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Physico-chemical Characteristics of Soil in Bamboo Dominated Homegardens Across Different Physiographic Conditions in Assam

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ABSTRACT

The various land use systems comprising trees, crops, and pastures are essential in improving soil fertility. Land use and soil management practices can significantly influence soil organic carbon (SOC) dynamics and C flux from the soil. Bamboo plays a vital role in maintaining and improving the nutritional condition of the soil. In the traditional agroforestry system, bamboos are grown on land of poor quality or degraded parts of the households. The present study was conducted to estimate the physico-chemical properties and to understand the impact of bamboo on the soil in the homegardens with bamboo stands under different physiographic conditions of the Hailakandi district of Assam. The soil bulk density up to 30 cm soil depth was 1.04 to 1.16 g/cm^3 in riverside villages, 1.00 to 1.19 g/cm^3 in flood-affected villages, and 1.01 to 1.13 g/cm^3 in flood-unaffected villages. The water holding capacity ranged from 40.72 to 47.52% in riverside villages, 47.73 to 53.88% in flood-affected villages, and 41.68 to 49.26% in flood-unaffected villages. Soil pH ranged from 5.20 to 5.74 in riverside villages, 5.08 to 5.50 in flood-affected villages, and 4.89 to 5.73 in flood-unaffected villages. The soil texture was dominated by silt loam in riverside villages and flood-unaffected villages, but in the flood-affected villages, it was silty clay loam. Soil organic carbon stock up to 30 cm soil depth ranged from 24.58 to 29.39 Mg/ha in riverside villages, 34.38 to 38.14 Mg/ha in flood-affected villages, and 27.67 to 42.24 Mg/ha in flood-unaffected villages. The soil in the riverside villages was of better quality because of low bulk density, pH, and sand % with high WHC, clay and silt %, SOC %, and high SOC stock. The existing bamboo management systems have many shortcomings and needs to be scientifically managed.

Key words: Village bamboo, bulk density**,** water holding capacity, Soil organic carbon.

INTRODUCTION

Soil is an essential natural resource and is useful for living organisms. It is vital for agriculture and fulfils many functions, including those essential for sustaining plant growth (Nwachokor et al. 2009). The different types of land use systems comprising trees, crops, and pastures play an essential role in improving the fertility and quality of soil in many ways (Sharma et al. 2009). According to the IPCC (Anonymous 2013) report, soil stores 1500 billion tons of C, which is double the amount of C stored in the atmosphere, and about 1.2 billion tons of soil C storage is possible in agriculture (Meyer et al. 2014). Bamboo is an economically important plant that can grow rapidly and also plays a vital role in protecting our planet from pollution and improving the soil (Emamverdian et al. 2020). Bamboo can grow on marginal land, which regenerates annually through an extensive rhizome system and has a significant potential for soil stabilization, reducing soil erosion, increasing the stability of slopes, and contributing remarkably to the restoration of degraded lands (Zhou et al. 2011, Ling et al. 2016, Anonymous 2018). From a comparative study, it was reported that the presence of bamboo in the forest significantly affected the physico-chemical characteristics of soil (Christanty et al. 1996). Bamboo can grow in relatively poor soil, efficiently use available nutrients, and build fertile soil around the clumps (Singh and Singh 1999, Mazumder 2020). Bamboo forests and plantations in different parts of India are mainly grown in soils with poor nutrients and are subjected to heavy biomass removal through bamboo harvest. Therefore, maintaining the organic pool and nutrient budget in these resource-poor bamboo forests is essential for sustained productivity that depends mainly on recycling nutrients contained in bamboo litter (Upadhyaya et al. 2012, Arunachalam and Arunachalam 2002). Bamboo plays an essential role in maintaining and improving the nutritional condition of the soil. In traditional agroforestry, bamboos are grown on land of poor quality or degraded part of the households (Nath et al. 2015).

According to Shukla et al. (2006), the functioning of soil can thus be better explained by considering its physical, chemical, and biological properties as well as environmental factors related to it. Bamboo can regenerate quickly without replanting and is highly effective in restoring soil degradation (AbadegaandAbawaji 2021, Kumari et al. 2018). The agricultural production and development of forests depend upon the physico-chemical parameters of the soil used. Therefore, soil testing is vital in the human interest of the product's quality and the different practices carried out for getting those products (Kekane et al. 2015). This study aims to assess the physico-chemical properties of soil and evaluate the impact of bamboo on soil quality in home gardens. To achieve these objectives, bamboo stands were examined across various physiographic conditions in the Hailakandi district of Assam.

METHODOLOGY

Study area

The present study was conducted in the villages of Hailakandi District located in Barak Valley, Assam, NE India, which is between $24^0 41'$ N and $24^0 68'$ N and between $92^0 34'$ E and $92^0 57'$ E. The district is bounded by the river Barak and Cachar district in the North and East, Mizoram State in the South and East, and Karimganj district in the West. The geographical area of Hailakandi is 1327 km^2. The district consists of plains and hilly areas and two reserve forests viz. Katakhal and Innerline reserve forest. Two main rivers, Katakhal and Dhaleshwari, run from south to north through the middle of the district, meeting the river Barak at Panchgram (http://hailakandi.gov.in/profile.htm).

The average annual rainfall of the district is 2388.54 mm. The annual mean maximum temperature ranges between 28.4 and 36.7°C, and the annual minimum temperature ranges from 10.0 to 24.4°C. The average annual humidity is 85%. The soil varies from sandy to clay, with pH ranging from 4.5 to 5.9. The major soil classes prevalent in the district are old riverine alluvial, old mountain alluvial, non-laterite red soil, and pit soil. The soil texture varies from sandy to silty loam (http://hailakandi.gov.in/profile.htm, Mazumder et al. 2019).

According to the India State of Forest Report (Anonymous 2019), 58.35 % of the total geographical area (1327 km^2) of the district, i.e., 774.33 km^2 is under forest cover of which 1.68% (13 km^2) is very dense forest, 47.27% (366.04km^2) is moderate dense forest and 51.05% (395.30 km^2) is open forests. Major forest types in these reserve forests of Hailakandi are Cachar tropical wet evergreen forests with small patches of semi-evergreen forests and some tropical deciduous forests (Champion and Seth 1968).

Sampling strategy

Soil samples were collected from the bamboo stands of the 5 priority species, viz., *Bambusa cacharensis*, *B. balcooa*, *B. vulgaris*, *B. nutans* and *B. polymorpha* of three physiographic conditions of the district - riverside (villages which are situated on the river bank and are affected by flood when river overflows), flood-affected (villages located on low-lying floodplain and are affected by flood every year) and flood-unaffected villages (villages situated on uplands and are least affected by the flood) (Mazumder et al. 2019). The soil sampling was done during the dry season (December and January).

