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Effect of elevation and aspect on carbon stock of bamboo stands (*Bambusa nutans* subsp. *Cupulata)* outside the forest area in Eastern Nepal

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ABSTRACT

Bamboo has emerged as a promising option for climate change mitigation due to its rapid growth, versatility, and renewability. However, in Nepal, there exists a substantial knowledge gap on carbon (C) stock and the influence of aspect and elevation on C stock of bamboo species, particularly in areas outside forests where bamboo is dominant. Therefore, this research was conducted to quantify C stock and aspect-elevation influence on the C stock of *Bambusa nutans* subsp. *cupulata* outside the forest area. For this study, three elevation zones (0–400 m, 400–800 m, 800–1200 m) and two aspects (East and West) were considered. A total of 30 square plots having a 100 m^2 area were established utilizing purposive sampling due to the scattered distribution of bamboo. Non-destructive methods were applied to measure bamboo culm diameters, while composite soil samples were systematically collected from 30 cm depth using soil augers and core samplers. Clump density (400 ha^{-1}), culm density (42,480 ha^{-1}) and culm diameter (6.82 ± 0.41 cm) were highest at middle elevations ($p < 0.05$), with no significant difference due to aspect ($p > 0.05$). The total mean C stock potential of *B. nutans* was 148.73 ± 3.43 Mg ha^{-1}. Our results indicated a significant difference in C stock among elevation zones, with middle elevation zones (161.77 ± 6.74 Mg ha^{-1}) exhibiting notably higher C stock compared to both lower (150.26 ± 2.69 Mg ha^{-1}) and higher (134.17 ± 4.26 Mg ha^{-1}) elevation zones. Furthermore, East aspect was found to have significantly ($p < 0.05$) higher soil organic C stock (18.52 ± 1.32 Mg ha^{-1}) compared to West aspect (11.4 ± 1.01 Mg ha^{-1}). Further research is needed to explore other complex environmental interactions with C stock potential for better climate change strategies. Incorporating bamboo C into Nepal's REDD+ initiative can be crucial for optimizing opportunities to earn C credits.

1. Introduction

In the contemporary era, climate change has emerged as a pressing issue that has garnered heightened attention from scientists, resource managers, and policymakers (Abbass et al., 2022). Among the contributors to global climate change, one significant cause stems from the atmospheric conversion of carbon (C) released from deforested areas into carbon dioxide (CO_2) (Condit, 2008; Pinto et al., 2010). According to international climate agreements, the capacity of forests to naturally remove C from the atmosphere is crucial for reducing climate change (IPCC, 2007). Consequently, the current focus on estimating forest C stock is of tremendous interest (Djomo et al., 2016). About 31 % of the world's total land area, is covered by forests, which store 289 gigatons of C in only their biomass (FAO, 2011). However various anthropogenic activities such as extensive forest clearing for agricultural use, overgrazing, and exploitation of the existing forest for fuel wood, fodder, and construction materials have resulted in a reduction of forest area with significant environmental degradation (Keenan et al., 2015). Therefore, it becomes urgent to call for action and another viable alternative for the fight against climate change.

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Bamboos, belonging to the subfamily *Bambusoideae* of the grass family *Poaceae*, encompasses over 1500 species distributed across 110 genera globally (Ahmad et al., 2021; Canavan et al., 2016; McClure, 1966). Renowned for their rapid growth, some bamboo species can reach towering heights of up to 30 m and diameters of 35 cm, making them among the fastest-growing plants on Earth (Moza and Koul, 2022). Encompassing 3.2 % of the world's total forest area, bamboo stands play a significant role in global ecosystems (Lobovikov et al., 2007). With a global distribution between 51ºN and 47ºS, primarily in tropical, subtropical, and equatorial regions, bamboos thrive across diverse altitudes, ranging up to 4000 m above sea level (m.a.s.l), with Asia hosting the largest number of species (Ahmad et al., 2021). Adaptable to various soil types and thriving in rainfall ranges of 750–1000 mm, bamboo, including species like *Dendrocalamus strictus Nees*, exhibit remarkable resilience (Rojas-Sandoval, 2022). The temperature range for bamboo growth spans from 8 to 36 °C, with some species such as *Fargesia rufa* T. P.Yi capable of withstanding temperatures as low as −20 °C (Koepke-Hill et al., 2020).

