Ecological Processes

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Biomass production and carbon stock inventory of high-altitude dry temperate land use systems in North Western Himalaya

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Abstract

Introduction: Carbon stock estimation in different land use systems is necessary for curbing global climatic crisis. In the present study, high-altitude dry temperate land use systems (LUS) at three altitudinal ranges "$A_{1,}$ 1900–2170 m.a.s.l., $A_{2,}$ 2170–2440 m.a.s.l., and $A_{3,}$ 2440–2710 m.a.s.l." were selected based on lapse rates in Kinnur district of Himachal Pradesh, India. The study was aimed at estimating the difference in biomass and carbon stocks in different land use systems and recommendation of the suitable environment-friendly land use for the region. Six land use systems viz.; agriculture, horticulture, agrihorticulture, agri-horti-silviculture, silvipasture, and barren land common at all the three altitudes were selected for experimental setup.

Results: Maximum mean aboveground biomass (84.65 t ha^{-1}), belowground biomass (19.50 t ha^{-1}), and total biomass (104.10 t ha^{-1}) were recorded in the silvipasture land use system. Total biomass production of different land use systems followed the order: silvipasture > agri-horti-silviculture > agrihorticulture > horticulture > agriculture > barren land respectively. Maximum soil organic carbon (1.41%) was recorded in silvipasture land use systems, which however remained statistically at par with the organic carbon contents of horticulture. Soil organic carbon, irrespective of the land use system increased with increase in altitudinal range and decreased with increase in soil depth. Maximum carbon density (155.77 t ha^{-1}) in 0–100 cm layer was in agri-horticulture LUS. The order of carbon density under different land use systems was agri-horticulture > agri-horti-silviculture > silvipasture > horticulture > agriculture > barren land. Irrespective of the land use system, the carbon density at different altitudinal gradient followed the trend A_1, 1900–2170 m.a.s.l., > A_3, 2440–2710 m.a.s.l and > A_2, 2170–2440 m.a.s.l.

Conclusions: The outcome of the study can play an important role, while selecting different land use systems and different crop combinations for effective management of carbon budget to mitigate climate change and global warming issues in other fragile Himalayan ecosystems.

Keywords: Altitude, Agroforestry, Management, Carbon density, Mitigation

Introduction

Livelihood opportunities can be enhanced, and vulnerability of natural resources to climate change can be reduced through adoption of suitable land use systems (Pandey 2007; De Stefano and Jacobson 2017). Agroforestry as a traditional land use system and resource management has potential to improve the livelihoods by providing ecosystem services like food, fruits, fodder, and firewood (Pandey 2007). Appropriate policy responses combining agroecosystems as key assets can strengthen adaptation and help to build the resilience of communities and households to local and global change (AFD et al. 2003). Pandey (2007) argues that adaptive management of natural resources and agroecosystems will improve economy and bring better results. Land management actions that enhance the uptake of CO_2 or reduce its emissions have the potential to remove a

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significant amount of CO_2 from the atmosphere by locking through non-destructive (Pandey 2007).

Apart from CO_2, the atmospheric concentration of CH_4 has increased to 1774 ppb in 2005 from the preindustrial value of 715 ppb (148% increase) (IPCC 2007). N_2O continues to rise at the rate of 0.26% per year, measured at 319 ppb in 2005, 18% higher than its pre-industrial value (IPCC 2007). The participating countries, including the USA at the third meeting of the FCCC in 1997 in Kyoto, Japan, agreed to reduce greenhouse gas emissions to 5% or more below 1990 levels by 2012 (https://unfccc.int/). According to the Kyoto protocol, only newly carbon sequestered through agroforestry practices is considered as carbon credits and can be sold to industrialized countries to meet their emission reduction targets, although there is pressure to include soil carbon also (Lal 2004). The problem in the Himalayas is complex, having intricate linkages between social, economic, and ecological concerns (Singh 2006). Landholding is often so small that for the survival of poor families, agroforestry land use system becomes a lifeline for sustaining daily needs. The introduction of more woody perennials in and around the orchards and other agriculture landscapes of the Himalayan region can enhance and safeguard the biodiversity and in turn will improve livelihood opportunities (Singh et al. 2017). These agroforestry land use systems provide ecosystem services by becoming reservoirs for carbon stock storage and mitigation of climate change along with the sustenance of livelihood (Rajput et al. 2015; Gokhale and Pala 2011; Pala et al. 2015).

Albrecht and Kandji (2003) reported carbon sequestration potential of tropical agroforestry systems between 12 and 228 Mg ha^{-1}, with a median value of 95 Mg ha^{-1}. Therefore, in the next 50 years, 1.1–2.2 Pg C could be stored in the terrestrial ecosystems based on the global estimates of the area suitable for the agroforestry (Albrecht and Kandji 2003). Introduction of more and more tree-based land use systems like agroforestry is one alternative to deal with problems related to land use and CO_2-induced global warming (Albrecht and Kandji 2003). The significance of agroforestry with respect to C sequestration and other CO_2 mitigating effects has gained praise in the past as well as in the present throughout the globe, but there is still paucity of quantitative data on specific systems. Several authors (Rajput et al. 2015; Rajput et al. 2017; Shah et al. 2014; Devi et al. 2013; Saha et al. 2018) in the past few years have carried their studies on carbon and climate change issues in other regions of the state of Himachal Pradesh, India, but no literature is available for higher altitudes from the region. The study is therefore the maiden attempt covering high-altitude dry temperate land use systems in Kinnur district off Himachal Pradesh, India, for estimation of above- and belowground carbon stock. This study will be helpful to estimate the potential of different land use systems and can be useful in providing information for planners, policy makers, and farmers for effective management in a climate change mitigation and carbon budgeting of the dry temperate region of the Himalayan ecosystem.