Physico-chemical analysis of soil

Five replicate soil samples were collected for each bamboo species at each location using a steel corer (5.4 cm internal diameter) at three soil depths (0-10, 10-20, and 20-30 cm). Three of the five replicates from each depth were mixed to create a composite sample, while the remaining two were reserved for bulk density analysis. Bulk density was determined using undisturbed soil cores, following methods by Prikner et al. (2004), Osunbitan et al. (2005), Reichert et al. (2009), and Nath et al. (2015). In the laboratory, the composite samples were divided into two portions. One portion was sieved through a 2 mm mesh and immediately analyzed for pH in a 1:2.5 soil-water suspension (Jackson 1973) using a digital glass electrode pH meter. The other portion was air-dried, sieved through a 2 mm mesh (BSS-8), and stored in plastic containers for soil texture and water holding capacity analysis. Soil texture was determined using the Bouyoucos Hydrometer method (Allen 1989), calculating the proportions of sand, silt, and clay based on hydrometer readings at

40 seconds and 2 hours. The textural classification was assigned using the USDA Soil Texture Triangle. Water holding capacity (WHC) was measured using the Keen-Raczkowski box method (Piper 1950, Baruah and Borthakur 1997) with custom-made tin cups (5.6 cm internal diameter, 1.6 cm height). Soil colour was determined using Munsell Soil-Colour Charts (Anonymous 2015). The remaining air-dried soil was ground and sieved through a 0.150 mm mesh (BSS-100) to analyze soil organic carbon (SOC), which was estimated by the wet digestion method of Walkley and Black (1934), as described by Jackson (1973).

Soil organic carbon stock (Mg ha^{-1} was calculated using the formula provided by Blanco-Canqui and Lal (2008).

SOC stock (Mg ha^{-1}) =104(m^2/ha) x soil depth (m) x BD (Mg/m^3) x SOC (%) /100

Statistical analysis

Statistical analysis was done using one-way ANOVA to study the effect of physiography and soil depth on soil parameters. The relationship between the various physico-chemical characteristics of the priority bamboo species was developed through correlation matrix analysis using MS Excel and IBM SPSS (version 21).

RESULTS

Bulk density

The study demonstrated that soil bulk density (BD) increases with depth across all five priority species – *Bambusa cacharensis*, *B. balcooa*, *B. vulgaris*, *B. nutans*, and *B. polymorpha* - within three physiographic regions: riverside, flood-affected, and flood-unaffected villages (Table 1; Fig. 1). For *B. cacharensis*, at depths up to 30 cm, the lowest BD (1.06 g/cm³) was found in riverside and flood-unaffected villages, while the highest (1.13 g/cm³) was recorded in flood-affected areas. For *B. balcooa*, the lowest BD (1.04 g/cm³) was observed in flood-affected villages, and the highest (1.09 g/cm³) in riverside regions. In *B. vulgaris* stands, the lowest BD (1.04 g/cm³) was in flood-unaffected villages, with the highest (1.08 g/cm³) in riverside areas. For *B. nutans*, BD ranged from 1.04 g/cm³ in flood-affected areas to 1.09 g/cm³ in riverside villages. Finally, *B. polymorpha* exhibited the lowest BD (1.04 g/cm³) in flood-unaffected regions and the highest (1.12 g/cm³) in riverside villages (Table 2). Significant differences in BD with soil depth were noted for *B. cacharensis* in flood-affected areas ($r=0.531$; $p<0.05$), but were not significant in riverside ($r=0.316$; $p>0.05$) or flood-unaffected regions ($r=00.265$; $p>0.05$). For *B. balcooa*, no significant differences in BD with soil depth were observed in riverside villages ($r=0.244$; $p>0.05$), though differences were significant in flood-affected ($r=0.580$, $p<0.01$) and flood-unaffected villages ($r= 0.531$; $p<0.05$). *B. vulgaris* showed insignificant BD differences in riverside ($r=0.401$; $p>0.05$) but significant differences in flood-affected ($r=0.615$; $p<0.01$), and flood-unaffected ($r=0.513$; $p<0.05$). No significant differences in BD were found for *B. nutans* across all conditions: riverside ($r=0.298$; $p>0.05$), flood-affected ($r= 0.300$; $p>0.05$), and flood-unaffected ($r=0.265$; $p>0.05$). For *B. polymorpha*, significant differences were detected in riverside ($r=0.465$; $p<0.01$) and insignificant in flood-affected areas ($r=0.415$; $p>0.05$) and flood-unaffected villages ($r=0.342$; $p>0.05$).

Water holding capacity

The water holding capacity (WHC) increased with soil depth across all five priority species – *Bambusa cacharensis*, *B. balcooa*, *B. vulgaris*, *B. nutans*, and *B. polymorpha* - within the three physiographic regions: riverside, flood-affected, and flood-unaffected villages (Table 1; Fig. 2). For *B. cacharensis* stands, the lowest WHC (43.18%) was observed in riverside villages, while the highest (51.41%) was found in flood-affected areas at depths up to 30 cm. In *B. balcooa* stands, the lowest WHC (46.76%) occurred in riverside regions, with the highest (51.72%) in flood-affected areas. For *B. vulgaris*, the lowest WHC (45.64%) was recorded in riverside villages, while the highest (51.05%) was in flood-affected areas. In *B. nutans* stands, the lowest WHC (43.05%) was found in flood-unaffected villages and the highest (50.18%) in flood-affected areas. For *B. polymorpha*, WHC ranged from 46.05% in flood-unaffected villages to 49.15% in flood-affected regions (Table 2). Significant differences in WHC with soil depth were observed across all three physiographic regions: riverside ($r=0.511$; $p<0.05$),

Table 1. Soil physico-chemical characteristics in different physiographic conditions at different soil depths for the 5 priority bamboo species in Hailakandi district, Assam

