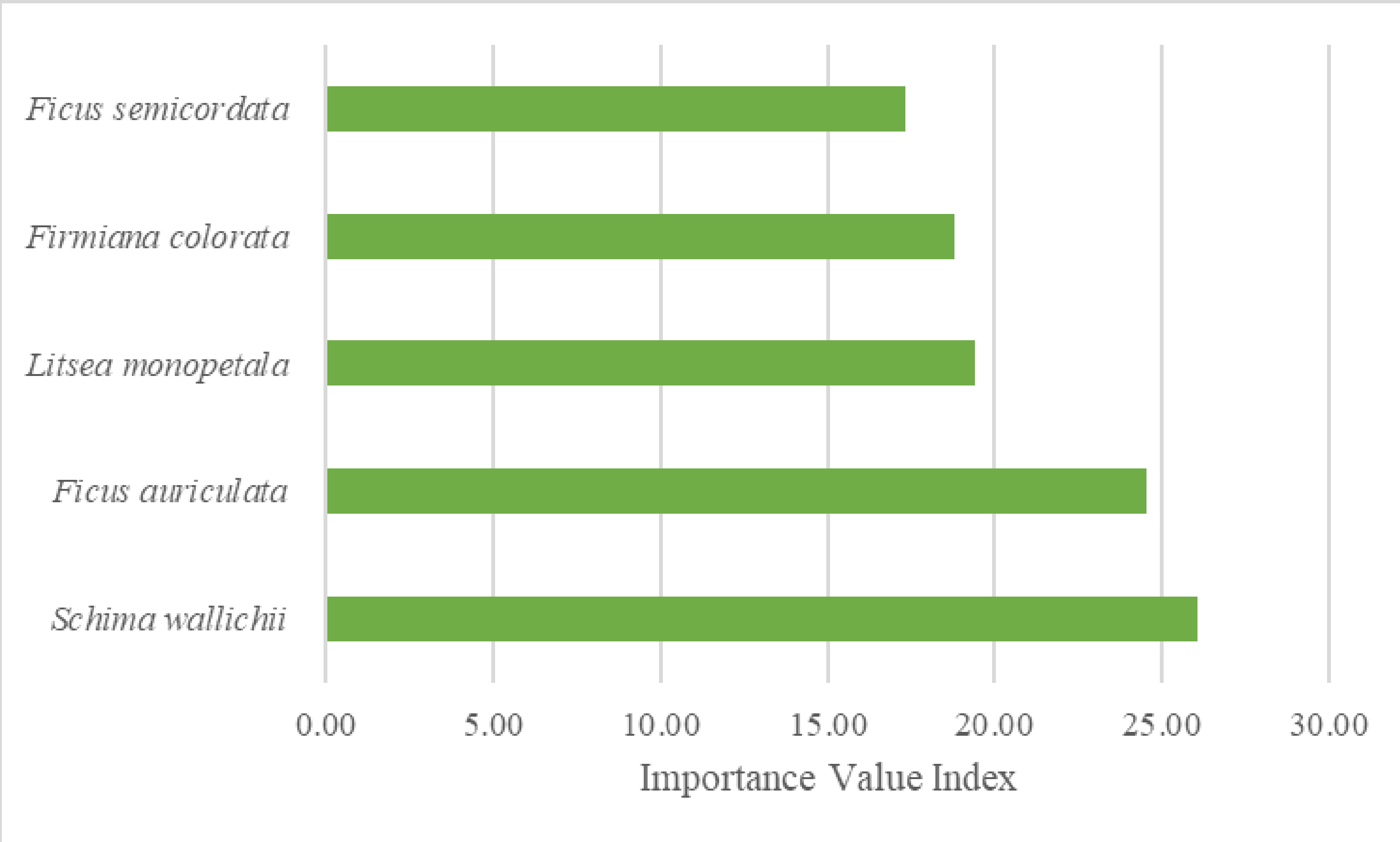

Figure 1

IVI value of 5 dominant species at altitude class 700-1200 m