Bamboo has emerged as a pivotal component in ecosystems, providing essential services, particularly C sequestration (Ayer et al., 2023a; Paudyal et al., 2022). Bamboo can act as a C sink due to its rapid and dense growth, adaptability to diverse soil types and climates, and its renewable nature (Dransfield and Widjaja, 1995). C storage and sequestration rates vary globally among different bamboo species, as reported by Dwivedi et al. (2019), revealing C storage within the range of 30 to 145 t ha^{-1}, depending on the species, with C sequestration rates ranging from 1.3 to 24 t ha^{-1} $year^{-1}$. Research conducted by the International Bamboo and Rattan Organization (INBAR) underscores the potential of well-managed bamboo ecosystems to serve as efficient C sinks, potentially surpassing other vegetation types under comparable conditions (INBAR, 2014). For instance, the rapid growth of a Moso bamboo (*Phyllostachys edulis*) forest in China resulted in the sequestration of 5.10 Mg C ha^{-1} of carbon during a single year, surpassing rates observed in a tropical mountain rainforest and a 5-year-old stand of *Cunninghamia lanceolata*, a fast-growing Chinese fir (King et al., 2021; Yuen et al., 2017). Abebe et al. (2021) reported mean C stock of *Oxytenanthera abyssinica* forests ranged from 152.5 Mg C ha^{-1} to 559.8 ton CO_2 ha^{-1} in Northern Ethiopia. Similarly, Jember et al. (2023) estimated mean biomass C of the *Oldeania alpine* in different niche; riverbank (87.52 Mg C ha−1), woodland (104.97 Mg C ha−1 and homestead (111.56 Mg C ha−1) in Northwestern Ethiopia. Furthermore, Ghale et al. (2020) recorded mean C of 124.98 ton ha^{-1} outside the forest area in Annapurna Conservation Area, Nepal. These studies suggest that bamboo holds promise as a potential alternative for global climate change mitigation.

Among various environmental variables, aspect and elevation play crucial roles in shaping the C stock dynamics of any forest type, including bamboo forests (Fang et al., 2018; Yuen et al., 2017). Previous studies have highlighted the importance of aspect in influencing vegetation patterns and C stock potential within bamboo forest ecosystems (Deng et al., 2016; Fang et al., 2018; Niu et al., 2020; Qian et al., 2019). In China, Niu et al. (2020) revealed significant variations in C stocks among different aspects, with the East aspect exhibiting significantly higher C stocks than the West and North aspects. Similarly, Qian et al. (2019) conducted a study to understand the effect of slope aspect on species functional groups and species diversity in the alpine meadow of the East Qilian Mountains and reported that the East aspect had higher C stocks compared to the North and West aspects. Another study by Deng et al. (2016) was conducted to investigate the effects of different slope positions on the growth of *Phyllostachys pubescens* and soil factors in China and found that the better bamboo growth in sunny slopes as compared to the shade slopes. Fang et al. (2018) studied the impact of aspect on soil organic carbon (SOC) content within bamboo ecosystems and reported that the northern aspect contained a statistically insignificant increase in SOC compared to the southern aspect. Similarly, elevation also plays a pivotal role in shaping the environmental characteristics of a location, leading to significant alterations in key factors such as temperature, precipitation, atmospheric pressure, solar radiation, and wind velocity (Djukic et al., 2010; Navarro-Serrano et al., 2020; Takeuchi et al., 2011;) ultimately affecting plant growth. Fang et al. (2018), Njeru et al. (2017) and Dai and Huang (2006) reported a positive and linear correlation between SOC stocks and elevation. Griffiths et al. (2009) noted that as elevation increases (typically from low to high altitudes, e.g., 0–200 m to 400–800 m), various soil properties change. Recent research by Li et al. (2013) also reinforces the relationship between elevation and SOC content in Moso bamboo forests. However limited studies have reported variation in bamboo C stock across elevation and aspect outside forest area (Ghale et al., 2020). Ghale et al. (2020) found higher C stock in 1000–1200 m (137.32 ton ha^{-1}) elevation range than 1200–1400 m (123.796 ton ha^{-1}) and 1400–1600 m (113.824 ton ha^{-1}) outside forest area in Annapurna Conservation Area, Nepal.

In Nepal, 12 genera and >53 species of bamboo have been reported (Das, 2002; Ghimire, 2008). Bamboos can be found in all ecological zones of Nepal: the Terai, Hill, and Mountains (Karki and Karki, 1996). While they are widespread throughout the country, they are particularly abundant in Eastern Nepal (Karki and Karki, 1996). *Dendrocalamus strictus, Bambusa nutans, Bambusa balcooa, Bambusa tulda, Dendrocalamus giganteus, Dendrocalamus hamiltonii,* and *Dendrocalamus hookerii* are the main bamboo species found in Nepal (Karki and Karki, 1996; MoFSC, 2004). Although such diversity and availability of bamboo species in Nepal, there has been limited research on bamboo in Nepal (Ayer et al., 2023a). Significant studies have been carried out to estimate biomass and C stock potential of different tree species in different land use types in Nepal (Aryal et al., 2018; Ayer et al., 2023b; Baral et al., 2009; Gautam et al., 2023; Joshi et al., 2023; Maharjan et al., 2024; Pandey and Bhusal, 2016). However, there are few studies carried out to estimate the biomass (Oli and Kandel, 2005, 2006; Oli, 2005,) and C stock (GC and Bhandari, 2010; Ghale et al., 2020) of different bamboo species in Nepal. Additionally, uncertainties persist regarding the precise extent of bamboo's C stock potential outside the forest area, particularly about influential factors such as elevation and aspect. Similarly, REDD+ scheme of Nepal which sells C credit from community forests also excludes bamboo forests regarding data unavailability of C stock by bamboo species in Nepal. To address these gaps, this study aims to quantify the C stock and assess the impact of elevation and aspect on the C stock potential of *Bambusa nutans* subsp. *cupulata* outside forest areas in Eastern, Nepal. Specifically, this research seeks to answer the following questions: i) What is the C storage potential of studied bamboo species?, ii) How does the C stock vary at different elevation ranges outside forest areas?, and iii) How does the aspect influence the C stock of the studied bamboo species? We hypothesize that elevation and aspect have a significant effect on C storage potential of studied bamboo species outside forest area. This research is not only scientifically relevant but also has practical applications, such as informing sustainable land management practices and contributing to climate change mitigation efforts. Furthermore, it addresses a notable knowledge gap of C stock potential to incorporate bamboo in prospective C trade for Nepal.