Bamboo species	Soil depth (cm)	BD (g/cm^3)	WHC (%)	pH	Clay (%)	Silt (%)	Sand (%)	SOC (%)	SOC stock (Mg/ha)
Riverside									
B. cacharensis	0-10	1.04 (0.01)	40.72 (0.02)	5.74 (0.02)	21.20 (0.00)	53.42 (0.03)	25.38 (0.30)	1.01 (0.01)	10.43 (0.69)
	10-20	1.06 (0.01)	43.70 (0.05)	5.71 (0.03)	22.63 (0.60)	54.99 (1.05)	22.38 (0.45)	0.83 (0.01)	8.77 (0.30)
	20-30	1.09 (0.00)	45.13 (0.03)	5.63 (0.02)	23.63 (0.45)	56.42 (1.05)	19.95 (0.60)	0.74 (0.00)	8.01 (0.59)
B. nutans	0-10	1.06 (0.03)	41.77 (0.03)	5.47 (0.02)	20.06 (0.00)	52.88 (0.00)	27.06 (0.00)	1.02 (0.00)	10.76 (0.60)
	10-20	1.09 (0.01)	44.09 (0.03)	5.37 (0.04)	22.06 (0.30)	53.02 (0.45)	24.92 (0.15)	0.87 (0.01)	9.45 (0.28)
	20-30	1.12 (0.01)	46.36 (0.02)	5.34 (0.02)	23.34 (0.45)	53.59 (0.75)	23.06 (0.60)	0.82 (0.01)	9.17 (0.36)
B. vulgaris	0-10	1.05 (0.01)	44.25 (0.03)	5.66 (0.01)	20.77 (0.45)	51.43 (0.60)	27.80 (0.45)	0.85 (0.00)	8.90 (0.86)
	10-20	1.08 (0.01)	45.72 (0.03)	5.56 (0.01)	22.49 (0.75)	51.71 (0.90)	25.80 (0.45)	0.74 (0.00)	7.94(0.61)
	20-30	1.10 (0.01)	46.97 (0.03)	5.49 (0.02)	23.49 (0.90)	52.43 (0.75)	24.09 (0.15)	0.71 (0.01)	7.74 (0.67)
B. balcooa	0-10	1.07 (0.02)	45.10 (0.02)	5.57 (0.01)	19.91 (0.15)	54.66 (0.75)	25.43 (0.60)	0.95 (0.01)	10.07 (0.66)
	10-20	1.09 (0.01)	46.38 (0.03)	5.48 (0.01)	21.63 (0.15)	56.09 (0.75)	22.29 (0.60)	0.83 (0.01)	8.92 (0.59)
	20-30	1.11 (0.00)	48.80 (0.02)	5.41 (0.02)	22.63 (0.60)	56.37 (0.75)	21.00 (0.15)	0.75 (0.01)	8.26 (0.55)
B. polymorpha	0-10	1.07 (0.01)	45.67 (0.03)	5.26 (0.01)	22.49 (0.15)	54.21 (0.30)	23.31 (0.15)	0.92 (0.00)	9.71 (0.72)
	10-20	1.12 (0.01)	46.79 (0.02)	5.21 (0.02)	24.34 (0.00)	54.06 (0.45)	21.59 (0.45)	0.80 (0.01)	8.95 (0.62)
	20-30	1.16 (0.00)	47.52 (0.03)	5.20 (0.04)	25.77 (0.15)	53.35 (0.90)	20.88 (0.30)	0.72 (0.01)	8.29 (0.54)
Flood-affected									
B. cacharensis	0-10	1.06 (0.01)	49.17 (0.02)	5.50 (0.03)	26.91 (0.00)	54.31 (0.30)	18.78 (0.30)	1.21 (0.00)	12.79 (0.50)
	10-20	1.13 (0.01)	51.19 (0.03)	5.42 (0.04)	28.77 (0.75)	55.45 (0.90)	15.78 (0.45)	1.13 (0.01)	12.65 (0.67)
	20-30	1.19 (0.01)	53.88 (0.03)	5.35 (0.07)	30.49 (0.75)	56.21 (0.60)	13.31 (0.45)	1.08 (0.01)	12.70 (0.92)
B. nutans	0-10	1.02 (0.01)	48.20 (0.04)	5.42 (0.03)	27.63 (0.45)	53.00 (0.45)	19.37 (0.30)	1.20 (0.00)	12.07 (0.77)
	10-20	1.03 (0.01)	50.30 (0.03)	5.39 (0.02)	30.49 (0.45)	54.14 (0.75)	15.37 (0.90)	1.09 (0.01)	11.20 (0.41)
	20-30	1.07 (0.01)	52.03 (0.05)	5.37 (0.02)	32.63 (0.30)	55.00 (0.45)	12.37 (0.45)	1.04 (0.01)	11.11 (0.49)
B. vulgaris	0-10	1.02 (0.02)	49.70 (0.04)	5.26 (0.01)	32.77 (0.90)	49.57 (1.05)	17.66 (0.45)	1.29 (0.00)	13.10 (0.34)
	10-20	1.04 (0.02)	50.99 (0.03)	5.23 (0.01)	34.48 (0.90)	51.14 (0.90)	14.38 (0.60)	1.17 (0.01)	12.18 (0.32)
	20-30	1.10(0.01)	52.47 (0.03)	5.22 (0.01)	36.34 (0.75)	51.14 (1.20)	12.52 (0.45)	1.12 (0.01)	12.26 (0.33)
B. balcooa	0-10	1.00 (0.06)	50.21 (0.05)	5.13 (0.01)	29.76 (0.00)	52.43 (0.15)	17.81 (0.15)	1.21 (0.00)	12.09 (0.19)
	10-20	1.06 (0.03)	51.65 (0.03)	5.11 (0.01)	33.19 (0.30)	51.43 (0.60)	15.38 (0.60)	1.15 (0.01)	12.10 (0.72)
	20-30	1.06 (0.02)	53.30 (0.03)	5.08 (0.02)	35.19 (0.30)	52.00 (0.90)	12.81 (0.60)	1.06 (0.01)	11.19 (0.65)
B. polymorpha	0-10	1.07 (0.01)	47.73 (0.05)	5.37 (0.01)	25.37 (0.45)	52.94 (0.15)	21.69 (0.30)	1.17 (0.00)	12.51 (0.41)
	10-20	1.10 (0.01)	49.11 (0.05)	5.31 (0.01)	28.51 (0.75)	54.27 (1.05)	17.22 (0.30)	1.09 (0.01)	11.95 (0.77)
	20-30	1.11 (0.01)	50.60 (0.05)	5.30 (0.01)	30.65 (0.30)	54.84 (0.75)	14.51 (0.75)	1.03 (0.00)	11.39 (0.77)

Bamboo species	Soil depth (cm)	BD (g/cm³)	WHC (%)	pH	Clay (%)	Silt (%)	Sand (%)	SOC (%)	SOC stock (Mg/ha)
Flood-unaffected									
B. cacharensis	0-10	1.05 (0.01)	41.70 (0.20)	5.73 (0.01)	24.77 (0.15)	51.86 (1.05)	23.37 (0.90)	1.45 (0.00)	15.11 (0.58)
	10-20	1.06 (0.01)	42.99 (0.10)	5.68(0.02)	26.34 (0.00)	52.29 (0.60)	21.37 (0.60)	1.31 (0.01)	13.95 (1.20)
	20-30	1.09 (0.01)	45.75 (0.06)	5.62 (0.02)	27.77 (0.90)	52.86 (0.60)	19.37 (0.90)	1.21 (0.02)	13.17(0.96)
B. nutans	0-10	1.04 (0.01)	41.68 (0.06)	5.41 (0.01)	22.34 (0.30)	56.57 (0.60)	21.09 (0.30)	1.09 (0.01)	11.26 (0.32)
	10-20	1.08 (0.01)	42.86 (0.05)	5.33 (0.01)	23.77 (0.00)	57.00 (0.15)	19.23 (0.15)	0.78 (0.01)	8.35 (0.32)
	20-30	1.09 (0.01)	44.61 (0.11)	5.28 (0.04)	25.06 (0.45)	57.71 (0.60)	17.23 (0.75)	0.68 (0.01)	7.32 (0.26)
B. vulgaris	0-10	1.02 (0.01)	45.54 (0.09)	5.48 (0.03)	21.63 (0.15)	55.47 (0.60)	22.90 (0.45)	1.13 (0.00)	11.42 (0.24)
	10-20	1.03 (0.01)	47.48 (0.18)	5.41 (0.03)	23.06 (0.45)	56.76 (1.05)	20.18 (0.60)	0.81 (0.01)	8.29 (0.75)
	20-30	1.07 (0.02)	49.03 (0.05)	5.34 (0.04)	24.06 (0.30)	57.90 (0.45)	18.04 (0.45)	0.75 (0.02)	7.95 (0.78)
B. balcooa	0-10	1.03 (0.01)	45.30 (0.07)	4.98 (0.03)	20.91 (0.30)	52.57 (1.20)	26.51 (0.90)	1.29 (0.00)	13.22 (0.39)
	10-20	1.06 (0.01)	47.16 (0.04)	4.93 (0.03)	23.63 (0.45)	54.71 (0.75)	21.66 (0.30)	1.12 (0.00)	11.87 (0.52)
	20-30	1.13 (0.01)	49.26 (0.04)	4.89 (0.01)	25.77 (0.60)	54.14 (0.15)	20.09 (0.45)	0.90 (0.01)	10.17 (0.14)
B. polymorpha	0-10	1.01 (0.01)	44.72 (0.04)	5.69 (0.04)	28.20 (0.15)	50.15 (0.30)	21.65 (0.15)	1.09 (0.01)	10.94 (0.32)
	10-20	1.05 (0.01)	45.82 (0.05)	5.63 (0.05)	29.91 (0.45)	51.01 (0.60)	19.08 (0.45)	0.94 (0.01)	9.82 (0.34)
	20-30	1.07 (0.01)	47.61 (0.05)	5.58 (0.04)	31.49 (0.30)	51.15 (0.45)	17.37 (0.75)	0.69 (0.02)	7.31 (0.25)

Figures in parenthesis are SEM at 95% confidence interval.

