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Distribution of soil carbon fractions under different bamboo species in northwest Himalayan foothills, India

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Abstract Soil carbon and its fractions are important in understanding the mechanism of soil carbon sequestration. The present study evaluated the impact of seven commercial bamboo species, viz., *Bambusa balcooa*, *B. bambos*, *B. vulgaris*, *B. nutans*, *Dendrocalamus hamiltonii*, *D. stocksii*, and *D. strictus*, on labile and non-labile carbon fractions. In the 0–15-cm layer, *B. nutans* had the highest very labile C (7.65 g kg^{-1}) followed by *B. vulgaris* > *B. balcooa* > *D. stocksii* > *D. hamiltonii* > *B. bambos* > *D. strictus* > open. The active carbon pool was significantly low under the control plot (i.e. the open) indicating the positive influence of bamboo in soil C build-up in the top 0–15 cm soil layer. Amongst the different species of bamboo evaluated in this study, *D. strictus* accumulated the highest active C pool in 0–30-cm soil layer followed by *B. vulgaris.* Of the total organic C in the 0–30 cm soil depth, majority (55–60%) was contributed by the passive C pool comprising the less labile and the non-labile fraction of SOC. A high value of carbon stratification ratio (> 2) was observed for *D. strictus*, *B. bambos*, and *D. hamiltonii* which proves their potential for restoration of the degraded lands. The majority of bamboo species except for *B. balcooa* and *D. stocksii* showed a higher carbon management index than open systems, thereby indicating higher rates of soil C rehabilitation. Of the seven bamboo species, *B. vulgaris*, *D. strictus*, and *B. nutans* can be adopted for cultivation in the northwest Himalayas given their ability to positively impact the SOC and its fractions in both surface and sub-surface soil.

Keywords Active carbon pools · Carbon stratification ratio · Carbon management index · Lability index · Passive carbon pools · Root biomass

Introduction

Soil organic carbon (SOC) is the central element of soil fertility and the most widely accepted indicator for monitoring soil quality. Any variation in the SOC content has a profound impact on soil's physical, chemical, and biological properties and, thus, impacts soil functions (Sahoo et al., 2019). Soils are important carbon sinks to combat the challenges of climate change and increasing atmospheric CO_2 concentration. The top 1 m of the soils globally stores around 1500–2400 Gt C (Sanderman et al., 2017), which

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is three times the amount in vegetation and twice the amount in the atmosphere (Smith, 2012). Land use–induced changes have led to the rapid depletion of the SOC content. It is estimated that 156 Pg C has been lost from soils across the world due to alteration in land uses in the past 150 years (Houghton, 2003). As a corollary, this gives the soil the capacity to store C and act as a sink, with an annual technical storage potential of 2–5 Gt CO_2/year (Fuss et al, 2018) when managed properly. This capacity of the soil to act as a C sink has increased the interest of researchers into how C is stored and distributed in the soil since small changes in the soil organic carbon pool could result in significant impacts on the atmospheric concentration of CO_2 (Guo & Gifford, 2002).

Soil organic carbon is broadly classified into two (labile and stable) or sometimes into three pools (active, intermediate, and passive). The active pool comprises the labile and very labile fractions mostly represented by the microbial biomass C. The passive pool is composed of the less labile and non-labile fractions. These fractions exhibit different stabilities with the mean residence time ranging from a few days for the labile fractions to thousands of years for the recalcitrant/less labile fractions (Jastrow et al., 2007; Stevenson, 1994). The relative proportion of different soil carbon fractions determines soil quality and mineralization pattern and therefore is a critical determinant of soil carbon dynamics (Ghosh et al., 2012). This makes estimates of SOC fractions critical to evaluate the impact of any land use on soil quality or its functions. The general presumption is that vegetation growth on any degraded or fallow land will increase SOC content and, consequently, enhance the soil function.

Recently, there has been an increased interest amongst researchers and policymakers regarding the role of bamboo in enhancing SOC and C sequestration. Bamboo is amongst the fastest growing plants on the earth and holds promise in solving the climate-related problems of resource-poor farmers by contributing to the process of carbon sequestration. Lobovikov et al. (2009) described bamboo as “poor man’s carbon sink”. Compared to trees, bamboo has a more rapid rate of growth and higher annual re-growth (INBAR, 2010), which makes it a net sink of carbon dioxide (Kleinhenz & Midmore, 2001). There are approximately 1500 species of bamboo belonging to 87 genera worldwide (Li & Kobayashi, 2004; Ohrnberger, 1999) of which around 136 species belonging to 23 different genera are present in India (IFSR, 2019). Bamboo clumps are retained by farmers on field boundaries/block plantations as agroforestry species. High litterfall and fine roots of the bamboo adds a considerable amount of carbon and nutrients to the soil which helps in improving soil quality and sequestering carbon in the soil (Nath et al., 2015a, b). In addition, bamboo produces phytolith occluded carbon (PhytOC) from decomposing vegetation which remains in the soil for several thousand years (Huang et al., 2014). Parr et al. (2010) reported that sequestration of PhytOC by bamboo is equivalent to 11% of the current increase in atmospheric CO_2. These attributes make bamboo a very good species for C storage, and acknowledging the importance of bamboo, various countries across the world have used bamboo as a tool for livelihood and environmental development.

India is the second richest country in the world after China in terms of bamboo genetic resources (ISFR, 2011). The bamboo area of the country is estimated to be 16.0 million hectares (https://fsi.nic.in/isfr19/vol1/chapter8.pdf, dated July 22, 2021). The Government of India (GOI) has allocated Rs.12.90 billion ($177.6 million) to promote the bamboo sector. The scheme is proposed to establish around 0.1 million ha area under bamboo plantations to enhance farm productivity and generate livelihood opportunities to meet the industrial demand (http://pib.nic.in/newsite/Print Release.aspx?relid = 180,805, dated April 25, 2018).