Methods

Study area

The study area is located in Kinnaur district of Himachal Pradesh, India, which lies in the north western part of the state having an elevational range from 1000 to over 6000 m above mean sea level (Fig. 1). The area is famous

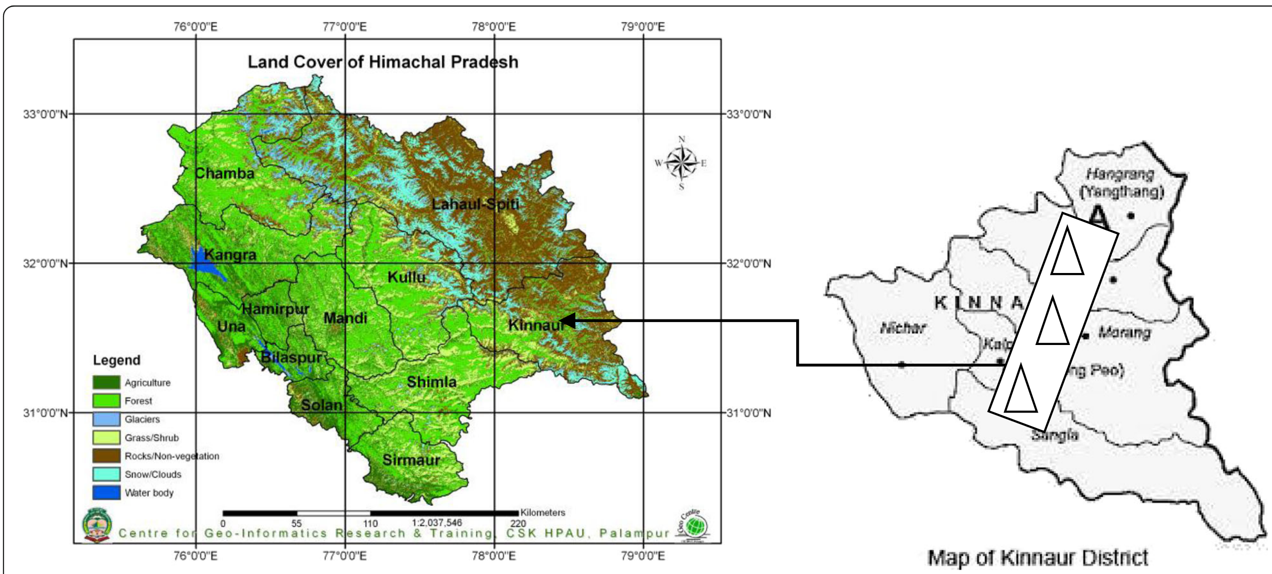

Fig. 1 Map of Himachal Pradesh showing location of experimental sites (www.himadventures.net)

for the Kinnaur Kailash, a sacred mountain, close to the Tibetan border. The experimental plots were laid between 31° 05′ 50″ and 32° 05′ 15″ North Latitude and 77° 45′ and 79° 00′ 35″ East Longitude between 1600 and 2710 m.a.s.l. The area experiences high hill dry temperate climatic conditions due to its high elevation, with long winters from October to May and short summers from June to September. The texture of the soil is sandy to loamy sand with pH of 6.0–6.8 having entisols and inceptisols as soil type. Kinnaur is a tribal district, which is one of the smallest but prosperous districts in India. The population and geographic area of the district is 83,950 and 6401 km^2, respectively. This is a mountainous district and covers around 47% areas under rocks/non-vegetation. The glaciers occupy 4%, i.e., 235.39 km^2 area. The area under agriculture is 3% of the total area. Snow/clouds cover is 10% of the area. The economy of the district is predominantly agrarian and about 64% of the population is dependent on farming for livelihood (Chisanga 2012). Portions of Kinnaur district are situated high in the Himalayas, where vegetation is sparse and consists primarily of hardy grasses. Alpine species such as juniper, pine, fir, cypress, and *Rhododendron* can be found at elevations between 3500 and 5000 m, primarily in middle Kinnaur (Chisanga 2012). At lower-altitude, tree species like oak, chestnut, maple, birch, alder, magnolia, apple, and apricot are found (HFS 2013).

Experimental setup and design

For conducting this study, six land use systems, viz. agriculture (T_1), horticulture (T_2), agrihorticulture (T_3), agri-horti-silviculture (T_4), silvipasture (T_5), and barren (T_6), which are common in the three altitudinal ranges, viz. (A_1) 1900–2170 m.a.s.l., (A_2) 2170–2440 m.a.s.l., and (A_3) 2440–2710 m.a.s.l., were selected based on the lapse rate (1 °C fall in temperature as we rise by 270 m in the Himalayan hills). For biomass and carbon estimation, RBD (factorial) design with 18 treatment combinations {6 (land use systems) × 3 (altitudinal ranges)} and for soil carbon RBD (factorial) with 54 treatment combinations {6 (land use systems) × 3 (altitudinal ranges) × 3 (soil layers)} were applied to observe the difference (Table 1).

Methodology

Three plots of size (50 m × 20 m) were selected for enumeration of trees for biomass estimation at every altitudinal land use. All the trees falling in the plots were enumerated. The diameter at breast height (dbh) was measured with caliper and height with Ravi's multimeter. Local volume equation developed for specific tree species and region were used for calculating the volume of the trees of the sample plot. Where volume equations were not available for the concerned species, form factor was calculated using a Spiegel relascope to find out the tree volume using the formula given by Pressler (1865) and Bitterlich (1984). Specific gravity values were also used to determine the biomass, and stem cores were taken to find out specific gravity using a maximum moisture method (Smith 1954). Total number of branches, irrespective of size, were counted on each of the selected tree and divided based on basal diameter into three groups, viz., < 6 cm, 6–10 cm and > 10 cm. Branch biomass and leaf biomass of forest tree species were measured by methods given by Chidumaya (1990) and Jenkin et al. (2003), respectively. Leaf carbon content was estimated by multiplying with a factor of 0.5 "IPCC default value". Addition of stem, branch, and leaf biomass was taken as total tree biomass and was converted into its carbon content by multiple shoot ratio (apple = 0.33; plum = 0.35) Rajput et al. (2015). Fallen leaves and pruned wood under each tree were collected, weighed, subsampled, and oven dried at 65 ± 5 °C to a constant weight.