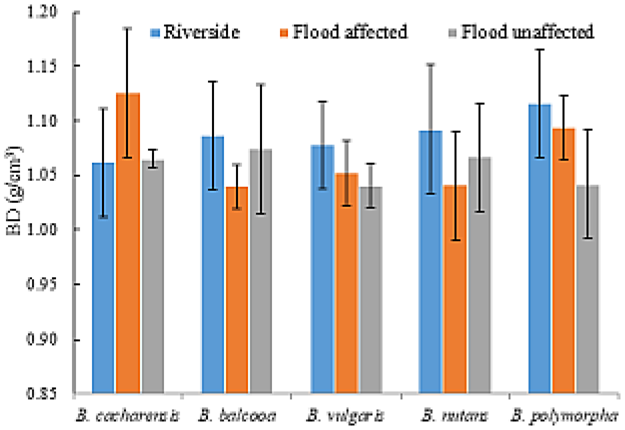

Figure 1. Soil Bulk density of the different bamboo stands in different physiography up to 30 cm soil depth

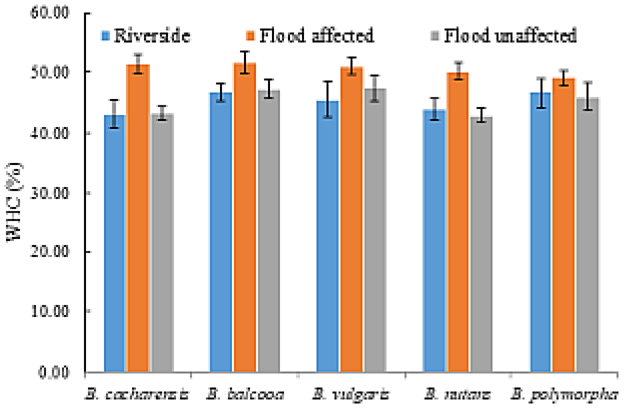

Figure 2. Soil WHC of the different bamboo stands in different physiography up to 30 cm soil depth

flood-affected (r=0.673; $p<0.01$), and flood-unaffected (r=0.747; $p<0.01$) for *B. cacharensis*. Similar trend was observed for *B. balcooa* in riverside (r=0.632; $p<0.01$), flood-affected (r=0.490; $p<0.05$) and flood-unaffected villages (r=0.644; $p<0.01$). For *B. nutans* significant differences in WHC with soil depth were observed in riverside (r=0.623; $p<0.01$), flood-affected (r=0.630; $p<0.01$) and in flood-unaffected villages (r=0.580; $p<0.01$). For *B. polymorpha* differences in WHC with soil depth was insignificant in riverside (r=0.245; $p>0.05$) and flood-unaffected (r=0.395; $p>0.05$) but significant in flood-affected (r=0.585; $p<0.01$). For *B. vulgaris*, differences in WHC were insignificant in riverside villages (r=0.269; $p>0.05$), but significant in flood-affected (r=0.503; $p<0.05$) and flood-unaffected areas (r=0.490; $p<0.05$).

Table 2. Soil physical parameters (up to 30 cm soil depth) in Hailakandi district, Assam

Bamboo species	**Parameter**	**Riverside**	**Flood-affected**	**Flood-unaffected**
Bambusa cacharensis	BD (g/cm³)	1.06 (0.05)	1.13 (0.06)	1.06 (0.08)
	WHC (%)	43.18 (2.35)	51.41 (1.54)	43.48 (1.10)
	Sand (%)	22.57 (2.16)	15.95 (1.02)	21.37 (4.40)
	Silt (%)	54.94 (3.10)	55.32 (1.99)	52.33 (5.69)
	Clay (%)	22.49 (1.39)	28.72 (1.87)	26.30 (5.31)
Bambusa balcooa	BD (g/cm³)	1.09 (0.05)	1.04 (0.02)	1.07 (0.06)
	WHC (%)	46.76 (1.42)	51.72 (1.78)	47.24 (1.47)
	Sand (%)	20.90 (3.78)	15.34 (1.00)	22.75 (0.94)
	Silt (%)	55.70 (2.92)	51.95 (2.21)	53.81 (3.33)
	Clay (%)	21.39 (2.31)	32.71 (2.59)	23.44 (2.53)
Bambusa vulgaris	BD (g/cm³)	1.08 (0.04)	1.05 (0.03)	1.04 (0.02)
	WHC (%)	45.64 (2.85)	51.05 (1.51)	47.35 (1.98)
	Sand (%)	25.90 (5.97)	14.85 (0.65)	20.37 (2.86)
	Silt (%)	51.86 (4.79)	50.62 (1.75)	56.71 (2.34)
	Clay (%)	22.25 (2.43)	34.53 (2.23)	22.91 (1.62)
Bambusa nutans	BD (g/cm³)	1.09 (0.06)	1.04 (0.05)	1.07 (0.05)
	WHC (%)	44.07 (1.80)	50.18 (1.46)	43.05 (1.28)
	Sand (%)	25.02 (2.30)	15.70 (1.79)	19.18 (1.09)
	Silt (%)	53.17 (2.16)	54.05 (2.28)	57.10 (1.27)
	Clay (%)	21.82 (1.56)	30.25 (1.21)	23.72 (0.57)
Bambusa polymorpha	BD (g/cm³)	1.12 (0.05)	1.09 (0.03)	1.04 (0.05)
	WHC (%)	46.66 (2.37)	49.15 (1.25)	46.05 (2.18)
	Sand (%)	21.93 (0.79)	17.81 (2.40)	19.37 (1.55)
	Silt (%)	53.87 (1.47)	54.02 (1.91)	50.77 (2.91)
	Clay (%)	24.20 (1.00)	28.18 (1.79)	29.87 (3.01)

Figures in parenthesis are SEM at 95% confidence interval

Soil colour

The soil colour ranged from 10YR-6/4 to 10YR-5/2, indicating light yellowish brown to greyish brown, for the bamboo stands of all species in riverside and flood-affected villages. In flood-unaffected villages, the Munsell soil colour ranged from 10YR-6/3 to 10YR-5/2, indicating pale brown to grayish brown (Table 3).