Though there are reports on the carbon sequestration potential of different bamboo species in the country (Nath et al., 2009; Nath & Das, 2011; Kaushal et al., 2016), information relating to changes in SOC fractions is lacking. We hypothesized that the inclusion of bamboo plantations with various inputs (litter, fine roots, root exudates) will impact SOC fractions vis-a-vis soil quality which will be species-specific. Also, the carbon management index (CMI) and the carbon stratification ratio (CSR) were worked out for the various bamboo species, as these are important indicators of how land use changes impact soil quality (Sainepo et al., 2018; Franzleubbers, 2002). This study aimed to identify the best species to be recommended for cultivation in the northwest Himalayas which will contribute to economic sustainability of the farmers and improve the soil quality by increasing SOC and its fractions, thus paving the way to a sustainable land use system.

Material and methods

Study site

The study was conducted at Dhulkot Research farm of ICAR-Indian Institute of Soil and Water Conservation, Dehradun, India, located at 30″ 20′ 59″ N latitude, 77″ 53′ 05″ E longitude at 548 m above mean sea level (m.s.1). Long-term average annual rainfall (last six decades) recorded is 1660 mm, out of which 82% is received during the monsoon months of June to September. The mean maximum temperature of the study site is 37 °C and the mean minimum temperature is 4 °C. The soil is an Inceptisols derived from heavy-textured, deep alluvium, yellowish-brown to dark yellowish-brown in colour, with gravel and coarse rock fragments. Analysis of soil revealed that it belongs to silty clay loam type having 37% silt, 40% sand, and 23% clay.

Experimental setup

Seven bamboo species, viz., *Bambusa balcooa*, *B. bambos*, *B. vulgaris*, *B. nutans*, *Dendrocalamus hamiltonii*, *D. stocksii*, and *D. strictus*, were planted at a spacing of 5 m × 4 m in July 2012. The experiment was laid out in Randomized Complete Block Design (RCBD) with three replications. Each plot (species) consists of nine plants that covered an area of 180 m^2. In total, 21 plots were covering a total area of 3780 m^2. A fallow plot (control) was left barren away from the canopy area to compare the long-term effect of bamboo species. All the selected species are of commercial importance and on the priority list of the National Bamboo Mission, Government of India, and International Bamboo and Rattan Organization (INBAR). Experimental plots were ploughed once a year to control weeds. Besides, mounding operation (heaping of soil near the base of clump) was done every year to provide support to the new culms which emerged annually. No manuring and fertilizer application was done until 7 years of age.

Soil sampling and analysis

Soil sampling was done in 2019 from the 7-year-old bamboo plantation as well as the open (fallow) plot (without bamboo) from two depths, viz., 0–15 cm and 15–30 cm. The collected soil samples were air-dried and ground to pass through a sieve for further analyzing different carbon fractions.

Fractions of organic C

The different organic C fractions in the soil were determined by the Modified Walkley and Black Method outlined by Chan et al. (2001) using 5, 10, and 20 ml of concentrated sulphuric acid (H_2SO_4) which correspond to 12 N, 18 N, and 24 N of H_2SO_4, respectively (Ghosh et al., 2010). The oxidation of soil organic C with varying strengths of acid allows the total soil organic C to be separated into four distinct fractions of decreasing oxidizability which are given in Table 1. These four fractions together correspond to the total organic C (TOC) present in the surface and sub-surface layer (Chan et al., 2001) which is used for calculations.

Root biomass

Root biomass estimation was done using soil cores taken under each species at a distance of 50 cm away from the bamboo clump in four different positions (east, west, north, south) by driving a sharp-edged core sampler into the soil to a depth of 0–10, 10–20, and 20–30 cm (Kaushal et al., 2020; Kaushal et al., 2020a). The roots were categorized into coarse roots (> 2.5 mm diameter) and fine roots (< 2.5 mm diameter). All the roots were oven-dried to a constant weight at a temperature of 65 ± 2 °C.

Statistical analysis

To understand the impact of different bamboo species on the soil C fractions, the data were subjected to analysis of variance and the critical difference was calculated at a 5% level of significance for the various C fractions.

Table 1 Methods used for calculating different carbon fractions and CMI

Fraction 1 (VLC)—very labile carbon	Organic C oxidizable under 12 N H_2SO_4
Fraction 2 (LC)—labile carbon	Difference in oxidizable organic C extracted between 18 and 12 N H_2SO_4 (18 N–12 N H_2SO_4)
Fraction 3 (LLC)—less labile carbon	Difference in oxidizable organic C extracted between 24 and 18 N H_2SO_4(18 N–24 N H_2SO_4)
Fraction 4 (NLC)—non-labile carbon	Difference in organic C extracted with 24 N H_2SO_4 and TOC (TOC–24 N H_2SO_4)
Active carbon pool (ACP)	VLC + LC (unstable/labile)
Passive carbon pool (PCP)	LLC + NLC (stable/non-labile)
Lability index for the organic carbon (LI)	$[(Cfrac_1/TOC) \times 3 + (Cfrac_2/TOC) \times 2 + (Cfrac_3/TOC) \times 1]$
Carbon pool index (CPI)	Sample total organic C (mg/kg)//reference total organic C (mg/kg)/, where reference total organic carbon is the total organic carbon content of control plot
Carbon management index (CMI) (Blair et al., 1995)	CPI × LI × 100
Carbon stratification ratio (CSR) (Franzleubbers, 2002)	CSR = (Carbon fraction in surface soil layer)/(Carbon fraction in the adjoining layer)

Results

Variation in labile C fractions

The very labile carbon (VLC) fraction showed significant variation ($P < 0.05$) amongst the different species for both the surface and the sub-surface soil (Table 2). In the 0–15-cm layer, the highest value of VL fraction was recorded in *B. nutans* (7.65 g kg^{-1}) followed by *B. vulgaris* > *B. balcooa* > *D. stocksii* > *D. hamiltonii* > *B. bambos* > *D. strictus* > open. The open fallow without any bamboo plantation showed significantly lower VLC in the surface layer compared to different bamboo species. However, the sub-surface soil layer showed a complete reversal in trend, and *B. nutans* recorded the least value (3.55 g kg^{-1}) at the sub-surface. Amongst all the species, *D. hamiltonii* accumulated the highest VLC at the sub-surface followed by *D. strictus* and *B. vulgaris*.