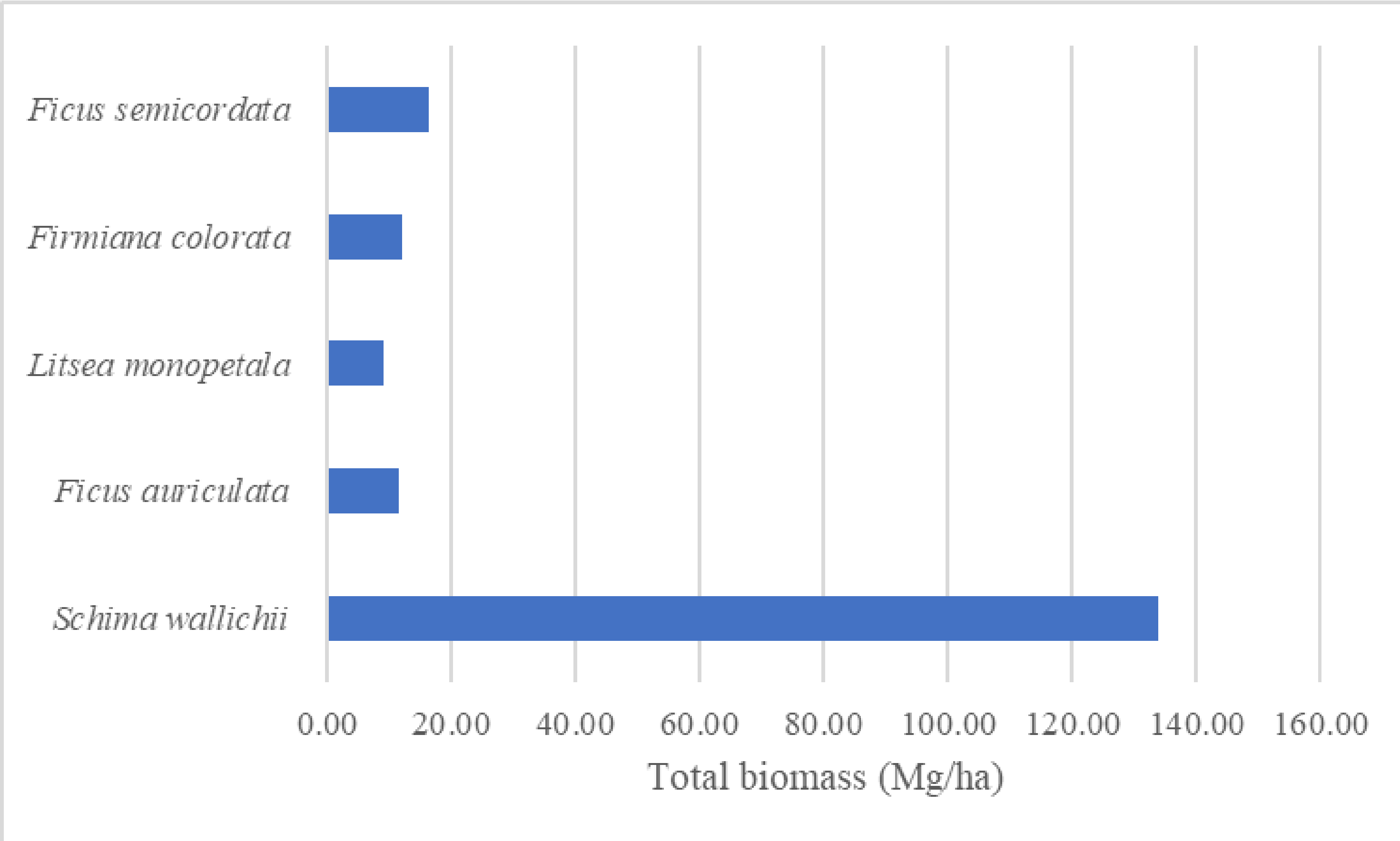

Figure 2

Total biomass of 5 dominant species at altitude class 700-1200 m