Soil texture

The soil texture in bamboo stands for *Bambusa cacharensis*, *B. balcooa*, *B. vulgaris*, *B. nutans*, and *B. polymorpha* in riverside villages was predominantly silty loam. In flood-unaffected villages, the soil texture for *B. cacharensis*, *B. balcooa*, *B. vulgaris*, and *B. nutans* was also silt loam, except for *B. polymorpha*, where the texture was silty clay loam. In flood-affected villages, the dominant texture across all species was silty clay loam (Table 1; Fig. 3). Insignificant differences in clay and sand percentages with soil depth were observed for *B. cacharensis*, *B. nutans*, and *B. polymorpha* stands in riverside villages ($p>0.05$). In contrast, silt percentage showed significant difference for *B. cacharensis* ($r=0.484$; $p<0.05$), *B. nutans* ($r=0.559$; $p<0.01$), and *B. polymorpha* ($r=0.705$; $p<0.01$) stands in riverside villages. In flood-affected villages, both clay and sand percentages varied insignificantly with depth for *B. cacharensis*, *B. nutans* and *B. polymorpha* ($p>0.05$), though silt percentage varied significantly with depth for *B. cacharensis* ($r=0.514$; $p<0.05$), *B. nutans* ($r=0.772$; $p<0.01$) and *B. polymorpha* ($r=0.678$; $p<0.01$). In flood-unaffected villages, no significant differences in clay, silt, or

Table 3. Soil colour in different physiographic conditions at different soil depths for the 5 priority bamboo species in Hailakandi district, Assam

Bamboo species	Soil depth (cm)	Riverside	Flood-affected	Flood-unaffected
B. cacharensis	0-10	Light brownish gray	Light brownish gray	Grayish brown
	10-20	Pale brown	Pale brown	Grayish brown
	20-30	Pale brown	Pale brown	Brown
B. nutans	0-10	Grayish brown	Light brownish gray	Grayish brown
	10-20	Brown	Pale brown	Pale brown
	20-30	Brown	Yellowish brown	Grayish brown
B. vulgaris	0-10	Grayish brown	Brown	Grayish brown
	10-20	Brown	Yellowish brown	Grayish brown
	20-30	Brown	Brown	Grayish brown
B. balcooa	0-10	Light brownish gray	Grayish brown	Grayish brown
	10-20	Pale brown	Pale brown	Brown
	20-30	Brown	Brown	Brown
B. polymorpha	0-10	Grayish brown	Grayish brown	Grayish brown
	10-20	Grayish brown	Light brownish gray	Pale brown
	20-30	Brown	Brown	Pale brown

sand percentages were observed for *B. cacharensis* stands ($p>0.05$). For *B. nutans* stands, clay ($r=0.811$; $p<0.01$) and sand ($r=0.-0.733$; $p<0.01$) percentages differed significantly with soil depth, but silt percentage was insignificant ($p>0.05$). In *B. polymorpha* stands, clay and silt percentages were insignificant ($p>0.05$), while sand percentage showed a significant difference ($r=-0.621$; $p<0.01$). Insignificant differences in clay, silt, and sand percentages were found for *B. balcooa* and *B. vulgaris* stands in riverside villages ($p>0.05$). In flood-affected villages, except *B. balcooa* all the other species showed significant differences in clay and sand percentages with depth ($p<0.01$), but silt percentage remained insignificant ($p>0.05$) for all the species except *B. balcooa* ($r=0.544$; $p<0.05$). Similarly, in flood-unaffected villages, significant variations in sand percentages were observed for *B. vulgaris* ($r=-0.480$; $p<0.05$), while *B. balcooa* showed significant difference with soil depth for clay ($r=0.496$; $p<0.05$) and sand ($r=-0.753$; $p<0.01$) percentage but did not show significant change for silt ($p>0.05$).

Soil pH

Among the soil chemical parameters, soil pH decreased with depth for all five priority species – *Bambusa cacharensis*, *B. balcooa*, *B. vulgaris*, *B. nutans*, and *B. polymorpha* - across the three physiographic regions: riverside, flood-affected, and flood-unaffected villages of Hailakandi district (Table 1; Fig. 4). For *B. cacharensis* stands, the lowest pH (5.42) was observed in flood-affected villages, while the highest pH (5.69) was recorded in riverside villages at depths up to 30 cm. In *B. balcooa* stands, pH ranged from 4.93 in flood-unaffected villages to 5.49 in riverside regions. For *B. vulgaris*, the lowest pH (5.24) was found in flood-affected areas, while the highest (5.57) was in riverside villages. In *B. nutans* stands, pH varied from 5.34 in flood-unaffected areas to 5.39 in riverside and flood-affected villages. For *B. polymorpha*, the lowest pH (5.22) was recorded in riverside villages, while the highest (5.63) was in flood-unaffected regions (Table 4). For *B. cacharensis*, significant differences in pH with soil depth were observed in riverside villages ($r=-0.621$; $p<0.01$) and flood-affected ($r=-0.817$; $p<0.01$) while insignificant in flood-unaffected ($r=-0.413$; $p>0.05$) areas. In *B. balcooa* stands, pH differences with soil depth were significant in flood-affected villages ($r=-0.803$; $p<0.01$) while insignificant across riverside and

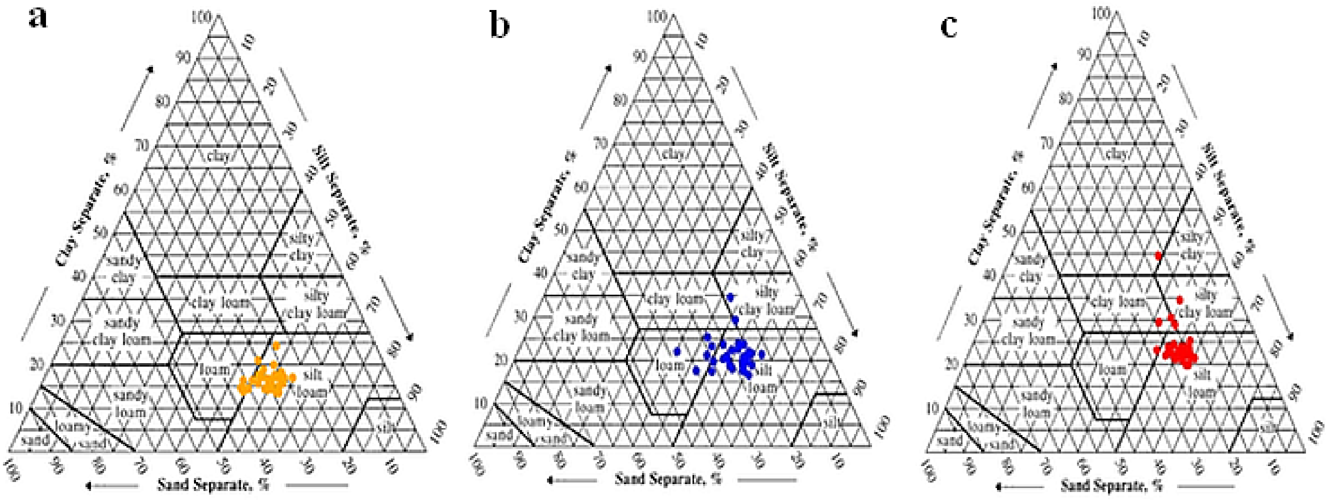

Figure 3. Soil Texture triangles (up to 30 cm soil depth) in the bamboo stands in different physiographic conditions of Hailakandi district; a - Flood-affected villages, b - Flood-unaffected villages, c - Riverside villages