2. Methodology

2.1. Study area

This study was carried out along the altitudinal gradient of Katari municipality (26.8372° N latitude and 86.3213° E longitude) of Udayapur, Eastern Nepal (Fig. 1). Both the Mahabharat and Shiwalik hills encircle the Udayapur district from the north and the south, and the two hills converge in the West to create the Udayapur valley (Lamichhane and Karna, 2009). The elevation of the district is moderately steep ranging from lower tropical (below 300 m.a.s.l) to subtropical tropical (ranging from 300 to 2000 m.a.s.l). The site has a tropical and subtropical climate with an annual minimum temperature of 16.8

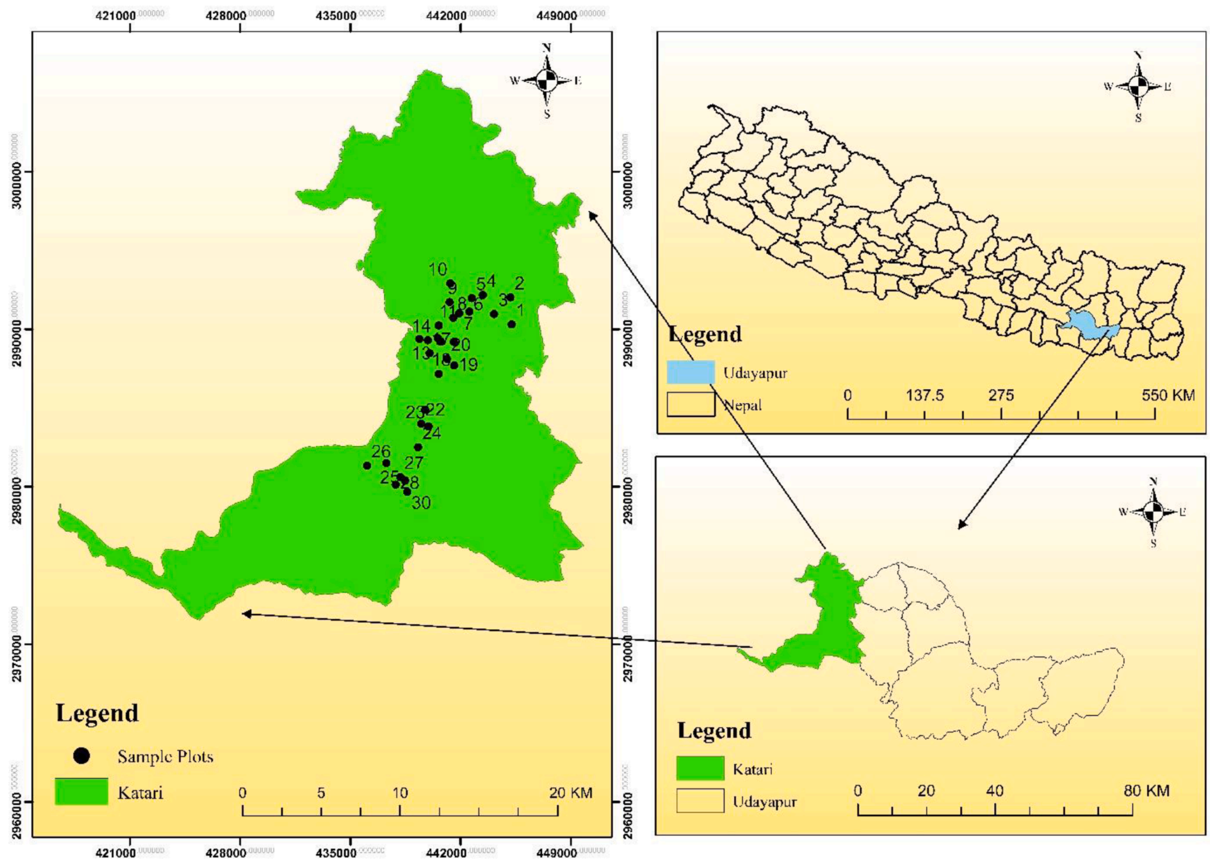

Fig. 1. Map showing Study area i.e. Katari Municipality of Udayapur district.