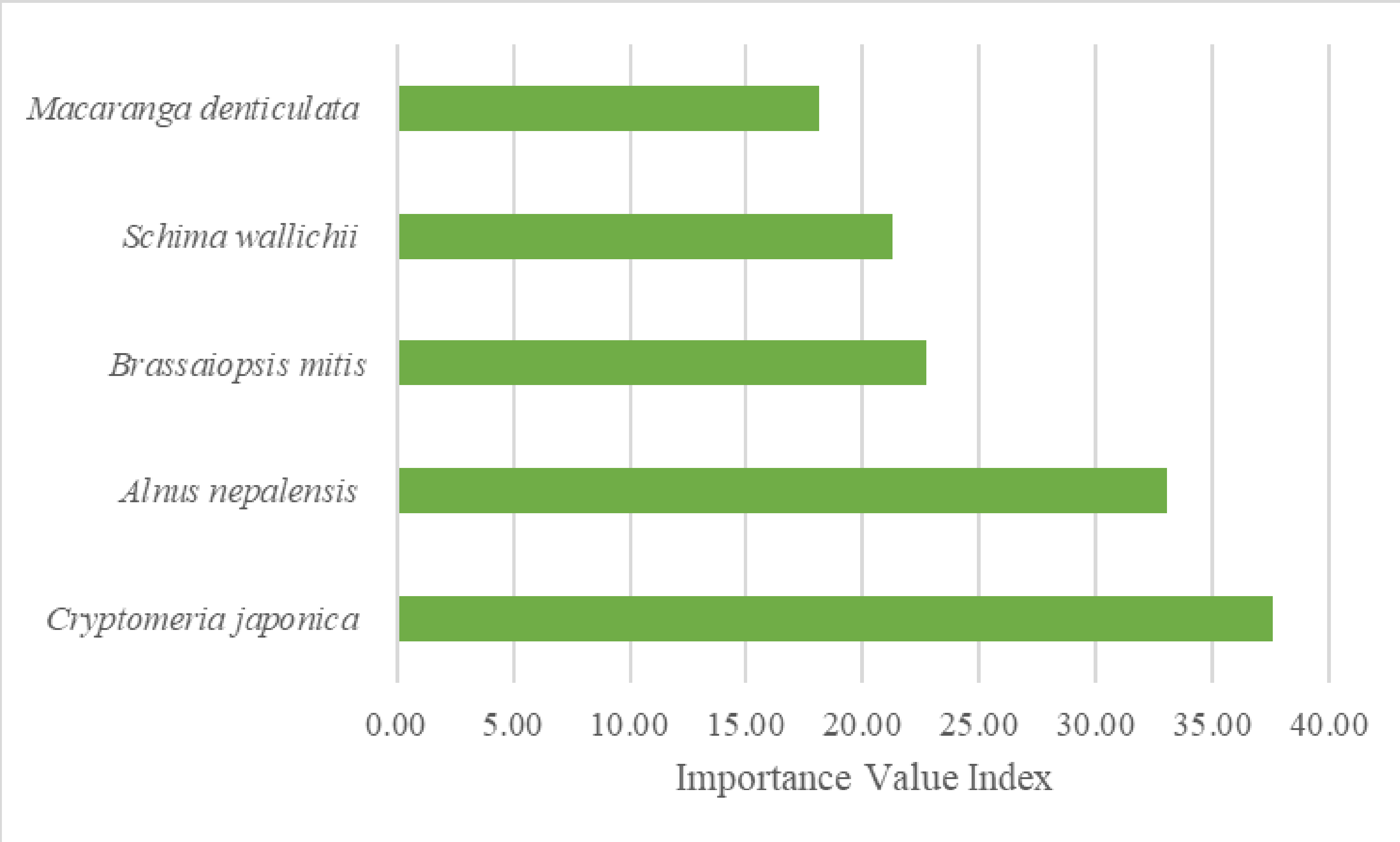

Figure 3

IVI value of 5 dominant species at altitude class 1200-1700 m

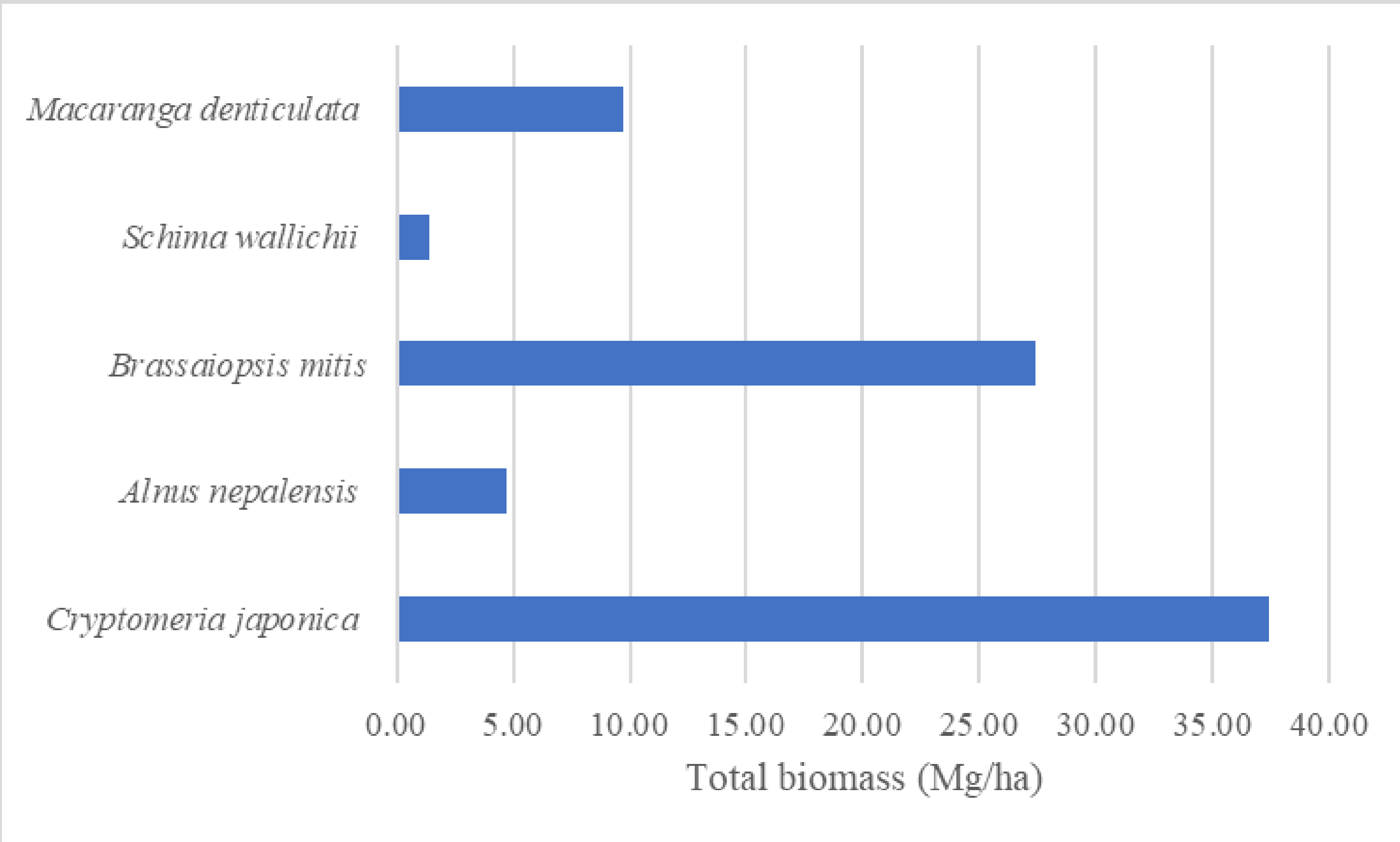