Shrub biomass

Shrub biomass was estimated using two 5 m × 5 m quadrates in every main plot. All the shrubs occurring within the borders of the quadrate were enumerated. The diameter of all tillers was measured at base with the help of a caliper (Chaturvedi and Khanna 1982). Local volume equations developed for specific shrub species and region were used for calculating the volume of the woody shrubs of the sample plots.

Grass biomass

Grass biomass was estimated using five 1 m × 1 m quadrates inside the every mail plot. Within the borders of laid quadrat, total grass biomass present were cut at ground level and collected samples were weighted, subsampled, and oven dried at 65 ± 5 °C to a constant weight and converted into carbon by multiplying with a IPCC default value factor of 0.5 (Rajput et al. 2015).

Belowground biomass and carbon stock/density

Belowground biomass of trees and shrubs was calculated by using Cairns et al. (1997) equation and as per the IPCC guidelines. Belowground biomass of the grasses and herbs was measured by using root to shoot ratio given by Mokany et al. (2006). Carbon stock was obtained by multiplying the biomass with the IPCC default value (0.5) and carbon density as carbon in tons hectare^{-1}.

Soil organic carbon (%)

Three composite soil samples were collected from every plot at different layers, viz. 0–20 cm, 20–40 cm, and 40–100 cm (Fig. 2). The composite soil samples were air dried, ground with mortar and pestles, and sieved with a

Table 1 Experimental details indicating specific tree crop combination and their distribution in the study area

Land use system/ elevation range	Code	Tree-crop combination	Plot size m^2	Net cropped area (ha)	Area under trees (ha)	Area under grasses ha	No. of trees ha–^{1}	Average age of the tree component
Agriculture	A		50 × 20					
1900–2170 m		Pea – Maize, Wheat – Rajmash		1.00	–	–	–	Annual
2170–2440 m		Barley – Rajmash,		1.00	–	–	–	Annual
2440–2710 m		Peas – cabbage		1.00	–	–	–	Annual
Horticulture	H		50 × 20					
1900–2170 m		Apple		–	1.00	–	185	25 year (A)
2170–2440 m		Apple		–	1.00	–	212	20 year (A)
2440–2710 m		Apple		–	1.00	–	400	18 year (A)
Agri-horticulture	AH		50 × 20					
1900–2170 m		Apple + Peas – Maize, Apple + Wheat – Rajmash, Apple + Barley – Rajmash		0.9	1.0	–	185	25 year (A)
2170–2440 m		Apple – Peas – Cabbage, Apple + Wheat – Rajmash, Apple + Barley – Rajmash		0.9	1.0	–	212	20 year (A)
2440–2710 m		Apple + Wheat – Rajmash, Apple + Barley – Rajmash,		0.9	1.0	–	400	18 year (A)
Agri-horti-silviculture	AHS		50 × 20					
1900–2170 m		*Robinia* + Apple – Pea + Maize, *Ailanthus altissima* + Apple – Pea + Maize,		0.3	0.4	–	55	~40 year (R)
		Salix tetraperma + Apple + Pea – Maize		0.4	0.3	–	63	~40 year (B-S)
2170–2440 m		*Robinia* + Apple + Pea – Cabbage, *Populus ciliata* + Apple + Wheat – Rajmash				–	120	~50 year (A-I)
		Cedrus deodara + Apple + Barley – Rajmash		0.5	0.2	–	100	~60 year (F-S)
24,410–2710 m		*Cedrus deodara* + Apple + Wheat – Rajmash, *P. gerardiana* + Apple +Wheat – Rajmash, *Cedrus deodara* + Apple + Barley– Rajmash				–	100	60 cm diameter (C)
Silvipasture	SP		50 × 20					26.4 cm diameter (P)
1900–2170 m		*Pinus gerardiana* + Grasses + *Artemisia inbia* + *A. brevifolia*		–	0.4	0.6	160	~70 year (A-I)
2170–2440 m		*Pinus gerardiana* + *A. brevifolia* + Grasses		–	0.5	0.5	171	~70 year (Ab)
2440–2710 m		*Cedrus deodara* + *A.brevifolia* + *Lespedeiza gerardiana* + Grasses		–	0.7	0.3	159	60 cm diameter (C)
Barren land	BL		50 × 20					
1900–2170 m		*Artemisia inbia* + Grasses, *Artemisia inbia* + Grasses, *Myrsine* species + Grasses		–	0.4	0.6	50	~70 year (A-I)
2170–2440 m		*A. inbia* + Grasses, *A. inbia* + Grasses, *A.brevifolia* + Grasses		–	0.3	0.7	60	~60 year (L)
2440–2710 m		Grasses + *Lespedeiza gerardiana,* Grasses + *Lespedeiza gerardiana,* Grasses + *Lespedeiza gerardiana*		–	0.4	0.6	50	~60 year (Ab)

A, apple; P, *Pinus gerardiana*; C, *Cedrus deodara*; B-S, *Ailanthus altissima*; F-S, *Populus ciliata*; S, *Salix tetraperma*; A-I, *Artemisia inbia*; Ab, *A. brevifolia*; L, *Lespedezia gerardiana*; R, *Robinia*