°C, and annual maximum temperature of 28.1 °C, and an annual rainfall is about 1349.2 mm (DoHM, 2017). The study area consists of four forest types: Hill Sal Forest, Chir Pine Forest, Chir Pine-Broadleaved Forest, and Lower Temperate Oak Forest. Major species include *Shorea robusta, Terminalia chebula, Adina cordifolia, Acacia catechu, Terminalia bellerica, Bombax ceiba, Dalbergia sissoo, Schima wallichii, Castanopsis indica, Pinus roxburghi, Alnus nepalensis, Rhododendron arboreum, Lyonia ovalifolia, Myrica esculenta, etc.* (Lamichhane and Karna, 2009; Ayer et al., 2023c; Khamcha et al., 2023).

Farmers in Nepal generally lack awareness regarding the potential of bamboo plantations to support shade-loving agricultural crops (Ayer et al., 2023a). Consequently, bamboo stands are often found in marginal, degraded fields, and slopes. Moreover, there exists a common belief among farmers that bamboo requires minimal care and management practices (Ghimire, 2008). Bamboo culms are typically harvested when they reach maximum size and strength, typically between 3 and 5 years of age (Ayer et al., 2023a). Hence, the study plots in our research were characterized by spontaneously grown bamboo clumps with scattered distribution, situated in marginal, degraded, and sloped fields without association with other plant species.

2.2. Sampling design

In the preliminary survey phase of the research, we conducted a comprehensive reconnaissance survey to identify suitable areas where bamboo species, specifically *B. nutans*, could be found within the study area. To enhance the understanding of potential bamboo habitats, we engaged in key informant surveys with various stakeholders, including community forest user committees, local political leaders, and officials from the Division Forest Office Udayapur (Triveni), Nepal. These interactions were instrumental in pinpointing areas with a high likelihood of bamboo presence, ensuring the effectiveness of the subsequent data collection efforts.

Regarding the sampling design, we employed a purposive sampling approach, given the relatively scattered distribution of bamboo species. The research design was structured to encompass three distinct geographic altitudinal zones, specifically ranging from 0 to 400 m.a.s.l (lower elevation), 400 to 800 m.a.s.l (middle elevation), and 800 to 1200 m.a.s.l (higher elevation). Additionally, we considered two predominant aspects; East and West to comprehensively assess the influence of aspect on C stock potential. Altogether, the sampling framework consisted of a total of 30 sampling plots (Fig. 2). Within the three elevation ranges, 10 plots were systematically chosen for data collection in each range. Simultaneously, for each aspect, 15 plots were designated for data collection. This meticulous selection process allowed us to capture the variability in C stock potential across different elevation zones and aspect orientations (Fig. 2).

2.3. Primary data collection

2.3.1. Biophysical measurement

For bamboo measurement, circular plots, each measuring 100 m^2 with a radius of 5.64 m, were established to conduct the inventory (Huy and Long, 2019). Circular plots are more efficient since the real circumference of the plot is smaller than that of square or rectangular plots, limiting the amount of bamboo culms on the edge (Huy and Long, 2019). Culms in each plot were categorized according to their ages, and then counted. Since it is not possible to measure each culm in a plot, a total of 18 culms per plot (6 culms per age group) were randomly selected following the method by Abebe et al. (2021) and Jember et al. (2023). Culm diameter was measured at 1.3 m height using diameter tape. The culm age was determined based on the exterior color of the culm, features of the culm sheath, and the development of branches and leaves (Abebe et al., 2021; Singnar et al., 2017).