Figure 4

Total biomass of 5 dominant species at altitude class 1200-1700 m

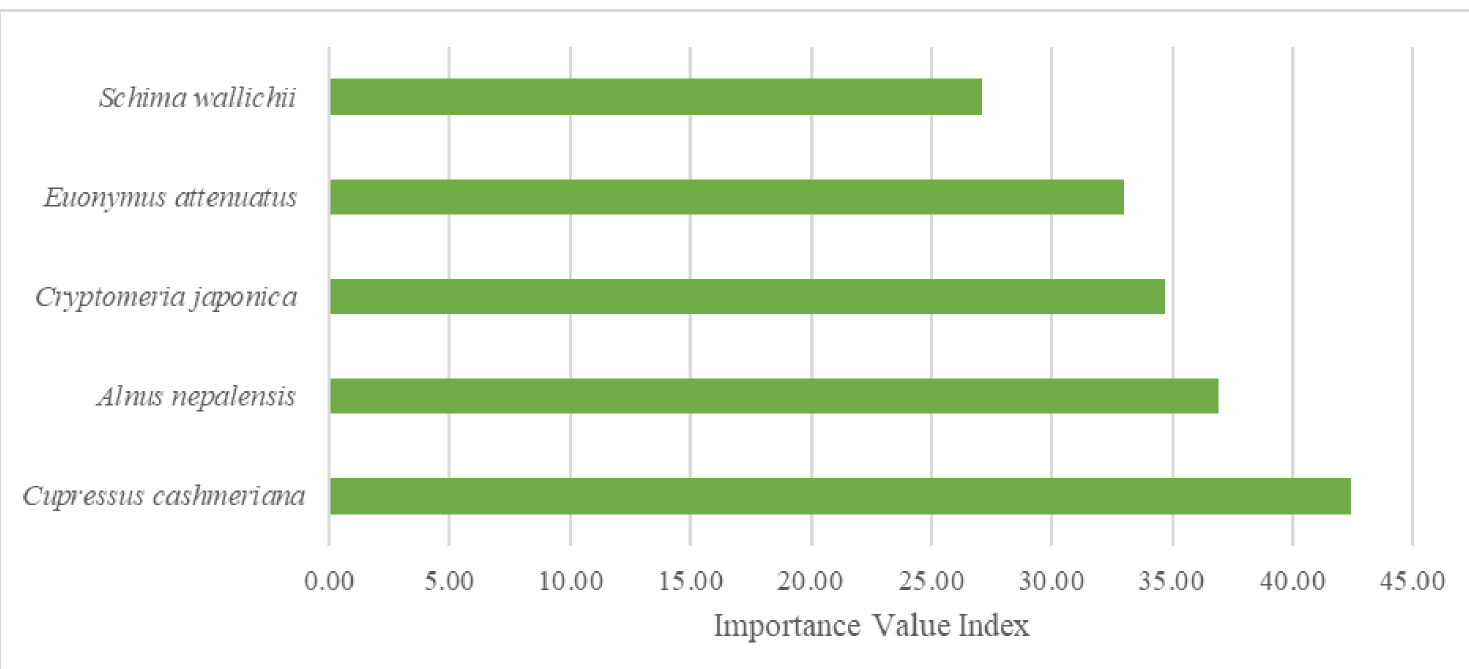