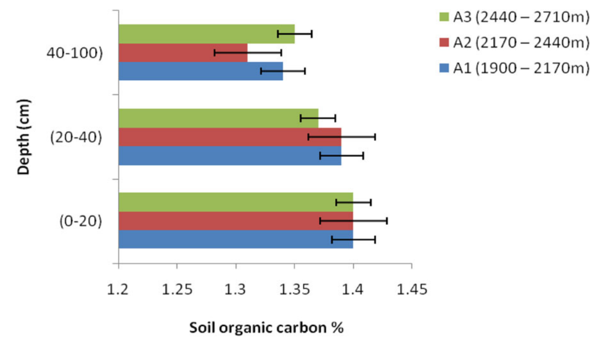

Fig. 2 Depthwise variation of soil organic carbon (%) at three altitudes

2-mm mesh sieve before analysis. The weight of the pebbles was measured and its proportion was calculated to know the percentage of pebble in each sample. Organic carbon (%) was calculated by Walkley and Black (1934). Actual mass of the soil was taken into consideration while calculating the carbon density. Bulk density was calculated by a specific gravity method (Singh 1980). Soil carbon (t ha^{-1}) was calculated by the method of Nelson and Sommers 1996.

$$[\text{Soil bulk density } (\text{gm}^{-3}) \times \text{Soil depth } (\text{cm}) \times \text{Soil Organic Carbon}(\%)] \times 100 \quad (1)$$

Methods suggested by Gomez and Gomez (1984) have been employed for the analysis of data in the present study.

Results

Biomass production levels

Aboveground biomass

The maximum overall aboveground biomass (84.65 t ha^{-1}) is recorded in the silvipasture system and minimum (5.4 t ha^{-1}) in barren LUS. The LUS recorded the aboveground biomass in the ascending order as barren land, agriculture, horticulture, agri-horticulture, agri-horti-silviculture, and silvipasture respectively (Table 2). The aboveground biomass increased with increase in altitudinal ranges. Maximum aboveground biomass (41.06 t ha^{-1}) is recorded at the highest altitude, i.e., A_3 (2440–2710 m.a.s.l.), which is significantly higher than A_1 and A_2. No consistent trend is observed at the land use level with the increase in altitudinal ranges. Maximum aboveground biomass is noticed in the silvipasture system at the A_3 (2440–2710 m.a.s.l.) altitudinal range, whereas minimum is found in barren LUS at the A_3 altitudinal range and is significantly lower than all other LUS (Table 2).

Belowground biomass

Irrespective of altitudinal gradients, maximum mean belowground biomass (19.50 t ha^{-1}) is recorded in the silvipasture system (Table 2), whereas minimum belowground biomass (1.36 t ha^{-1}) is recorded in the agriculture land use. Among altitudinal ranges, maximum belowground biomass production (35.47 t ha^{-1}) is recorded in the silvipastoral system at the A_3 altitudinal range followed by 23.08 t ha^{-1} in agri-horti-silviculture at A_1 altitude. The minimum belowground biomass is recorded in the barren land use system at the A_3 altitudinal range, which is lower than all other LUS.

Total biomass

Total biomass (above + below) is significantly influenced by LUS, altitudinal gradient and interaction effect between LUS and altitudinal gradient (Table 2). Maximum mean total biomass (104.10 t ha^{-1}) is accumulated in the T_5 (silvipasture) LUS, and minimum (6.79 t ha^{-1}) is recorded under T_1 (agriculture), which is significantly at par with T_6 (barren land). Maximum mean total aboveground biomass is observed in the altitudinal ranges 2440–2710 m.a.s.l., which is significantly higher than A_1 (1900–2170 m) and A_2 (2170–2440 m), whereas minimum total biomass (37.01 t ha^{-1}) is recorded in the lowest altitudinal range, i.e., A_1, and is significantly at par with A_2. The value of total biomass decreased with increase in altitudinal ranges in T_1 and T_4, whereas in T_5, the value increased with the increase in the altitudinal range. Maximum total biomass (198.20 t ha^{-1}) is noticed in the silvipasture system at A_3 and minimum is in the barren LUS at the same altitudinal range.

Biomass carbon density

Total biomass carbon density

The total biomass carbon density is higher (52.88 t ha^{-1}) in T_5 (silvipasture) LUS (Table 3). Minimum biomass carbon density (3.34 t ha^{-1}) is observed in agriculture land but is significantly at par with T_6 (barren land) LUS. In the altitudinal range, the maximum biomass carbon density (25.52 t ha^{-1}) is recorded at A_3 (2440–2710 m). Minimum value of mean biomass carbon density is recorded in A_1 (1900–2170 m.a.s.l.), which however remained statistically at par with A_2. In the interaction effect between the LUS and altitudinal range, maximum total biomass carbon stock (99.10 t ha^{-1}) is displayed by silvipasture LUS at the elevation range of A_3 (2440–2710 m) and minimum value (1.41 t ha^{-1}) is recorded in barren LUS at an elevation range of 2440–2710 m.a.s.l.

Total ecosystem carbon density

The data presented in Table 3 reveals that maximum total ecosystem carbon density (166.36 t ha^{-1}) is in the agri-horticulture LUS. The order of carbon density

Table 2 Aboveground, belowground and total biomass (t ha^{-1}) in different land use systems across three altitudes