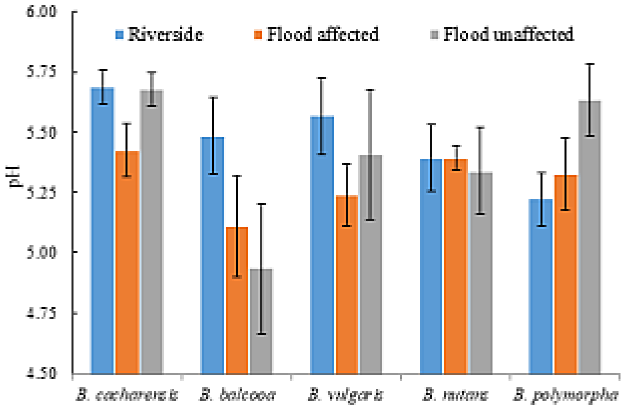

Figure 4. Soil pH of the different bamboo stands in different physiography up to 30 cm soil depth

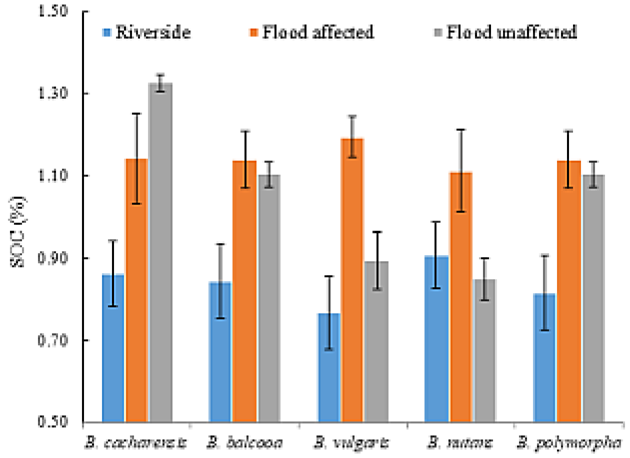

Figure 5. SOC % of the different bamboo stands in different physiography up to 30 cm soil depth

flood-unaffected villages (p>0.05). Significant differences in soil depth were found for *B. vulgaris* (r=-0.883; p<0.01) in flood-affected villages but insignificant across riverside and flood-unaffected villages (p>0.05). For *B. nutans* significant differences with soil depth was found in riverside (r=-0.491; p<0.05), flood-affected (r=-0.754; p<0.01), but insignificant in flood-unaffected villages (p>0.05). For *B. polymorpha* stands significant differences with soil depth was found in riverside (r=-0.678; p<0.01), flood-affected (r=-0.677, p<0.01) but insignificant in flood-unaffected villages (p>0.05).

Soil organic carbon content

The study of soil organic carbon content (SOC %) revealed a decline with increasing soil depth for all five priority species – *Bambusa cacharensis*, *B. balcooa*, *B. vulgaris*, *B. nutans*, and *B. polymorpha* - across the three physiographic regions: riverside, flood-affected, and flood-unaffected villages (Table 1; Fig. 5). For *B. cacharensis* stands, the lowest SOC (0.86%) was recorded in riverside villages, while the highest SOC (1.33%) was found in flood-unaffected villages at depths up to 30 cm. In *B. balcooa* stands, SOC ranged from 0.84% in riverside villages to 1.14% in flood-affected areas. For *B. vulgaris*, the lowest SOC (0.77%) was observed in riverside villages, while the highest (1.19%) was in flood-affected areas. In *B. nutans* stands SOC varied from 0.85% in flood-unaffected villages to 1.11% in flood-affected areas. For *B. polymorpha*, SOC ranged from

Table 4. Soil chemical parameters (up to 30 cm soil depth) across all age groupsin Hailakandi district, Assam

Bamboo species	Soil parameters	Riverside	Flood-affected	Flood-unaffected
Bambusa cacharensis	pH	5.69 (0.07)	5.42 (0.11)	5.68 (0.07)
	SOC (%)	0.86 (0.08)	1.14 (0.11)	1.33 (0.02)
	SOM (%)	1.49 (0.14)	1.97 (0.19)	2.29 (0.04)
	SOC STOCK (Mg/Ha)	27.21 (0.47)	38.14 (0.67)	42.24 (0.89)
Bambusa balcooa	pH	5.49 (0.16)	5.11 (0.21)	4.93 (0.27)
	SOC (%)	0.84 (0.09)	1.14 (0.07)	1.10 (0.03)
	SOM (%)	1.45 (0.16)	1.96 (0.11)	1.90 (0.04)
	SOC STOCK (Mg/Ha)	27.25 (0.59)	35.39 (0.49)	35.26 (0.33)
Bambusa vulgaris	pH	5.57 (0.16)	5.24 (0.13)	5.41 (0.27)
	SOC (%)	0.77 (0.09)	1.19 (0.05)	0.89 (0.07)
	SOM (%)	1.32 (0.15)	2.06 (0.09)	1.54 (0.13)
	SOC STOCK (Mg/Ha)	24.58 (0.68)	37.54 (0.25)	27.67 (0.56)
Bambusa nutans	pH	5.39 (0.14)	5.39 (0.05)	5.34 (0.18)
	SOC (%)	0.91 (0.08)	1.11 (0.10)	0.85 (0.05)
	SOM (%)	1.56 (0.14)	1.91 (0.18)	1.46 (0.08)
	SOC STOCK (Mg/Ha)	29.39 (0.39)	34.38 (0.54)	26.93 (0.15)
Bambusa polymorpha	pH	5.22 (0.11)	5.33 (0.15)	5.63 (0.15)
	SOC (%)	0.81 (0.09)	1.10 (0.08)	0.90 (0.02)
	SOM (%)	1.40 (0.16)	1.89 (0.14)	1.56 (0.04)
	SOC STOCK (Mg/Ha)	26.95 (0.59)	35.85 (0.43)	28.07 (0.29)

Values in parenthesis are SEM at 95% confidence interval

0.81% in riverside villages to 1.10% in flood-affected areas (Table 4). Significant differences in SOC% with soil depth were observed in *B. cacharensis* stands in riverside ($r=-0.702$; $p<0.01$) and flood-unaffected villages ($r=-0.898$; $p<0.01$) but not in flood-affected areas ($p>0.05$). In *B. balcooa* stands, significant SOC differences with depth were noted in all regions: riverside ($r=-0.568$; $p<0.01$), flood-affected ($r=-0.568$; $p<0.01$), and flood-unaffected villages ($r=-0.972$; $p<0.01$). For *B. polymorpha* stands also significant difference were observed in riverside ($r=-0.569$; $p<0.01$), in flood-affected ($r=-0.501$; $p<0.05$) and in flood-unaffected ($r=-0.968$; $p<0.01$). For *B. nutans* significant difference were observed in riverside ($r=-0.610$; $p<0.01$), in flood-affected ($r=-0.432$; $p<0.05$) and in flood-unaffected ($r=-0.905$; $p<0.01$). *B. vulgaris* SOC showed significant variation with soil depth in all three physiographic regions: riverside ($r=-0.453$; $p<0.05$), flood-affected ($r=-0.699$; $p<0.01$) and flood-unaffected ($r=-0.800$; $p<0.01$).