The labile carbon (LC) fraction ranged from 1.20 to 4.75 g kg^{-1}in the surface layer and was lower than the concentration of the VLC fraction (Table 2). The soil under *D. strictus* accumulated maximum labile C fraction followed by open > *B. bamboos* > *B. balcooa* > *D. hamiltonii* > *B. vulgaris* > *B. nutans* > *D. stocksii.* In the sub-surface soil, the LC fraction

Table 2 Variation in different labile carbon fractions and active carbon pools(g kg^{-1}) under different bamboo species

Species	VLC		LC		ACP	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
B. balcooa	6.600 ± 0.304bc#*	3.650 ± 0.527c	2.650 ± 0.507c	1.900 ± 0.700bc	9.250 ± 0.568ab	5.550 ± 0.589
B. bamboos	5.750 ± 0.444 cd	5.100 ± 0.427b	3.500 ± 0.265b	1.450 ± 0.087bcd	9.250 ± 0.229ab	6.550 ± 0.427
B. nutans	7.650 ± 0.433a	3.550 ± 0.918c	1.300 ± 0.304d	3.275 ± 0.953a	8.950 ± 0.626ab	6.825 ± 1.539
B. vulgaris	7.200 ± 0.705ab	5.350 ± 0.693b	1.577 ± 0.225d	1.800 ± 0.200bc	8.777 ± 0.654bc	7.150 ± 0.872
D. hamiltonii	6.100 ± 0.482 cd	6.650 ± 0.436a	1.650 ± 0.312d	0.600 ± 0.779d	7.750 ± 0.229 cd	7.250 ± 0.726
D. stocksii	6.350 ± 0.361bc	4.827 ± 0.280b	1.200 ± 0.687d	1.150 ± 0.173 cd	7.550 ± 0.444d	5.977 ± 0.453
D. strictus	5.250 ± 0.626d	5.750 ± 0.577ab	4.750 ± 0.312a	1.025 ± 0.681 cd	10.000 ± 0.889a	6.775 ± 1.106
Open (control)	3.500 ± 0.661e	4.900 ± 0.527b	4.050 ± 0.776ab	2.400 ± 0.180ab	7.550 ± 0.1.136d	7.300 ± 0.656
CD ($p < 0.05$)	**0.93**	***1.09***	***0.74***	***0.97***	***1.13***	***NS***

(#* ± The standard deviation from mean while the letters indicate that values followed by similar letters are statistically at par while different letters indicate they are significantly different from each other) concentration showed a reversal of trend for species as observed in ease of VLC fraction. The highest concentration at the sub-surface was recorded under *B. nutans* plantation (3.28 g kg^{-1}) which was significantly higher than all the other species.

The active carbon pool (ACP) which is the total of vary labile and labile fractions was calculated for both surface and sub-surface (Table 2). On the surface, the accrual of ACP followed the order *D. strictus* > *B. bambos* > *B. balcooa* > *B. nutans* ≫ *B. vulgaris* > *D. hamiltonii* > *D. stocksii* > open. At the sub-surface, however, the peak concentration of ACP was observed in the open fallow (7.30 g kg^{-1}) followed by *D. hamiltonii* (7.52 g kg^{-1}) and *B. vulgaris* (7.15 g kg^{-1}).

Variation in non-labile C fractions

The passive carbon pool (PCP) is the summation of the less labile carbon (LLC) fractions and the non-labile carbon (NLC) fractions. Experimental data indicated significant variation in the LLC fraction at the surface layer (Table 3). However, at the sub-surface layer, there was no significant variation amongst the different species. The highest accumulation of LLC fraction occurred under *D. stocksii* (2.55 g kg^{-1}) while at the sub-surface, *B. vulgaris* had the maximum concentration (2.35 g kg^{-1}). Amongst all the four fractions of soil C estimated in both the surface as well as the sub-surface layer, the contribution of LLC fraction towards the TOC was the lowest. For 0–15 cm, it was only 8.6% of the TOC, while for 15–30 cm, its contribution was 9.8%.

The NLC fractions had the maximum contribution towards the total carbon pool (TCP) amongst all the four fractions in both surface and sub-surface soil (Table 3). The NLC fraction ranged from 9.20 to 11.55 g kg^{-1} in the surface soil, and the maximum accumulation was observed under *D. strictus* (11.55 g kg^{-1}) (Table 2). The sub-surface layer showed comparatively lower accretion of NLC fraction with soil under *B. vulgaris* having the maximum value of 9.17 g kg^{-1} followed by open fallow (9.00 g kg^{-1}).

The PCP ranged from 10.65 to 13.25 g kg^{-1} in the surface layer and 8.62 to 11.51 g kg^{-1} in the sub-surface layer with *B. vulgaris* recording the maximum concentration of passive C pool in both the layers followed by *D. strictus* at the surface and open fallow at the sub-surface, respectively (Table 3).

Contribution of active and passive C pools towards total organic C

The total carbon pool (active + passive) in the surface and sub-surface layer is presented in Table 4. In the surface layer, open fallow and *D. hamiltonii* had the lowest values of TCP, while in the sub-surface, the open fallow had a considerably higher concentration of TCP. The per cent contribution of the active and passive C pools towards the total organic C was calculated (Fig. 1 and Fig. 2). For both the layers, similar

Table 3 Variation in different non-labile carbon fractions and passive carbon pools (g kg^{-1}) under different bamboo species