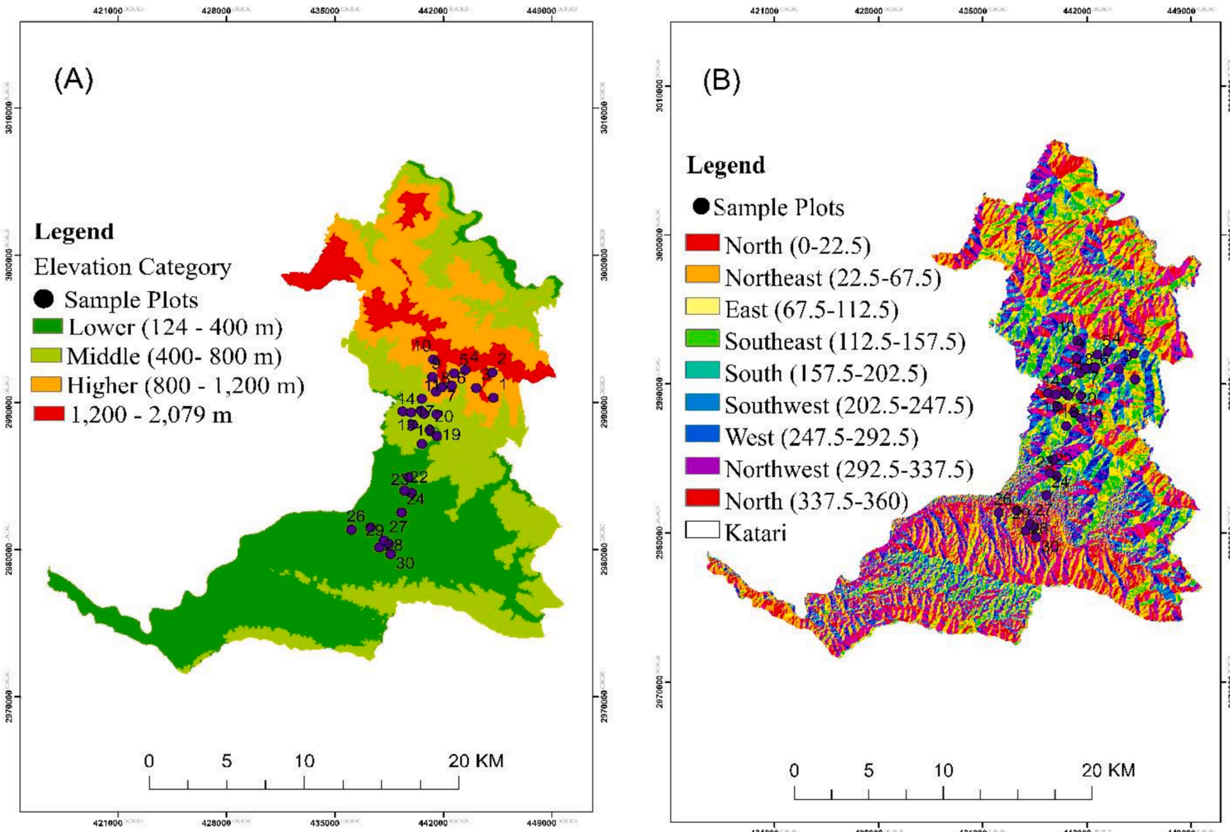

Fig. 2. A) Elevation map of study area B) Aspect map of study area. These maps are prepared on ArcGis 10.8 by using Digital Elevation Model from US Geological Service webpage (https://earthexplorer.usgs.gov/).

2.3.2. Soil sample collection

We collected soil samples from 0 to 30 cm depth across the entire set of sampling plots. Soil samples from this depth are adequate as most of the SOC is concentrated at 0–30 cm (IPCC, 2003). It is also difficult to collect samples from more than a 30-cm depth due to shallow soils and the occurrence of rocks in the subsurface (Subedi et al., 2010). Soil samples from four subplots within each main plot were combined from these subplots to create composite samples. These composite samples were stored in labeled zip lock bag and transported to the laboratory promptly after collection to maintain sample integrity and freshness. Hence, 60 soil samples for determining SOC (%) and 60 samples for bulk density were collected at the study site. This comprehensive soil sampling strategy, involving replicates from each elevation level and aspect orientation, yielded a total of 120 soil samples (60 for SOC% and 60 for bulk density).

2.4. Data analysis

2.4.1. Calculation of above and belowground biomass and C stock

The aboveground bamboo biomass was calculated using the following allometric equation which takes into account the diameter at breast height (DBH) (Yuen et al., 2017)

$$AGB = 0.269 \times DBH^{2.017} \quad (1)$$

Where, AGB = aboveground bamboo biomass (Kg), DBH= diameter at breast height.

Similarly, 25% of AGB was used to estimate the BGB (Yuen et al., 2017).

The BGB will be then computed as follows:

$$BGB = AGB \times 0.25 \quad (2)$$

Finally, bamboo biomass C storage (Mg ha^{-1}) was calculated from bamboo biomass (AGB and BGB), as follows (IPCC, 2006)

$$Bamboo\ biomass\ C = C\ fraction\ (0.47) \times (AGB + BGB) \quad (3)$$

2.4.2. Calculation of SOC stock

We determined percentage of soil organic matter using Walkley and Black method (Walkley and Black, 1934) and SOC (%) was estimated using a ration of 58% of soil organic matter. Undisturbed soil core samples were collected from 0 to 30 cm depth using a core sampler having 22.9 cm circumference. Soil cores were oven-dried at 105°C for 24 h. The amount of organic C stored in soil (Mg ha^{-1}) was derived by using the following formula (Pearson et al., 2007)

$$SOC\ stock\ (Mg\ ha^{-1}) = BD \times d \times (\%\ SOC) \times 10000 \quad (4)$$

Where, SOC, BD, d,% SOC represents soil organic carbon stock per unit area (Mg ha^{-1}), soil bulk density (g cm^{-3}), depth of the sampled soil layer (cm), soil organic carbon concentration (%) respectively. Bulk density (BD) was calculated from the following formula (Pearson et al., 2007)

$$BD = MS/VC \quad (5)$$

Where BD, MS, VC represent Bulk density (g cm^{-3}), Mass of the dried soil (g), and volume of core sampler (cm^3) respectively.