	Aboveground biomass (t ha^{-1})				Belowground biomass (t ha^{-1})				Total biomass (t ha^{-1})			
	A_1 (1900–2170 m)	A_2 (2170–2440 m)	A_3 (2440–2710 m)	Mean	A_1 (1900–2170 m)	A_2 (2170–2440 m)	A_3 (2440–2710 m)	Mean	A_1 (1900–2170 m)	A_2 (2170–2440 m)	A_3 (2440–2710 m)	Mean
Agriculture	6.66	4.98	4.98	5.54	1.33	1.75	1.00	1.36	7.99	6.73	5.99	6.79
Horticulture	18.78	23.58	18.93	20.43	6.22	7.78	6.25	6.75	25.00	31.36	25.17	27.18
Agri-horticulture	26.05	18.73	21.67	22.15	8.59	6.29	7.15	7.34	34.64	25.02	27.89	29.18
Agri-horti-silviculture	85.49	59.79	36.18	60.49	23.08	15.68	10.04	16.27	108.60	75.48	46.21	76.75
Silvipasture	31.27	59.93	162.80	84.65	6.87	16.16	35.47	19.50	38.13	75.95	198.20	104.10
Barren land	5.38	8.94	1.87	5.40	2.70	4.47	0.95	2.71	8.08	13.41	2.82	8.10
Mean	28.94	29.33	41.06		8.13	8.69	10.14		37.01	37.99	51.05	
	SE(d)		$CD_{0.05}$		SE(d)		$CD_{0.05}$		SE(d)		$CD_{0.05}$	
T	5.86		11.91		1.46		2.96		7.30		14.85	
A	4.15		8.42		1.03		2.10		5.17		10.50	
T × A	7.18		10.15		1.79		2.53		8.95		12.65	

Table 3 Biomass carbon density, total ecosystem carbon density and soil to plant carbon density (t ha^{-1}) in different land use systems across three altitudes

	Biomass carbon density (t ha^{-1})				Total ecosystem carbon density (soil + plant) (t ha^{-1})				Soil to plant carbon density (t ha^{-1})			
	A_1 (1900–2170 m)	A_2 (2170–2440 m)	A_3 (2440–2710 m)	Mean	A_1 (1900–2170 m)	A_2 (2170–2440 m)	A_3 (2440–2710 m)	Mean	A_1 (1900–2170 m)	A_2 (2170–2440 m)	A_3 (2440–2710 m)	Mean
Agriculture	3.82	3.36	2.82	3.34	163.21	109.35	135.68	136.08	41.73	31.54	47.11	23.10
Horticulture	12.49	15.68	12.75	13.64	163.66	161.59	137.22	154.16	12.10	9.31	9.76	5.97
Agri-horticulture	17.32	12.51	13.94	14.59	163.77	135.39	199.93	166.36	8.46	9.82	13.34	6.06
Agri-horti-silviculture	54.28	37.73	23.11	38.37	176.51	166.04	148.68	163.74	2.25	3.40	5.43	2.12
Silvipasture	19.07	40.48	99.10	52.88	146.41	133.44	205.70	161.85	6.68	2.50	1.08	1.93
Barren land	4.04	6.70	1.41	4.05	86.88	106.59	71.27	88.25	20.50	14.91	49.55	12.94
Mean	18.50	19.41	25.52		150.07	135.40	149.75		15.29	11.91	21.05	
	SE(d)		$CD_{0.05}$		SE(d)		$CD_{0.05}$		SE(d)		$CD_{0.05}$	
T	3.64		7.39		9.43		19.18		2.99		6.08	
A	2.57		5.23		6.67		13.55		2.12		4.29	
T × A	4.45		6.30		11.55		16.35		3.67		5.18	

under different land use systems is agri-horticulture > agri-horti-silviculture > silvipasture > horticulture > agriculture > barren land. Irrespective of the land use system, the carbon density at different altitudinal gradients followed the trend $A_1 > A_3 > A_2$. However, A_1 and A_3remained statistically at par with one another but both displayed significantly higher values than A_2. Maximum total carbon density (205.70 t ha^{-1}) is recorded in the treatment combination of T_5A_3, which however remained statistically at par with T_3A_3. In general, barren LUS displayed quite low values of the total carbon density than other treatment combinations.

Soil to plant carbon density ratio

Irrespective of altitudinal gradient, maximum soil to plant carbon density ratio (23.10:1) is recorded in agriculture LUS. In the altitudinal ranges, irrespective of the LUS, the A_3 altitudinal range displayed maximum soil to plant carbon density ratio and followed the trend $A_3 > A_1 > A_2$. In the interaction effect between LUS and altitudinal gradient, no definite trend could be established in different LUS with altitudinal gradient. In agriculture, horticulture and barren land lower values were recorded at the A_2 altitudinal range. The soil to plant carbon density ratio increased with increasing altitude in agri-horticulture and agri-horti-silviculture LUS and the trend was just reverse in silvipasture LUS. Maximum and minimum values of soil to plant carbon density ratios are recorded in the treatment combinations of T_6A_3 and T_4A_1, respectively (Table 3).

Soil organic carbon

The mean maximum organic carbon (1.41%) is recorded in silvipasture, and mean minimum organic carbon content (1.33%) is found in agriculture LUS. In the altitudinal range, maximum carbon percent (1.39%) is displayed by 2440–2710 m.a.s.l. and remained statistically at par with the value of percent carbon recorded in 2170–2440 m.a.s.l. (Fig. 3). The minimum value of percent carbon (1.36%) is recorded in the 1900–2170-m altitudinal range. In the L_1 (0–20 cm), soil layer depicted significantly higher values of organic carbon than other two layers under study (Table 4). Altitudinal range A_3 (2440–2710 m.a.s.l.) under horticulture LUS displayed higher organic carbon percent, whereas minimum value of organic carbon percent (1.31%) is recorded both each in agri-horticulture and agriculture LUS at the 1900–2170-m elevation range. All the altitudinal ranges displayed identical values (1.40%) of organic carbon (%) at 0–20 cm soil layer. At each altitudinal range, the value of organic carbon declined with increasing soil depth (Fig. 3). But the rate of decrease in the organic carbon content is more pronounced at the A_2 (2170–2440 m) altitudinal range than at A_1 and A_3 (Figs. 3 and 4).