Species	LLC		NLC		PCP	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
B. balcooa	0.850 ± 0.218c#*	1.950 ± 0.200	10.100 ± 0.550bc	7.500 ± 0.444c	10.950 ± 0.614bc	9.450 ± 0.527bcd
B. bamboos	1.400 ± 0.229c	1.200 ± 0.100	10.650 ± 0.661ab	7.750 ± 0.976bc	12.050 ± 0.477ab	8.950 ± 1.033 cd
B. nutans	1.700 ± 0.676abc	1.725 ± 0.783	10.650 ± 0.300ab	8.550 ± 0.361ab	12.350 ± 0.976a	10.275 ± 1.126abc
B. vulgaris	2.500 ± 0.770a	2.350 ± 0.300	10.750 ± 0.650ab	9.167 ± 0.603a	13.250 ± 1.400a	11.517 ± 0.902a
D. hamiltonii	1.450 ± 0.265bc	1.650 ± 0.477	9.200 ± 0.614c	8.900 ± 0.346a	10.650 ± 0.541c	10.550 ± 0.786ab
D. stocksii	2.550 ± 0.266a	1.475 ± 0.751	10.100 ± 0.541bc	7.450 ± 0.826c	12.650 ± 0.614a	8.925 ± 0.715 cd
D. strictus	1.550 ± 0.482bc	0.925 ± 0.697	11.550 ± 0.409a	7.700 ± 0.458bc	13.100 ± 0.100a	8.625 ± 0.344d
Open (control)	2.350 ± 0.676ab	1.700 ± 0.673	9.900 ± 0.958bc	9.000 ± 0.912a	12.250 ± 0.400ab	10.700 ± 1.562ab
CD ($p < 0.05$)	***0.93***	***NS***	***1.12***	***1.05***	***1.34***	***1.61***

(#* ± The standard deviation from mean while the letters indicate that values followed by similar letter are statistically at par while different letters indicate they are significantly different from each other)

Table 4 Variation in ACP + PCP (g kg^{-1}) under different bamboo species

Species	Active + passive carbon pool	
	0–15 cm	15–30 cm
B. balcooa	20.200 ± 0.265bcd#*	15.000 ± 0.700c
B. bamboos	21.300 ± 0.500abc	15.500 ± 1.308bc
B. nutans	21.300 ± 1.600abc	17.100 ± 0.533abc
B. vulgaris	22.027 ± 1.905ab	18.667 ± 1.747a
D. hamiltonii	18.400 ± 0.458d	17.800 ± 1.217ab
D. stocksi	20.200 ± 0.265bcd	14.902 ± 1.015c
D. strictus	23.100 ± 0.985a	15.400 ± 1.114bc
Open (control)	19.800 ± 1.253 cd	18.000 ± 1.015a
CD ($p < 0.05$)	***2.13***	***2.05***

(#* ± The standard deviation from mean while the letters indicate that values followed by similar letters are statistically at par while different letters indicate they are significantly different from each other)

trend was observed with the PCP contributing more towards the TOC compared to ACP. The mean contribution of PCP was marginally higher for the sub-surface layer (59.6%) compared to the surface layer (58.5%) with the reverse trend true for the ACP.

Amongst all the species, the contribution of ACP towards the TOC was highest for *B. balcooa* followed by *B. bambos* and *D. strictus* in the surface layer, while at the sub-surface *D. strictus* had the maximum contribution of ACP (44%) towards TOC. The passive CP contribution towards TOC was highest for *D. stocksii* (62.6%) followed by open fallow (61.9%) while at the sub-surface *B. balcooa* recorded maximum contribution of PCP towards TOC (63%) followed by *B. vulgaris* and *D. stocksii*.

Lability index and carbon management index

The carbon management index (CMI) and lability index (LI) was computed for the surface soil layer (Fig. 3a and Fig. 3b). The LI was lowest for the open fallow (1.058) and was highest for *B. balcooa* (1.285) followed by *B. nutans* (1.279). The CMI values under bamboo plantation were higher than that observed under open fallow irrespective of the species. The highest CMI was recorded under *B. nutans* and *B. vulgaris* (137.6) followed by *D. strictus* (135.4). The per cent increase in CMI values over the open fallow ranged from 10.02 to 30.1% indicating the positive impact of bamboo on conservation and build-up of C in the soils. The CMI obtained for different bamboo species followed a similar trend as the concentration of VLC fraction at the surface layer where *B. nutans, B. vulgaris*, and *B. balcooa* recorded the maximum concentration. However, *D. strictus* which had a lower concentration of VLC fraction had a significantly higher concentration of LC fractions at the surface layer which resulted in high CMI.

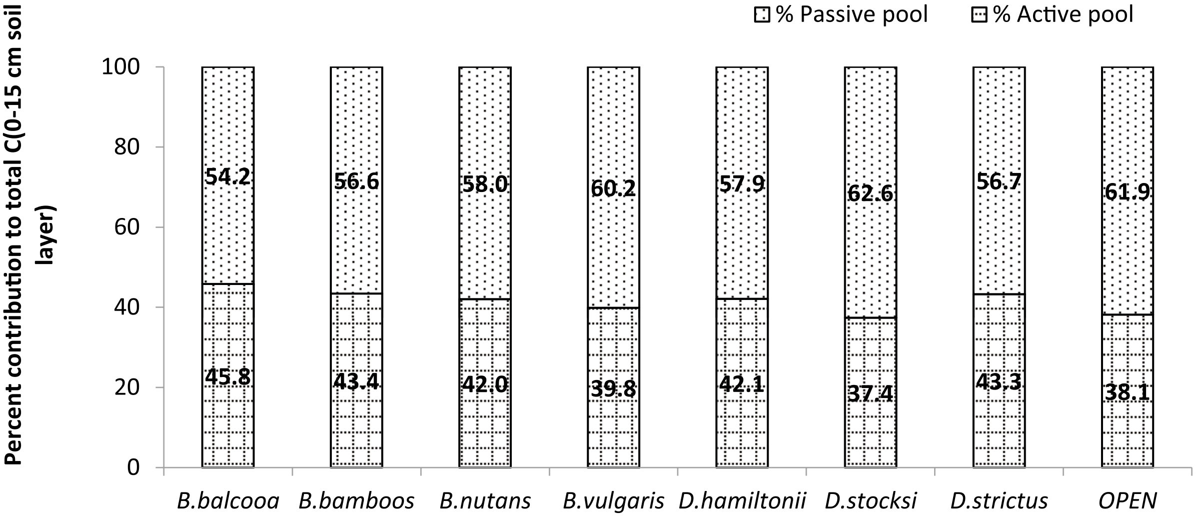

Fig. 1 Percent contribution of different C pools to total C (0–15 cm soil depth)