Figure 5

IVI value of 5 dominant species at altitude class >1700 m

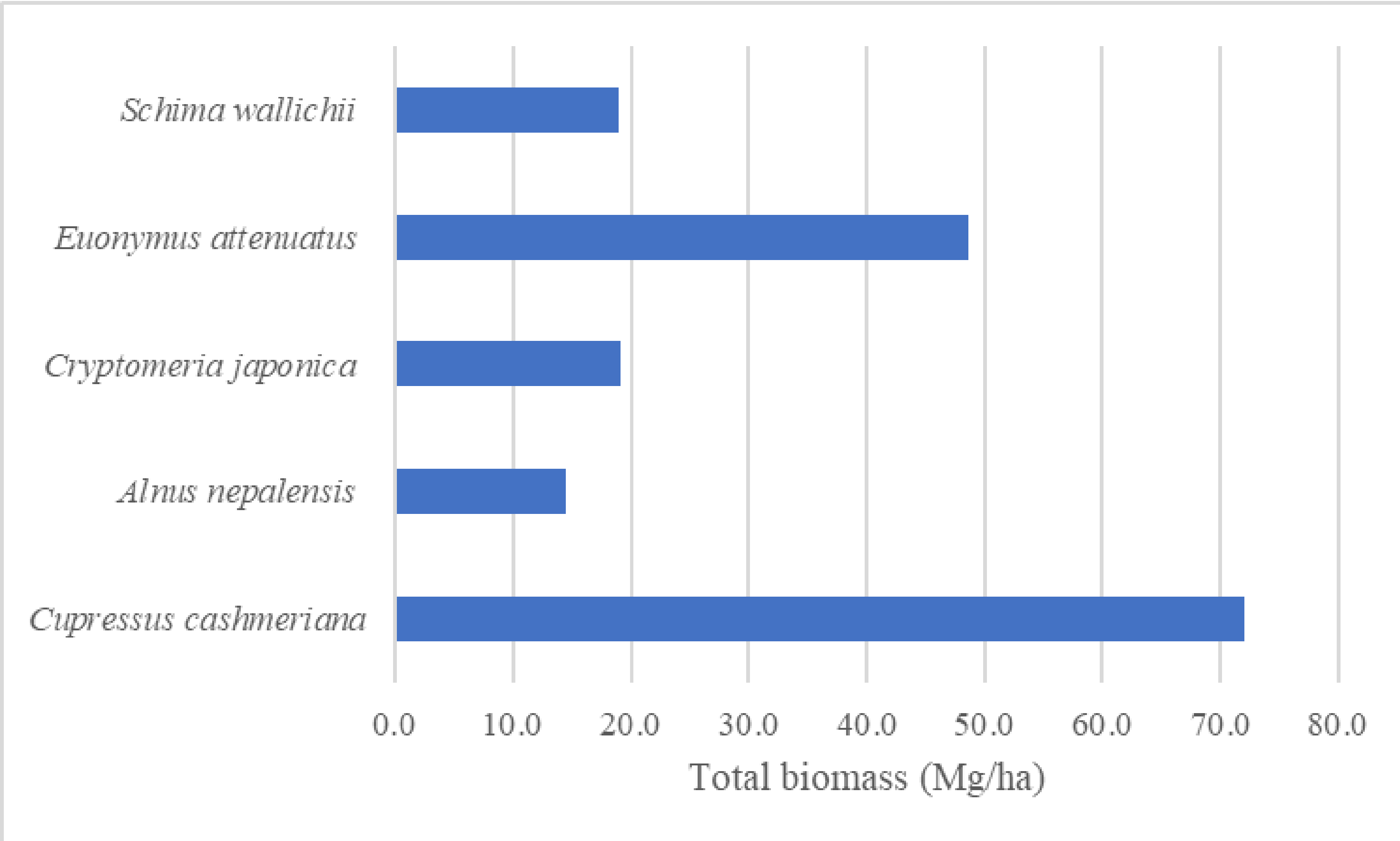