Soil organic carbon stock

The study of soil organic carbon (SOC) stock revealed that it decreased with soil depth for all five priority species – *Bambusa cacharensis*, *B. balcooa*, *B. vulgaris*, *B. nutans*, and *B. polymorpha* - in riverside and flood-affected villages. However, the trend was reversed in flood-unaffected villages with increasing clump age (Table 1; Fig. 6). For *B. cacharensis* stands, the lowest SOC stock (27.21 Mg/ha) was found in riverside villages, while the highest (42.24 Mg/ha) was recorded in flood-unaffected areas at depths up to 30 cm. In *B. balcooa* stands, SOC stock ranged from 27.25 Mg/ha in riverside villages to 35.39 Mg/ha in flood-unaffected areas. For *B. vulgaris*, the lowest SOC stock (24.58 Mg/ha) occurred in riverside villages, while the highest (37.54 Mg/ha) was in flood-affected areas. In *B. nutans* stands, SOC stock ranged from 26.93 Mg/ha in flood-unaffected villages to 34.38 Mg/ha in flood-affected regions. For *B. polymorpha* stands, SOC stock varied from 26.95 Mg/ha in riverside villages to 35.85 Mg/ha in flood-affected areas (Table 4). Significant differences in SOC stock with soil depth were observed in *B. cacharensis* stands in riverside

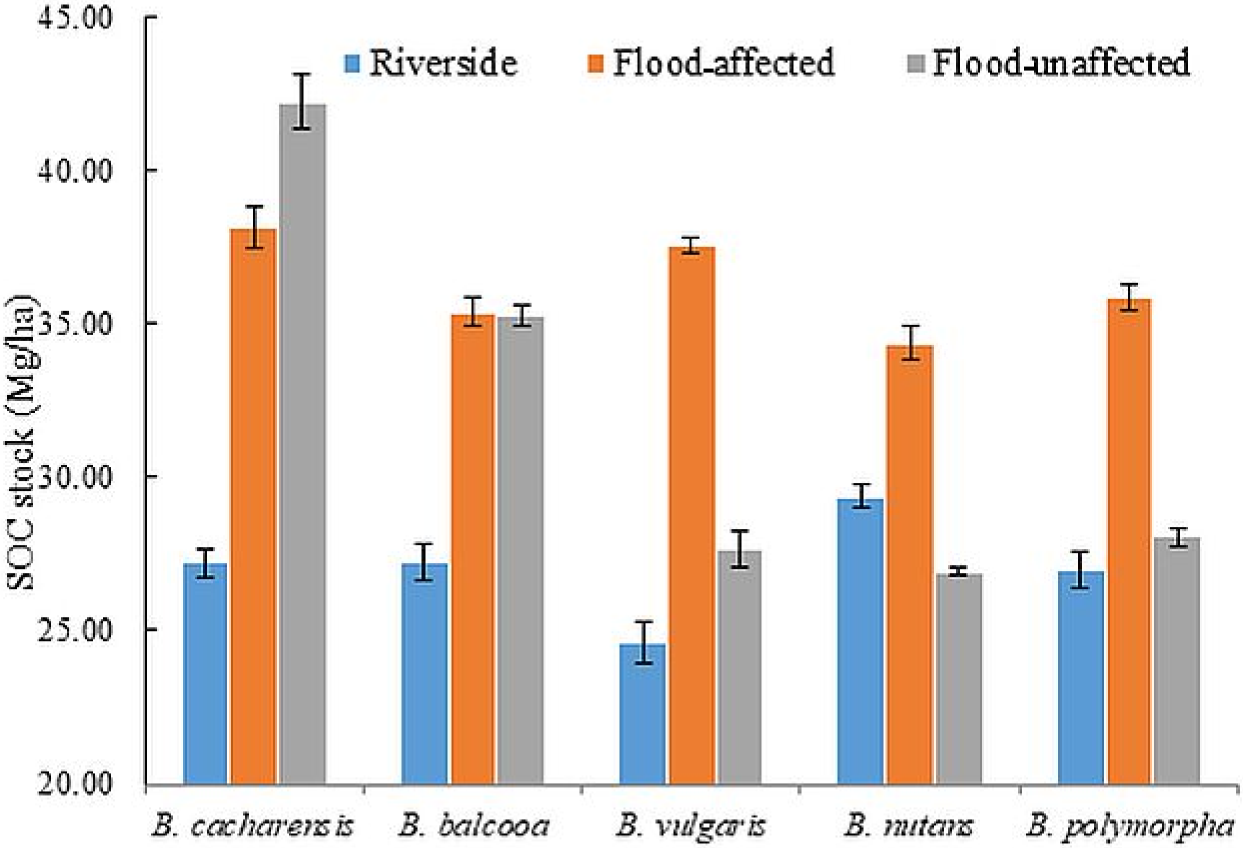

Figure 6. SOC stock of the different bamboo stands in different physiography up to 30 cm soil depth

(r=-0.809; p<0.01) and flood-unaffected villages (r=-0.556; p<0.01) but not in flood-affected areas (p>0.05). For *B. balcooa*, SOC stock showed significant variation with depth in riverside (r=-0.696; p<0.01), flood-affected (r=-0.443; p<0.05), and flood-unaffected regions (r=-0.931; p<0.01). In *B. vulgaris* stands, SOC stock differed significantly with depth in riverside (r=-0.456; p<0.05), flood-affected (r=-0.584; p<0.01), and flood-unaffected villages (r=-0.809; p<0.01). For *B. nutans*, significant differences in SOC stock with soil depth were observed in riverside (r=-0.734; p<0.01), flood-affected (r=-0.466; p<0.05), and flood-unaffected villages (r=-0.940; p<0.01). Similarly, *B. polymorpha* stands exhibited significant SOC stock variation with soil depth in riverside (r=-0.591; p<0.01), flood-affected (r=-0.478; p<0.05), and flood-unaffected areas (r=-0.947; p<0.01).

Soil physical and chemical characteristics in relation to village physiographic conditions

Soil physical and chemical parameters, including bulk density, water holding capacity (WHC), clay %, sand %, pH, SOC %, and SOC stock, showed significant variation across physiographic conditions (p<0.01), except silt % (p>0.05). ANOVA analysis indicated that soil physico-chemical characteristics in riverside and flood-affected villages differed significantly among bamboo species (p<0.05). In flood-unaffected villages, all parameters except bulk density (p>0.05) showed significant differences (p<0.05) among all bamboo species. The various physico-chemical properties of the soil across different depths for all species in the three physiographic regions are presented in Supplementary Table 1. The study highlights that soil in riverside villages is of superior quality, characterized by low bulk density, pH, and sand %, along with high WHC, clay %, silt %, SOC %, and SOC stock. A comparative analysis of the physical (Table 2, 3; Figs. 1, 2, 3) and chemical (Table 4; Figs. 4, 5, 6) properties of the bamboo area up to 30 cm soil depth across the three physiographic conditions revealed that *B. cacharensis* had the highest bulk density (1.13 g/cm³) and WHC (51.41%) in flood-affected villages compared to the other regions.