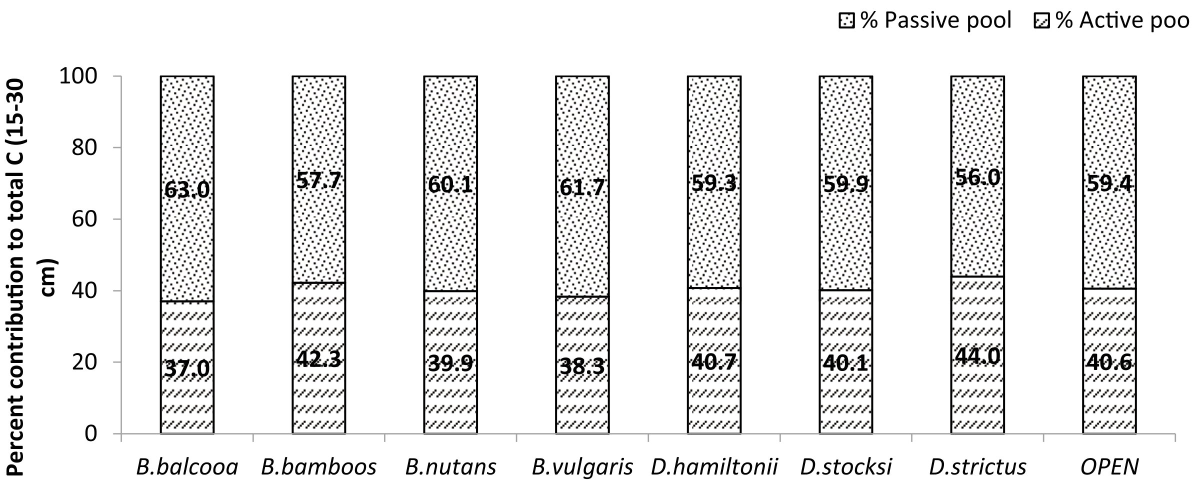

Fig. 2 Percent contribution of different C pools to total C (15–30 cm soil depth)

Carbon stratification ratio as influenced by bamboo plantation

The carbon stratification ratio (CSR) for the different C fractions had wide variation amongst the species (Fig. 4 and Fig. 5). The CSR for ACP showed wider variation amongst the bamboo species compared to the PCP. For the LC fraction, soil in open fallow recorded the lowest CSR (1.03), while soil under *D. strictus* had the highest CSR (4.63). For the VLC fraction, *B. nutans* had the highest stratification ratio of 2.15. The CSR values for the PCP were lower than 2.0 for all the bamboo species. For the LLC fraction, the CSR was highest for *D. stocksii* (1.73) followed by *D. strictus* (1.68), while for the non-labile fraction of C, *D. strictus* had a CSR of 1.50. The TOC had CSR ranging from 1.03 to 1.50 and *D. strictus* again had the highest CSR. Barring *D. hamiltonii* which recorded a lower CSR compared to open fallow (for TOC), all species recorded higher CSR. Compared to the absolute values of different C fractions under different species, the CSR values gave a better insight into how the species affected the C accumulation in the different soil layers.

Root biomass

Both fine roots and coarse root biomass for all the seven species of bamboo were enumerated for 0–30 cm depth (Fig. 6). The coarse root biomass was highest under *B. vulgaris* (1483 gm^{-3}) followed by *D. strictus* (1384 gm^{-3}). The fine root biomass accumulation was significantly higher (3626 g m^{-3}) in *D. hamiltonii* in 0–30 cm soil depth compared to all other bamboo species. This was followed by *D. strictus* and *B. bambos* which accumulated fine roots to the tune of 2198 gm^{-3} and 2151 g m^{-3}, respectively. The lowest fine root biomass was recorded in *B. nutans* (893 gm^{-3}).

Discussion

Labile carbon fractions and active carbon pools

The present study reflected the potential of different bamboo species to effectively build up soil C in the 0–30-cm soil layer. The ACP was significantly low under the control plot, i.e. the open fallow indicating the positive influence of bamboo in soil C build-up in the top 0–15-cm soil layer. The vigorous growth rate of bamboo and its ability to complete the growth cycle within a short temporal scale of 120 to 150 days makes it a highly potent species for carbon sequestration (Ben-zhi et al., 2005; Nath et al., 2015a, b). Higher ACP under bamboo can be attributed to continuous litterfall (Kaushal et al., 2020; Kaushal et al., 2020) in the form of leaves, twigs, branches, and huge fine root biomass produced by bamboo as evident from the present study