2.4.3. Statistical analysis

Before conducting statistical analysis, we ensured that our data met the assumptions for parametric tests by performing Shapiro's test for normality and Bartlett's test for equal variance. Both tests yielded non-significant p-values ($p > 0.05$), indicating satisfactory conditions for normality and equal variance. Our investigation into the impact of elevation and aspect (independent variables) on carbon stock (dependent variable) followed a multifaceted approach. Initially, one-way

ANOVA tests were executed for each carbon pool to assess the influence of elevation on individual carbon pools. Recognizing potential interaction effects between elevation and aspect, we conducted a two-way ANOVA to explore interaction effects and determine if their joint influence on carbon stock was significant. Additionally, *t*-tests were employed to compare mean carbon pool values between East and West aspects. Microsoft Excel 2016 was used for descriptive analysis, and R software (version 4.2.3) was utilized for statistical analyses.

3. Results

3.1. Stand characteristics

Table 1 represents the stand characteristics of bamboos outside the forest area across elevation and aspect categories. Higher clump and culm density was observed in middle elevation and East aspect. However, the difference in culm density across elevation category was only statistically significant ($p < 0.01$). In terms of culm age composition, 1–2-year-old bamboo culms were the most common across all elevation and aspect categories followed by 5–6 and 3–4 year-old culms. Elevation wise, thicker bamboo culms were observed in middle elevation (6.82 ± 0.41 cm) followed by lower elevation (6.79 ± 0.25 cm) and higher elevation (6.21 ± 0.34 cm) . Aspect wise, bamboo culm on East-facing slopes (6.59 ± 0.26 cm) had a higher thickness than West-facing slopes (6.62 ± 0.31 cm). However, there was no significant difference in DBH among aspect category ($p > 0.05$).

3.2. Carbon stock potential

Aboveground C pool had the highest mean C stock (106.17 ± 2.71 Mg ha^{-1}), followed by the belowground C pool (27.60 ± 0.70 Mg ha^{-1}) and the SOC pool (14.96 ± 1.05 Mg ha^{-1}) (Fig. 3). Total C stock that represents sum of all C pools showed a range from 114.32 Mg ha^{-1} to 184.68 Mg ha^{-1} having mean value of 148.73 ± 3.43 Mg ha^{-1} (Fig. 3).

3.3. Influence of elevation on carbon stock

Fig. 4 shows pool wise C distribution across elevation categories. Aboveground C stock was found higher at middle elevation (114.10 ± 5.75 Mg ha^{-1}) followed by lower elevation (110.59 ± 2.37 Mg ha^{-1}) and higher elevation (93.82 ± 2.50 Mg ha^{-1}). Belowground C stock exhibited greater carbon stock at middle elevation (29.67 ± 1.50 Mg ha^{-1}) followed by lower elevation (28.75 ± 0.62 Mg ha^{-1}) and higher elevation (24.39 ± 0.65 Mg ha^{-1}). Similarly, SOC stock was higher at Middle elevation (18.01 ± 1.75 Mg ha^{-1}) compared to both higher elevation (15.96 ± 1.62 Mg ha^{-1}) and lower elevation (10.92 ± 1.41 Mg ha^{-1}).

Overall, TC demonstrated a similar pattern with middle elevation (161.77 ± 6.74 Mg ha^{-1}) having highest C stock than lower elevation (150.26 ± 2.69 Mg ha^{-1}) and higher elevation (134.17 ± 4.26 Mg ha^{-1}) with significant differences ($p < 0.05$) in C stock among elevation categories in each C pools. Post hoc analysis further revealed significant differences in aboveground, belowground and total C stock between lower-middle, middle-higher and lower-higher pairs.

Table 1
Stand structure of bamboo stands of the study area.

Category	Clump (ha^{-1})	Culm (ha^{-1})				DBH (cm)
		1–2 Yrs	3–4 Yrs	5–6 Yrs	Total	
Elevation						
Lower	367^{a}	19,389	1133	9044	29567^{a}	6.79 ± 0.25^{a}
Middle	400^{a}	28,520	2200	11,760	42480^{a}	6.82 ± 0.41^{a}
Higher	300^{a}	2440	1180	1120	4740^{b}	6.21 ± 0.34^{b}
Aspect						
East	374^{a}	18,507	1440	6500	26447^{a}	6.59 ± 0.26^{a}
West	335^{a}	14,750	1600	8050	24400^{a}	6.62 ± 0.31^{a}

Different letters represent significant differences and similar letters represent no significant difference at 0.05 significance level.