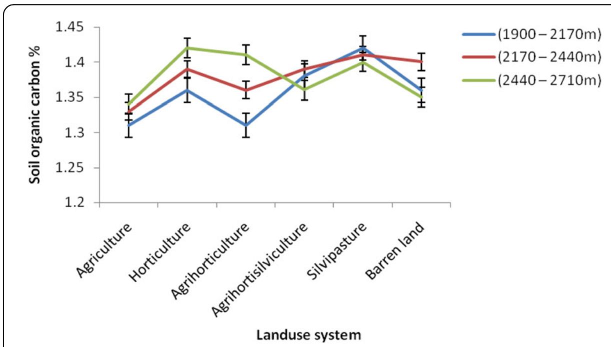

Fig. 3 Variation of SOC (%) in different land use systems along altitudinal gradient

Maximum soil organic carbon percent (1.48%) is recorded in 0–20 cm soil layer under silvipasture LUS, and minimum value of carbon percent (1.31%) is recorded in 40–100 cm soil layer of T_1 (agriculture) and T_5 (silvipasture) displaying identical values. Under each land use system, soil organic carbon decreased with increasing soil depth. The decline is more marked under the silvipasture system than any other LUS. Maximum soil carbon percent (1.46%) is recorded at 0–20 cm soil layer of the silvipasture system at the 1900–2170-m altitudinal range, whereas minimum value of soil organic carbon (1.25%) is recorded at 40–100 cm soil layer in agri-horticulture LUS in the 1900–2170-m altitudinal range. In general, in all the land use systems, the soil organic carbon (%) declined at each altitudinal gradient with increasing soil depth (Figs. 4 and 5).

Soil carbon density

Maximum carbon density (151.77 t ha^{-1}) in 0–100 cm layer is in agri-horticulture LUS and minimum in the barren land. Irrespective of the land use, maximum carbon density (131.57 t ha^{-1}) is recorded at the A_1 (1900–2170 m.a.s.l) altitudinal range, which is found to be significantly higher than A_2 (2170–2440 m.a.s.l) (Fig. 6). The significantly highest values of soil carbon density (185.99 t ha^{-1}) is found in agri-horticulture LUS situated at an altitudinal range of 2440–2710 m.a.s.l., whereas minimum values are displayed by barren LUS at an altitude of 2440–2710 m.a.s.l. At L_1 (0–20 cm) as well as L_2 (20–40 cm) soil layer, the carbon density did not vary significantly at a different altitude. However, at 40–100 cm soil layer, maximum carbon density is recorded at the A_1 altitudinal range which is found to be significantly higher than treatment combinations of L_3A_2 and L_3A_3. The data shows that carbon density at L_1 (0–20 cm) and L_2 (20–40 cm) layer did not vary appreciably among different LUS at all altitudinal gradients, except for barren land (Fig. 7). However, wide variation exist at L_3 (40–100 cm) layer at the three altitudinal ranges. Soil carbon density does not vary significantly between L_1 and L_2 layer at different altitude under different LUS (Figs. 6 and 7).

Table 4 Depth, land use and altitudinal wise soil carbon density (t ha^{-1}) and soil organic carbon (%) status of study area

Land use Systems	soil carbon density (t ha^{-1})									Soil organic carbon (%)								
	(1900–2170 m)			(2170–2440 m)			(2440–2710 m)			(1900–2170 m)			(2170–2440 m)			(2440–2710 m)		
	L_1 (0–20 cm)	L_2 (20–40 cm)	L_3 (40–100 cm)	L_1 (0–20 cm)	L_2 (20–40 cm)	L_3 (40–100 cm)	L_1 (0–20 cm)	L_2 (20–40 cm)	L_3 (40–100 cm)	L_1 (0–20 cm)	L_2 (20–40 cm)	L_3 (40–100 cm)	L_1 (0–20 cm)	L_2 (20–40 cm)	L_3 (40–100 cm)	L_1 (0–20 cm)	L_2 (20–40 cm)	L_3 (40–100 cm)
Agriculture	31.65	31.13	96.61	20.13	22.84	63.02	28.89	28.70	75.28	1.34	1.28	1.27	1.38	1.29	1.26	1.41	1.40	1.29
Horticulture	27.50	30.03	93.62	29.60	27.79	88.52	24.84	24.16	75.47	1.39	1.39	1.29	1.42	1.38	1.37	1.43	1.42	1.42
Agri-horticulture	27.32	26.70	92.50	24.84	24.09	73.86	34.27	36.74	114.99	1.43	1.26	1.25	1.43	1.36	1.29	1.43	1.41	1.40
Agri-horti-silviculture	26.69	24.14	71.39	24.49	25.29	78.53	23.68	24.67	77.23	1.40	1.39	1.37	1.41	1.40	1.37	1.42	1.34	1.30
Silvipasture	25.06	26.40	75.87	20.55	19.84	54.96	23.68	20.62	62.31	1.46	1.44	1.38	1.43	1.40	1.37	1.43	1.40	1.40
Barren land	22.72	18.69	41.43	24.67	15.27	59.96	19.98	16.73	33.68	1.41	1.30	1.40	1.41	1.41	1.39	1.41	1.39	1.37
SE (d)	4.93									0.03								
$CD_{0.05}$	6.97									0.05								