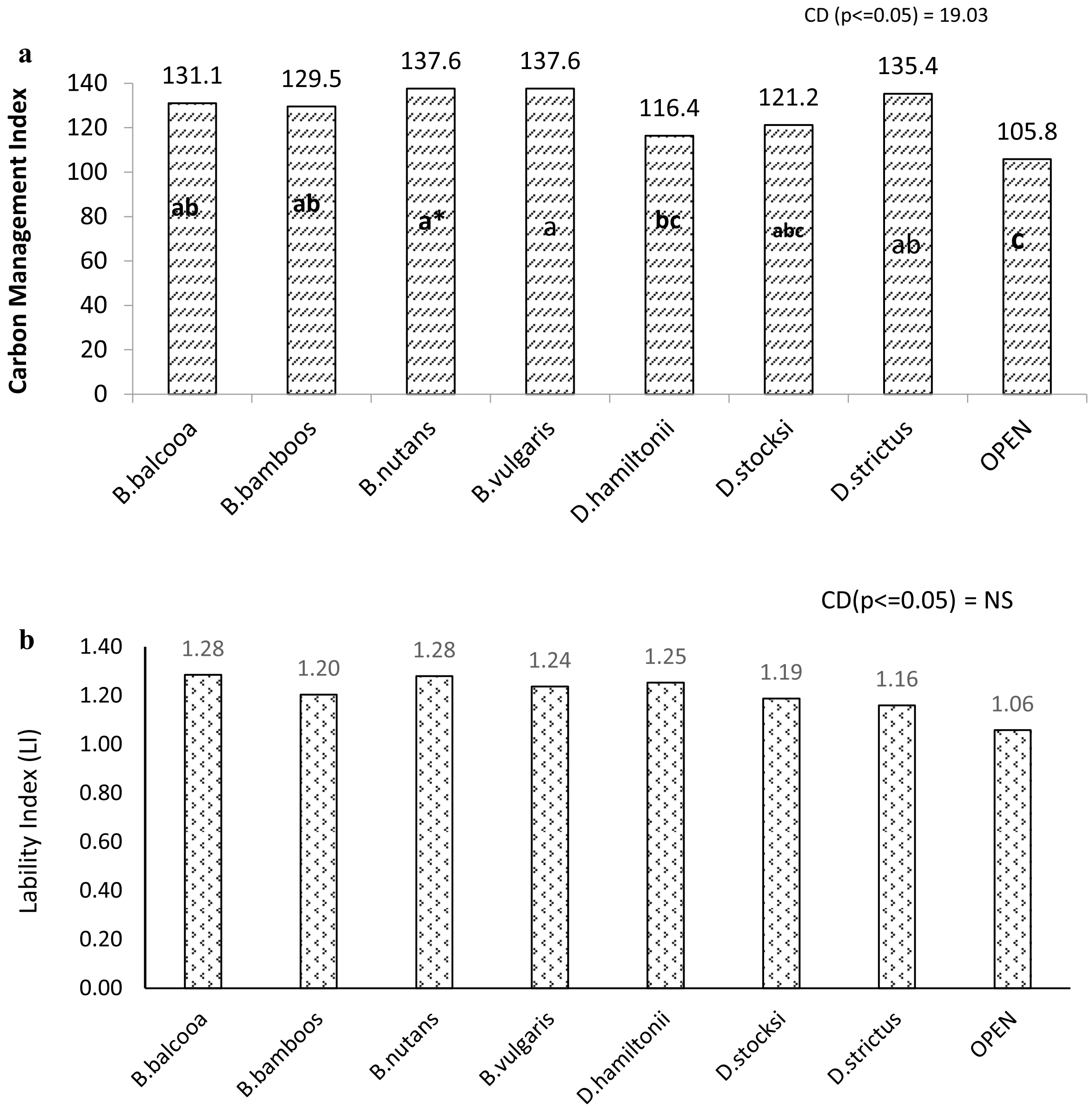

Fig. 3 **a** Carbon management index (CMI) under different bamboo species (*the letters in the bar diagram indicate that treatments with same letter are statistically similar, while if different, they are significantly different from each other). **b** Lability index (LI) of carbon under different bamboo species

(Fig. 6) which is absent in the open fallow. However, moving to the lower layers (15–30 cm), the open fallow had a significantly higher value of ACP which may be attributed to the leaching of labile C to the sub-surface. The litterfall data (Kaushal et al., 2020) in the same experiment revealed that during the years 2015 and 2016, *B. vulgaris* recorded significantly higher litterfall amongst all species, while during 2017, *D. hamiltonii* recorded the highest litterfall. In the year 2017, litterfall increased significantly and reached a maximum of 12.4 Mg ha^{-1}in *D. hamiltonii* which was followed by *B. vulgaris* (12.1 Mg ha^{-1}), *B. balcooa* (11.5 Mg ha^{-1}), *D. strictus* (10.7 Mg ha^{-1}), and *B. nutans* (9.7 Mg ha^{-1}). The

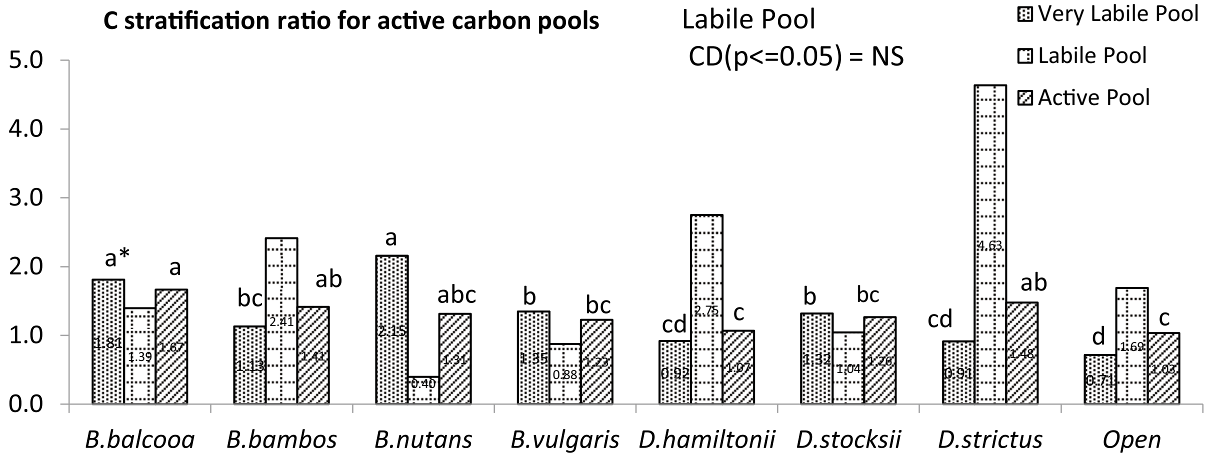

Fig. 4 C stratification ratio for active C pools under different bamboo species (*the letters in the bar diagram indicate that treatments with same letter are statistically similar, while if different, they are significantly different from each other)

lowest litterfall in the year 2017 was recorded in *D. stocksii* (8.1 Mg ha^{-1}). Higher carbon fractions in the surface layer (0–15 cm), therefore, can be attributed to litterfall in this layer and due to availability and supplying of mineralizable and easily hydrolyzable carbon leading to the greater activity of microbes and their population on the surface soil layer (Kaur et al., 2008). Benbi et al. (2015) also reported that the woody perennial-based agroforestry system has a significant labile carbon pool as compared to an uncultivated system.