3.4. Influence of aspect on carbon stock

Fig. 5 shows pool wise C distribution across East and West categories. Aboveground C stock was found higher in West aspect (107.13 ± 4.23 Mg ha^{-1}) than East aspect (105.20 ± 3.52 Mg ha^{-1}). Similarly, belowground C stock was higher in the West aspect (27.85 ± 1.10 Mg ha^{-1}) than East aspect (27.35 ± 0.92 Mg ha^{-1}). However, these differences in aboveground C and belowground C were not statistically significant ($p > 0.05$). In contrast, SOC stock showed significant difference ($p < 0.05$) with its higher value in East aspect (18.52 ± 1.32 Mg ha^{-1}) than West aspect (11.4 ± 1.01 Mg ha^{-1}). However, total C stock levels showed no significant differences ($p > 0.05$), between East aspect (151.08 ± 4.37 Mg ha^{-1}), and West aspect (146.38 ± 5.37 Mg ha^{-1}).

3.5. Interaction effect of elevation and aspect on c stock

Aboveground C, belowground C, and total C stock were notably higher at middle elevation with West aspect (Fig. 6). In contrast, SOC stock was notably higher at middle elevation with East aspect. However, these interactions had no statistically significant effect on C stock across any pool ($p > 0.05$) (Table 2).

4. Discussion

4.1. Stand characteristics

Our study observed higher bamboo clump and culm density in the middle elevation category (Table 1). This could be attributed to different harvesting intensity of bamboo culms in different elevation categories (Abebe et al., 2021). Lower elevations experience intense human pressure due to higher population density and extensive agricultural activities (Mammides, 2020). Strict management policies in these regions often limit the felling of multipurpose trees such as *Shorea robusta* (Basnyat, 2021), leading communities to rely heavily on bamboo for their needs. Although less populated, higher elevations face localized intensive exploitation of bamboo due to fewer alternative timber resources and difficult topography. In contrast, the lower dependence on bamboo in middle elevations, combined with access to a variety of forest products, supports a more balanced and sustainable use of resources. This could also affect mean size (diameter) of culm which we observed higher in the middle elevation in the study area (Table 1). Our study observed higher culm density of the young and overmatured age group than 3–4 years age group (Table 1). This finding contrasts with Abebe et al. (2021) and Jember et al. (2023) in Ethiopia where they reported higher proportion of bamboo culm in 3–4 years age group. This could be due to selective harvesting of mature and thicker culms with no sustainable management practices in the study area. This is common in Nepal as farmers believe that bamboo requires minimal care and management practices (Ayer et al., 2023a). This selective harvesting and over harvesting of mature bamboo culms could hinder the structural integrity and reproductive capacity of the bamboo stand (Franklin, 2006; Nath et al., 2012). The removal of these mature culms disrupts the natural age distribution, resulting in a stand dominated by younger and overmatured, less robust culms which was also observed in our study (Table 1). With respect to aspect, we found no significant difference in mean DBH, clump and culm density which could be due to lack of bamboo management practices in the study area. When bamboo stands across different aspects are managed similarly or are totally unmanaged, this can reduce potential differences in studied parameters that could

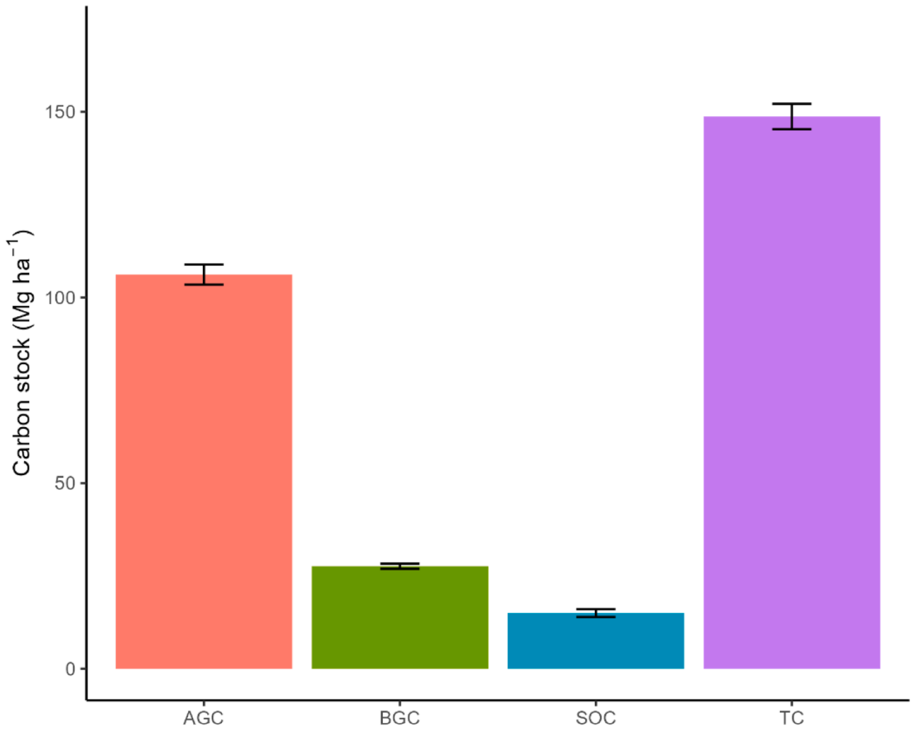

Fig. 3. Bar plot showing C stock across various C pools (Mean ± St. Error). AGC, BGC, SOC and TC stands for Aboveground C, Belowground C, Soil Organic C, Total C respectively.

arise from aspect-related environmental factors.