DISCUSSION

The study revealed that bulk density increased with soil depth across all five bamboo species – *Bambusa cacharensis*, *B. balcooa*, *B. vulgaris*, *B. nutans*, and *B. polymorpha* - in all three physiographic conditions. This increase may be attributed to the higher organic matter content in the upper soil layers, which makes the soil more porous and less compact. Organic matter and bamboo roots in the surface layer contribute to this porosity, improving soil fertility. Similar findings have been reported by Tripathi and Singh (1994), Embaye et al. (2005), Nath (2008), Handique (2011), Nath et al. (2016a,b), Tripathi et al. (2005), and Xu et al. (2018). A significant relationship between bamboo species and bulk density and SOC concentration has also been observed in soils of the montane region of Ecuador for *Guadua angustifolia* (Tian et al. 2007). A similar trend was found in *Dendrocalamus strictus* from coal-mined areas in central India (Singh and Singh 1999) and Moso bamboo (*Phyllostachys pubescens*) in Japan (Hiraoka and Onda 2012). Bulk density values in bamboo plantations in Northern Mindanao, Philippines, ranged from 1.11 to 1.59 g/cm³ (Pongon et al. 2016), while the bulk density of Poli soils in Barak Valley, Assam was reported to be 0.67 g/cm³ (Das and Das 2005).Water holding capacity (WHC) increased with soil depth for all species, likely due to a higher proportion of silt and clay particles at greater depths and a reduced sand content. This increase in WHC aligns with findings by Birmingham (2003), who noted that WHC is a key texture-dependent soil property. In Barak Valley, Assam, the WHC of Poli soil was reported to be 52.63% (Das and Das 2005). Soil texture in bamboo stands varied across the different physiographic conditions. In riverside villages, silt loam dominated the stands of all five species. In flood-unaffected villages, *B. cacharensis*, *B. balcooa*, *B. vulgaris*, and *B. nutans* were also associated with silt loam, except for *B. polymorpha*, found in silty clay loam. In flood-affected villages, silty clay loam dominated for all species. With increasing soil depth, the percentage of sand decreased, while silt and clay content increased, indicating higher organic carbon levels, a sign of greater soil fertility (Brady 1990). Similar findings were reported for bamboo soils in southeast Queensland, Australia (Kleinhenz et al. 2003), and in Barak Valley, Assam, where Poli soils were classified as sandy clay loam (Das and Das, 2005). Soil pH was slightly acidic across all depths and species, decreasing with depth but increasing with clump age. This trend is likely due to the distribution of organic matter within the soil profile. Similar observations were made by Nath (2008), Caiet al. (1985), and Kleinhenz and Midmore (2001). In bamboo stands in southeast Queensland, Australia, soil pH was reported to be 5.1 (Kleinhenz et al. 2003), while soils in Japan containing *Sasa kurilensis* were strongly acidic (Tripathi et al. 2005). Soil pH in bamboo soils of mountainous Japan was measured at 4.35 ± 0.53 (Takamatsu et al. 1997). Soil organic carbon (SOC) content decreased with soil depth across all species and sites, likely due to the accumulation of organic matter in the upper layers. The decomposition of litter and root inputs in surface soils enriches them with SOM and SOC. Similar trends were observed by Tripathi et al. (2005) and Xu et al. (2018), with surface SOC being highly variable and influenced by factors like litter decomposition, root exudates, and microbial activity (Mora et al. 2014, Filley et al. 2014, Leppalammi-Kujansuu et al. 2014). SOC stock is also influenced by soil texture (Lal 2005a,b), with higher clay content improving water and nutrient retention, thus enhancing SOC (Causarano et al. 2008). Studies by Franzluebbers et al. (1996) and Keller and Hakansson (2010) support the relationship between soil texture and carbon dynamics, with finer-textured soils generally having higher SOC concentrations. The SOC stock was significantly correlated with silt and clay content (Zhang et al. 2015), and SOC content increased with bamboo stand age in *Phyllostachys praecox* forests in southeast China (Li et al. 2010). Changes in land use and management practices, such as conversion to agricultural ecosystems, can deplete SOC stocks (Lal 2005a,b). The negative correlation between SOC and bulk density has been noted by Lobovikov et al. (2009), Curtis and Post (1964), while some studies also report a positive correlation (Leifeld et al. 2005, Catherine and Ouimet 2008). The study concluded that the soil quality of flood-affected villages is superior to that of riverside and flood-unaffected villages, due to the deposition of sediments during floods, which increases silt, clay, and SOC content. Soils in lowland floodplains of Barak Valley, identified as Poli soils, are less sandy, darker, and more fertile (Das and Das 2005). Improvements in physical properties in flood-affected soils may result from organic matter inputs from decaying roots and leaf litter (Krishan and Toky 1993).

CONCLUSIONS

The study reveals that soil physico-chemical characteristics in bamboo plantations vary significantly across different physiographic conditions. It also shows that soils in flood-affected villages are better quality than those in riverside and flood-unaffected areas, primarily due to sediment deposition during floods, increasing silt, clay, and SOC content. Therefore, bamboo plantations hold significant potential for soil carbon sink management in the context of climate change mitigation. However, further research is required to explore the SOC stock and sequestration potential of other bamboo species and plantations.

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Supplementary Table 1. Soil physico-chemical characteristics in different physiographic conditions at different soil depths for all species in Hailakandi district, Assam

Soil depth (cm)	BD (g/cm^3)	WHC (%)	pH	Clay (%)	Silt (%)	Sand (%)	SOC (%)	SOM (%)	SOC stock (Mg/ha)
Riverside									
0 -10	1.06 (0.06)	43.50 (2.88)	5.54 (0.22)	20.89 (2.13)	53.32 (4.04)	25.80 (4.69)	0.95 (0.13)	1.64 (0.23)	9.97 (0.98)
10 -20	1.09 (0.06)	45.33 (2.77)	5.47 (0.21)	22.63 (2.25)	53.97 (3.77)	23.40 (4.05)	0.81 (0.09)	1.40 (0.16)	8.81 (0.71)
20 - 30	1.11 (0.06)	46.95 (2.86)	5.41 (0.19)	23.77 (2.33)	54.43 (3.39)	21.80 (3.68)	0.75 (0.09)	1.29 (0.16)	8.30 (0.75)
Flood affected									
0 -10	1.03 (0.05)	49.00 (1.69)	5.34 (0.20)	28.49 (3.30)	52.45 (2.97)	19.06 (2.56)	1.21 (0.10)	2.09 (0.18)	12.51 (0.64)
10 -20	1.07 (0.06)	50.65 (2.01)	5.29 (0.18)	31.09 (3.25)	53.29 (2.89)	15.63 (1.98)	1.13 (0.10)	1.94 (0.17)	12.01 (0.79)
20 - 30	1.10 (0.06)	52.46 (2.17)	5.27 (0.18)	33.06 (3.12)	53.84 (2.80)	13.10 (1.69)	1.07 (0.10)	1.84 (0.18)	11.73 (0.93)
Flood unaffected									
0 -10	1.03 (0.06)	43.79 (2.39)	5.46 (0.33)	23.57 (4.08)	53.32 (4.61)	23.10 (3.79)	1.21 (0.14)	2.08 (0.23)	12.39 (1.47)
10 -20	1.06 (0.07)	45.26 (2.49)	5.40 (0.33)	25.34 (4.16)	54.35 (4.52)	20.30 (3.12)	0.99 (0.19)	1.71 (0.32)	10.46 (2.09)
20 - 30	1.09 (0.07)	47.25 (2.63)	5.34 (0.33)	26.83 (4.27)	54.75 (4.55)	18.42 (2.65)	0.84 (0.19)	1.46 (0.32)	9.18 (2.10)

Figures in parenthesis are SEM at 95% confidence interval