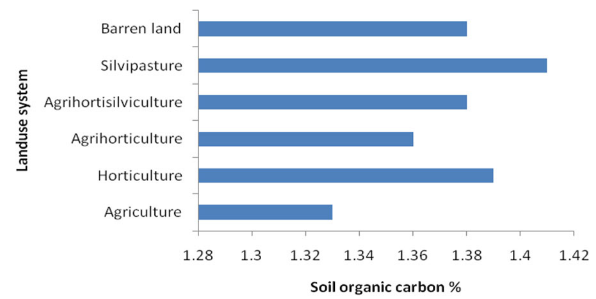

Fig. 4 Status of SOC (%) in different land use systems

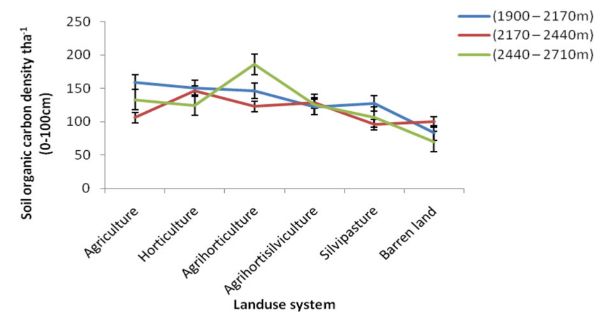

Fig. 6 Variation of SCD t ha^{-1} in different land use systems along altitudinal gradient

Discussion

Introduction of more and more tree-based land use systems like agroforestry is one alternative to deal with problems related to land use and global warming (Albrecht and Kandji 2003; Li et al. 2012). The amount of C sequestered largely depends on the agroforestry system, structure and functions, determined by environmental and socio-economic factors (Albrecht and Kandji 2003). Maximum aboveground biomass (84.65 t ha^{-1}) was recorded in the silvipasture system, followed by agri-horti-silviculture. Maximum belowground biomass (19.50 t ha^{-1}) was also in the silvipasture which was found significantly higher than all other LUS. Analysis of biomass production from published literature showed strong variations (1–37 Mg ha^{-1}) depending on climate, soil type and system management (Viswanath et al. 1998; Kang et al. 1999). Silvipastoral systems help in greater accumulation of soil organic matter and thus more carbon storage when compared to grass only or tree only (Kaur et al. 2002). The plant component of the silvipastoral system invests higher proportion of growth into the development of the root system compared to those growing singly (Swamy and Puri 2005). Mangalassery et al. (2014) also reported highest total plant biomass in the silvipastoral system involving acacia + *C. ciliaris* followed by acacia +*C. setegerus*. The results of the present study indicate that total biomass production is influenced by the old age tree layer, herbaceous nature of plants, nature and number of woody components and is supported by the findings of Rajput et al. (2015, 2017).

The LUS recorded the aboveground biomass in ascending order as barren land, agriculture, horticulture, agri-horticulture, agri-horti-silviculture and silvipasture respectively. Kumar et al. (2012) also reported the highest above- and lowest belowground biomass in the silvipasture and agriculture land use systems of north western Himalaya. The values reported by Kumar et al. (2012) are on the higher side of the present study and may be due to difference in an altitudinal range of 1000 m. The biomass carbon storage capacity reported in our fruit-based LUS was quiet low than reported by Sanneh (2007) and Singh (2010) for fruit-based agroforestry systems of the wet temperate north western Himalaya. This variation can be attributed to the prevailing climatic conditions like temperature and rainfall pattern, which affects the biomass carbon accumulation in the fruit-based LUS.

In the present study, increase in biomass with increasing altitude has got support from reported literature of Zhao et al. (2014), Zhu et al. (2010), Rajput et al. (2015) and Rajput et al. (2017). The above variation in the biomass level at different altitudes can be explained on the basis of combined effect of age of woody species, soil organic carbon (%) and human population density. It is

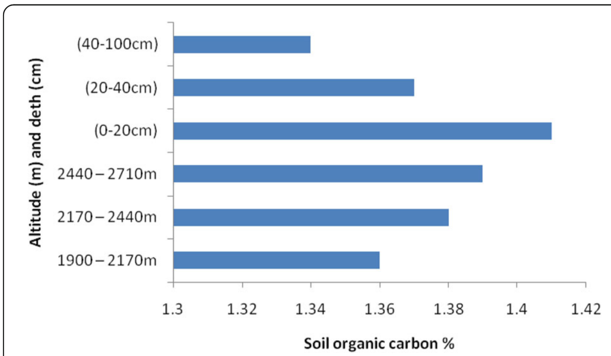

Fig. 5 Variation of SOC (%) in three altitudinal ranges and soil depths

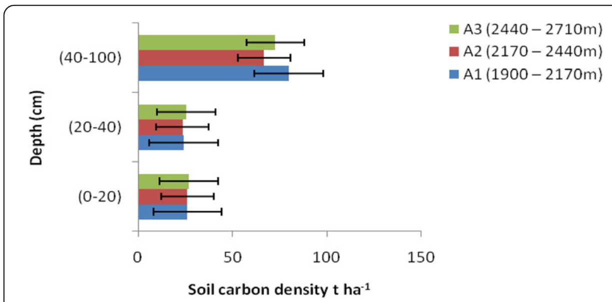

Fig. 7 Depthwise variation of soil carbon density t ha^{-1} at three altitudes

clearly evident from the data that a major contributor of biomass at different altitudinal ranges is woody perennial and the average age of tree species increases with increasing altitudinal. This may be one of the major reasons for biomass variation at different altitudinal ranges.

A higher level of organic carbon at the upper altitudinal range might have been favorable for more biomass production. Similar views were also expressed by Lehmann et al. (1998), Sanneh (2007) and Singh (2010). Population density at these high-altitude dry regions is normally very low than plain areas due to freezing cold in winter months and hence less disturbance and anthropogenic pressure. The frequency of rainfall and snowfall and their intensity keeps on increasing as we move upward in the higher hills of Kinnaur district and lower elevation ranges falls under almost complete shadow zone.

Biomass carbon density of different land use systems

The differences in the productivity of agroforestry systems may also be due to differences in soil conditions, phenology of dominant species (Gupta and Singh 1981), better root networking and efficient and economical use of limited resources for maintaining higher photosynthetic activities, leaf area index, better light interceptions and water use efficiency (Sehgal 1999). The biomass carbon densities in the present study might be varying due to variation in temperature and other locality factors and hence affecting the carbon density across different land uses. The maximum biomass carbon density is in the silvipasture system (52.88 t ha^{-1}), which differed significantly from other LUS and followed the trend: silvipasture > agri-horti-silviculture > agri-horticulture > horticulture > agriculture.