Amongst the different species of bamboo evaluated in this study, *D. strictus* accumulated the highest ACP in 0–30-cm soil layer followed by *B. vulgaris* which was also evident from the coarse root biomass and total root biomass incorporated by the two species during the 7 years of experiment. *D. hamiltonii* despite the higher root biomass accumulation and comparable litter fall did not show significant improvement in the ACP particularly for the surface layer. *D. strictus* is an important species of the dry, deciduous forests and prefers low relative humidity, coarse-textured, well-drained slightly acidic soil (pH 5.5–7.5) which is characteristic of the Doon valley in the lower Himalayas (Nath & Das, 2008). The favourable agro-climatic condition for the species

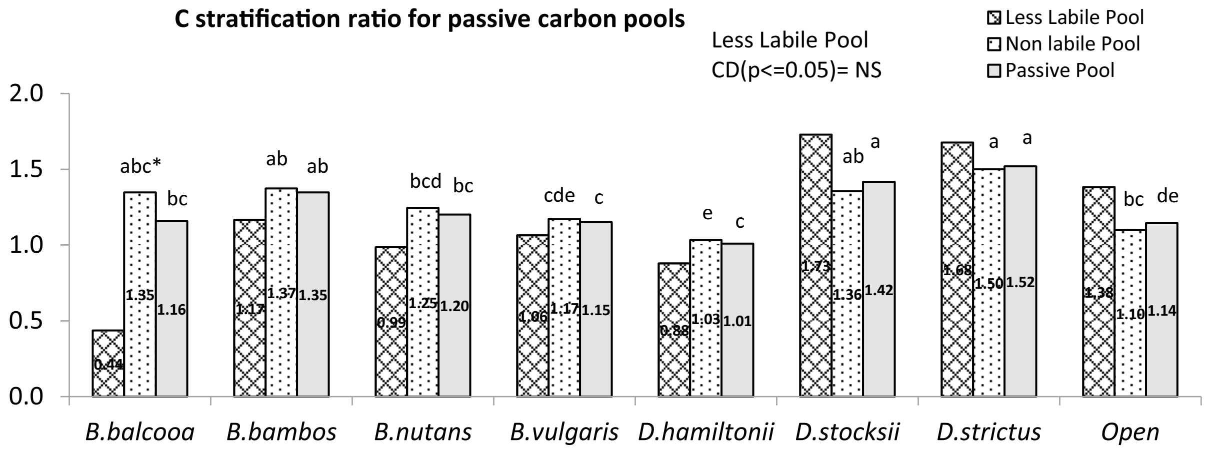

Fig. 5 C stratification ratio for passive C pools under different bamboo species (*the letters in the bar diagram indicate that treatments with same letter are statistically similar, while if different, they are significantly different from each other)

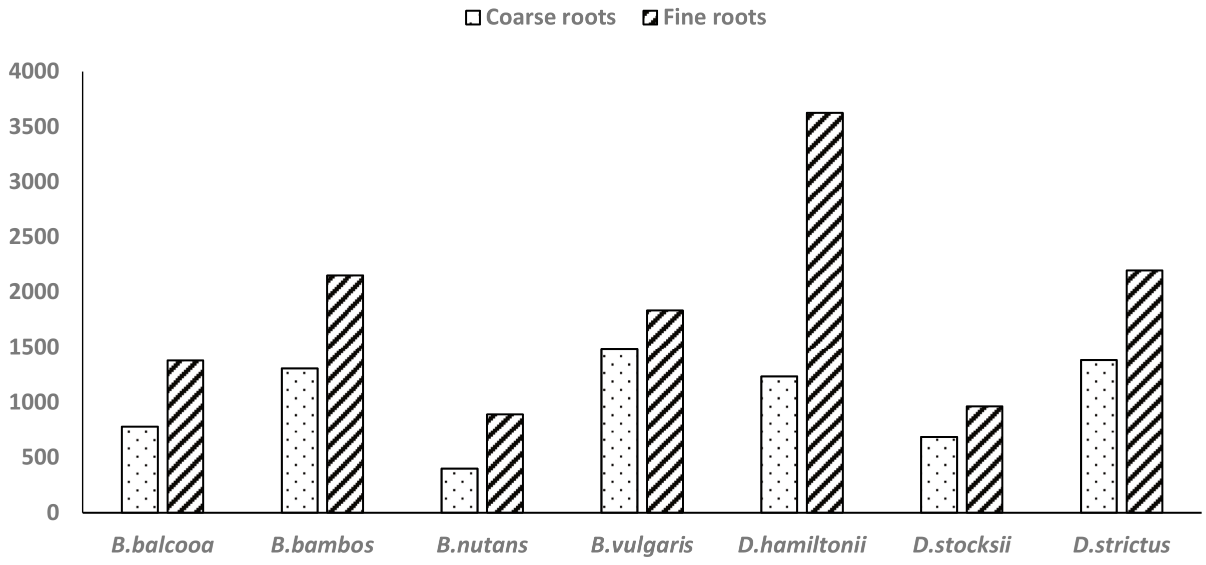

Fig. 6 Root biomass (g m^{-3}) in different bamboo species at 0–30 cm soil depth

could have triggered better stocking of C in the soil system compared to other bamboo species. Also, the proportion of fine roots to coarse roots was much higher in *D. hamiltonii* (2.59) compared to *D. strictus* (1.58) and *B. vulgaris* (1.23) which could potentially control the decomposition of root C and its eventual accrual in the soil. Generally, the fine roots (<2 mm) are more easily decomposed in comparison to the coarse roots (>2 mm) (Zhang & Wang, 2015). Thus, a higher proportion of fine roots would indicate a higher rate of decomposition, leading to the lesser build-up of soil C in comparison to the coarse roots which would decompose at a slower pace. This plays a vital role in the build-up of the soil organic C over time and plays an important role in the C turnover as well as productivity of any ecosystem in the long run (Raz-Yaseef et al., 2013; Mao et al., 2011; Langley & Hungate, 2003).

The build-up of active C or labile C fractions in soil is an important indicator of soil quality which is highly sensitive to land use/land management changes and forms a smaller proportion of the total organic C in soil. Generally, when cultivated land is brought under perennial vegetation cover like bamboo, a significant increase in the soil organic C stock is observed (Zhang et al., 2013) which was also evident in the present study. The variation in ACP is the most prominent as this is the pool subjected to rapid changes owing to any alteration or perturbation in the system. However, if we critically analyze the absolute difference in C accumulation between the bamboo species and open fallow, some species like *B. balcooa* and *D. stocksii* recorded lesser ACP than the fallow land. However, overlooking the disturbance bamboo essentially enhanced the active pool of SOC, and land use changes induced C losses could be easily restored by bringing the degraded lands under bamboo cultivation (Sahoo et al., 2019).