Figure 6

Total biomass of 5 dominant species at altitude class >1700 m

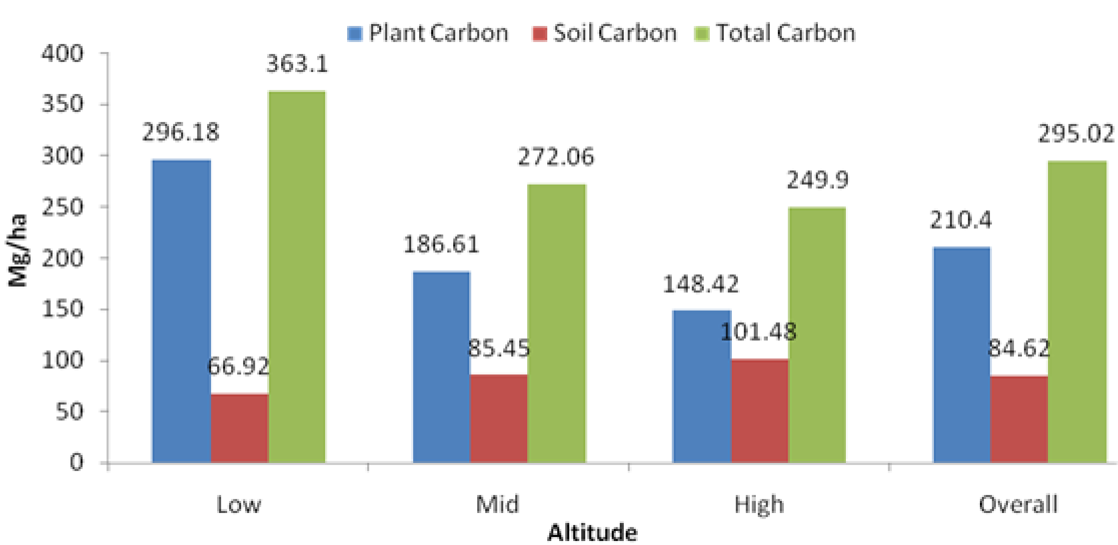

Figure 7