Species density and management practices have also been observed to influence biomass under different agroforestry systems in hilly agro ecosystems Rajput et al. (2015, 2017). Management practices, input components, disturbance levels and site quality may have influenced the variability in the carbon density of different LUS. In the present study, the mean and total carbon densities reported are at par with the values of Shah et al. (2013) for the forests of solan Himachal Pradesh. Fang et al. (2005) from temperate forests of Japan and Manhas et al. (2006) in temperate Indian forests reported vegetation C density of 53.60 and 47.42 t ha^{-1}-respectively and are both are almost neck to neck with the values of the present study. The lower biomass and carbon densities in the barren and agriculture land use systems may be due to poor fertility and intensive management practices. Proper design and management of such agroforestry/farm forestry plantations can increase biomass accumulation rates, making them effective carbon sinks (Shepherd and Montagnini 2001). Maikhuri et al. (2000) observed aboveground biomass of 3.9 t ha^{-1} $year^{-1}$ from the Central Himalayan agroforestry system to 1.1 t ha^{-1} $year^{-1}$ compared to degraded forestlands.

Soil organic carbon and soil carbon density

It is clear from the data that organic carbon (%) varied significantly under soil layers of different LUS, under different altitudinal ranges and their interaction effects. Maximum organic carbon percent was in the silvipasture system, which however remained statistically at par with all other LUS except agriculture and agri-horticulture. The greater soil organic carbon density of the silvipastoral system could be due to more total root biomass offered by the system that facilitates organic matter in the top as well as deep layers, thus making carbon less prone to oxidation as observed for deep-rooted grasses (Fisher et al. 1994). Significantly increased organic carbon contents in soils under these land-based use systems may be ascribed to more leaf litter deposition followed by decomposition and root turn over from trees (Kater et al. 1992; Rajput et al. 2015, 2017) and extremely low-temperature conditions between October and March months, whereas in agriculture and agri-horticulture high amount of organic carbon gets exhausted due to the intensive cultivation in these LUS and removal of high amount of harvest annually in the form of agriculture produce, fruits and pruned branches. The introduction of trees may increase the SOC stocks in agricultural systems and support the potential of agroforestry systems (Don et al. 2011; Li et al. 2012; Poeplau and Don 2015).

The carbon fixed by the plants is the primary source of organic matter input into the soil, which provides substrate for microbial process accumulation of soil organic matter. The belowground allocation of photosynthates is also an important factor for improving soil organic carbon content (Kaur et al. 2002). The result from the present study also demonstrates that maximum accumulation of soil organic carbon is in the surface layer and decreased with increase in soil depth. Gradual decline in the availability towards lower soil layers could be due to more accumulation and mineralization and reduced root biomass in deeper soil layers. The other reason may be cycling of nutrients and depositing them in surface soils (Shah et al. 2013). Sanneh (2007) and Singh (2010) have also reported decrease of soil organic carbon with increase in soil depth from the same state. The carbon density values under different LUS in the present study are quite higher than the values reported by Rajput et al. (2015, 2017) for subtropical and temperate regions of the northwestern Himalayas. Shah et al. (2014) reported carbon density values of 190.89 t ha^{-1} for the pine forests of subtropical parts of the sub-Himalayan region and are more than the reported values of the present study. Similar results were reported by Bandana (2011) for the forests of Solan, Himachal Pradesh, who reported a soil C density of 156.64–238.53 t ha^{-1} and Raina et al. (1999) reported a soil C density of 140.30–261.30 t ha^{-1} in the Garhwal Himalaya, India.

Total ecosystem carbon density (plant and soil) was reported highest in the agri-horticulture and closely followed by agri-horti-silviculture, silvipasture > horticulture > agriculture > barren land. The carbon density in the tree-based agroforestry systems is appreciably higher than agriculture and barren LUS. A higher amount of carbon stock in the tree-based LUS can be ascribed to continuous locking up of carbon in trees and regular addition of leaf litter to the soil, which helps in the buildup of carbon in the soil layers and in turn helps in greater productivity of the systems. The ratio ranges from 1:1 in tropical forests to 5:1 in boreal forest and much larger factors in grasslands and wetlands (IPCC 2000). Lower soil-plant carbon density means that these systems have more carbon in the plant components which need to be protected in order to avoid these systems becoming source of CO_2 in future.

Conclusions

The carbon stock storage and climate change mitigation cannot be easily achieved in the high-altitude Himalayan regions, because of the type of land use available, cold climate and the land holding capacity of the people. As evident from the results, maximum biomass density capacity has been reported for the silvipasture system followed by the agri-horti-silviculture system. Fruit-based systems, viz., horticulture and agri-horticulture displayed about four times more carbon storage potential than the agriculture land use system. In the altitudinal ranges, 1900–2170 m.a.s.l displayed higher carbon storage potential than A_3 and $A_{2.}$ These fruit-based LUS, like horticulture, agri-culture and agri-horti-silviculture are first choice of the farmers of the region because fruit grown under these land uses are of high quality, have better storage life and have low disease infestation and at the same time fulfill both objectives of carbon mitigation and economic growth.

Abbreviations

a.s.l.: Above sea level; IPCC: Intergovernmental Panel on Climate Change; LUS: Land use system; Mg: Mega gram

Authors' contributions

KC, DRB and CLT did the field work and data analysis. DBR and NAP drafted and revised the manuscript. All authors read and approved the final manuscript.

Ethics approval and consent to participate

This manuscript does not contain any individual person's data and ethics approval is not required.

Competing interests

The authors declare that they have no competing interests.

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