Non-labile carbon fractions and passive carbon pool

Of the total organic C in 0–30 cm, soil depth majority share was contributed by the PCP comprising the less labile and the non-labile fraction of SOC. It was almost 55–60% of the TOC present in the soil. The PCP is the stable fraction of SOC that is not affected by the changes in management practices or by the alteration in land use within short time frames (Sainepo et al., 2018). Dwivedi et al. (2019) reported that the stable fraction of C is strongly bound with the soil mineral matrix to form mineral-humus complexes and thus are shielded from the microbial action and least decomposed. Bamboos are known to produce phytolith occluded carbon (PhytOC) from decomposing vegetation which is highly stable and remains in the soil for several thousand years (Parr et al., 2010; Huang et al., 2014). The open fallow also had comparable values of the PCP as compared to the different bamboo species, particularly at the sub-surface. Huang et al. (2014) reported that in bamboo plantations, the stable PhytOC storage in 0–40-cm soil layer increased by 217 Mg C ha^{-1} when converted from paddy fields after 20 years. The PhytOC was accumulated at 79 kg C ha^{-1} year^{-1}, a rate far exceeding the global mean long-term soil C accumulation rate of 24 kg C ha^{-1} year^{-1} reported in the literature.

Soil erosion by water is one of the most important causes of land degradation and the bamboo plantation performed better in stocking soil organic C at the surface compared to the open fallow which would eventually help to reduce soil erosion and prevent land degradation. The open fallow due to lack of vegetation is prone to more erosion as well as C losses from the surface soil and degrades further compared to the soil under bamboo plantations.

Carbon stratification ratio

The carbon stratification ratio (CSR) reflects the proportion of C at the surface layer to the underlying layers rather than the absolute quantity of C in the soil (Franzleubbers, 2002). A high CSR ratio indicates better soil quality as the surface soil organic C concentration is a prime indicator of soil properties like aggregate stability, infiltration rate, microbial activities, nutrient cycling, and susceptibility of the soil to erosion (Franzleubbers, 2002). A high CSR value of 4.63 for the labile C pool under *D. strictus* indicates superior soil quality and higher resistance to degradation compared to other bamboo species. *B. bambos* and *D. hamiltonii* with CSR > 2 for LCP are also suitable for restoration of the degraded lands as a CSR > 2 indicates improved soil quality, and such values are rare in degraded sites (Franzleubbers, 2002). The CSR was the least for the open fallow, indicating a poor surface soil quality in comparison to bamboo. The stratification of C and its various fractions are likely to occur under managed ecosystem (Schnabel et al., 2001; Van lear et al., 1995) due to the differential rate of C inputs and the exposure of the soil surface to various biotic and abiotic factors. Interestingly, the CSR for the PCP for all the species was < 2. *D. strictus* again was the most effective species for improving the CSR for PCP as compared to all other bamboo species.

Carbon management index

The CMI is a derivative of the total organic C pool and the labile C pool (Vieira et al., 2007) and serves as a better appraisal means for studying the potential of different management systems to promote soil quality in comparison to TOC as such (Ghosh et al., 2012; Vieira et al., 2007). CMI is an indicator of soil C rehabilitation; greater values indicate soil C rehabilitation, whereas smaller values suggest that C molecules are being degraded (Blair et al., 1995). The role of bamboo in C sequestration and mitigation of climate change impacts have been well-established (INBAR, 2006, 2010; Nath et al., 2009, 2015a, b). The CMI serves as an important tool to develop management practices for sequestration of C in soils (Sodhi et al. 2009). The majority of bamboo species except for *B. balcooa* and *D. stocksii* depicted higher CMI than open systems which indicate that fallow land had significantly lower rates of soil C rehabilitation than under bamboo plantation. Of all the bamboo species, the CMI was highest for *B. vulgaris* followed by *D. strictus* which was in corroboration with the TOC accumulated in the soil. *D. stocksii* had the lowest CMI amongst all the bamboo species along with open fallow which was again a reflection of poor C input as evident from lower root biomass and litterfall for *D. stocksii* and no organic input at all in case of the open fallow. Higher CMI values under different bamboo species has also been reported by Kaushal et al. (2021) though the species showing highest CMI were different from the present study. *Dendrocalamus hamiltonii* had the highest CMI along with *D. strictus* and *B. nutans*, indicating their effectiveness in enriching the upper soil layer with C (Kaushal et al., 2021). The higher the CMI values the more is the potential for storing soil C and reduce the losses consequent upon the improvement of soil quality (Blair, 2000; Kalambukattu et al., 2013). Also, a higher CMI under bamboo is indicative of the high labile fraction C assimilated in the soil which is essential for improving the various physical and chemical properties and microbial dynamics in the soil (Kalambukattu et al., 2013).

Conclusions

Bamboo cultivation can play a significant role in influencing SOC, carbon fraction, and CMI. From the present study, we can draw the following inferences: (a) Significant higher soil organic C fractions occurred under the evaluated bamboo species compared to the open fallow; (b) the leaf litter and root biomass of bamboo act as a source of C input which enhance the C storage in the soil and having great potential for rehabilitation of degraded lands; (c) the enrichment of labile and very labile C fractions in the surface layer under the different bamboo species shows its ability to sequester C and play a major role in averting land use–induced climate change impacts. Almost all the bamboo species had significantly positive impact in terms of improving the different soil C fractions and a higher CMI. However, three species, i.e. *B. vulgaris*, *D. strictus*, and *B. nutans*, had distinct advantage over the other species in consideration when build-up of active and passive C pool in surface soil (0–15 cm) was concerned. Thus, the present study recommends the adoption and cultivation of *B. vulgaris*, *D. strictus*, and *B. nutans* in the foothills of northwest Himalayas which could tackle the problem of erosion-induced land degradation in these areas and reinvigorate the degraded lands, thus leading to the adoption of sustainable land use systems.

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Data availability Data will be made available on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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