4.2. Carbon stock potential of B. nutans

The aboveground C content was 106.17 Mg ha^{-1} (Fig. 3) which is higher than prior estimates for the same species reported by Kumar et al. (2022) (59.69 Mg ha^{-1}) and (Kaushal et al. (2016) (98.32 Mg ha^{-1}) in managed bamboo plantation in India. Similarly, Lou et al. (2010) reported lower aboveground C stock (25 to 32 t ha^{-1}) from 10-year-old Moso bamboo (*P. pubescens*) plantation in China. Another Study conducted in a four-year-old mixed village bamboo plantation (*B. vulgaris, B. balcooa, B. cacharensis*) in India shows that the aboveground C stock was about 61.05 t ha^{-1} (Nath et al., 2009). These discrepancies might be attributed to variations in local climatic environment, stand age, species type, and management regimes (Rinnan et al. 2011; Yuen et al., 2017).

SOC stock was found to be 14.96 Mg ha^{-1} which falls below the range (70–200 Mg C ha^{-1}) based on a meta-study of 184 bamboo C studies (Yuen et al., 2017). SOC values are also lower than those reported by both Tariyal (2014) (57.28 Mg ha^{-1}) and Sharma et al. (2020) (51.15 Mg ha^{-1}) in India. Higher SOC stock (36.68 Mg ha^{-1}) was observed in Moso bamboo forests in China (Fang et al., 2018). Additionally, higher content of SOC i.e. 70 Mg ha^{-1} in *Oxytenathera abyssinica* bamboo species in Ethiopia (Abebe et al., 2021). Similarly, the average C density of managed and abandoned bamboo stands were 84.9 Mg C ha^{-1} and 115.1 Mg C ha^{-1} for *Phyllostachys pubescens* and 24.1 Mg C ha−1 and 46.4 Mg C ha^{-1} for *Phyllostachys bambusoides*, respectively in Japan (Yamamoto and Inoue, 2023). Lower SOC stock in this study (Fig. 3) might be due to variations in climatic conditions, such as temperature and precipitation, which can influence rates of organic matter decomposition and C storage in soils (Huy et al., 2019). Moreover, lower SOC stock may be attributed to the fact that our study area lies outside the forest area. Prior studies also reported lower SOC stock in bamboo stands outside forests than those of both evergreen broad-leaved forests and bamboo mixed forests (Li et al., 2018; Song et al., 2020; Zhao et al., 2017).

The estimated total C stock was found to be 148.73 Mg ha^{-1} (Fig. 3) which is higher than tropical mountain rain forest because of fast growing nature of bamboo (Zhou and Jiang, 2004). This figure falls within the range of values i.e., 94–392 Mg C ha^{-1} for C stored in bamboo plant biomass and soil within bamboo ecosystems worldwide (Yuen et al., 2017). Interestingly, the observed value in this study exceeds the C stock value reported from some timber-based forests in Nepal (Aryal et al. 2013; Ayer et al., 2023b; Gurung et al., 2022; Shrestha and Devkota, 2013; Thapa-Magar and Shrestha, 2015; Sharma et al., 2020). For instance, Sharma et al. (2020) reported C stock value of 102.1 Mg ha^{-1} in Chir Pine (*Pinus roxburghii* Sarg.) plantation forest of Kathmandu Valley, central Nepal. Shrestha and Devkota (2013) found 70.70 Mg C ha^{-1} in the Pakhapani Pine forest in Salyan District, Nepal. Similarly, mean C stock of 120 Mg C ha^{-1} was reported in the community-managed Hill *Shorea robusta* forests of Central Nepal (Thapa-Magar and Shrestha, 2015). This could be due to bamboo's rapid growth, dense stems, and high C sequestration potential (Ayer et al., 2023a; Jember et al., 2023). Furthermore, differences in meteorological and terrain conditions can also significantly impacts the growth of bamboo and ultimately aboveground C (Fan et al., 2013; Ji et al., 2013). Additionally, bamboo species vary in their growth and decomposition rates, which can impact the accumulation of C in both aboveground biomass and soil (Zhang et al., 2011). On the other hand, local management practices, such as harvesting and land use, can also significantly affect C dynamics within bamboo ecosystems (Gaikwad et al., 2019). Therefore, bamboo can play a crucial role in climate change mitigation because of its significant C storage potential (Yiping et al., 2010).

4.3. Influence of elevation on carbon stock

Elevation is an important factor influencing environmental conditions such as temperature, precipitation patterns, and soil characteristics, all of which can significantly impact bamboo growth and distribution (Ayer et al., 2023a; Fang et al., 2018; Ghale et al., 2020; Huang et al., 2014). For instance, the abundance and distribution of bamboo species is strongly tied to the amount and distribution of rainfall which generally increases with increasing elevation (Ayer et al., 2023a;

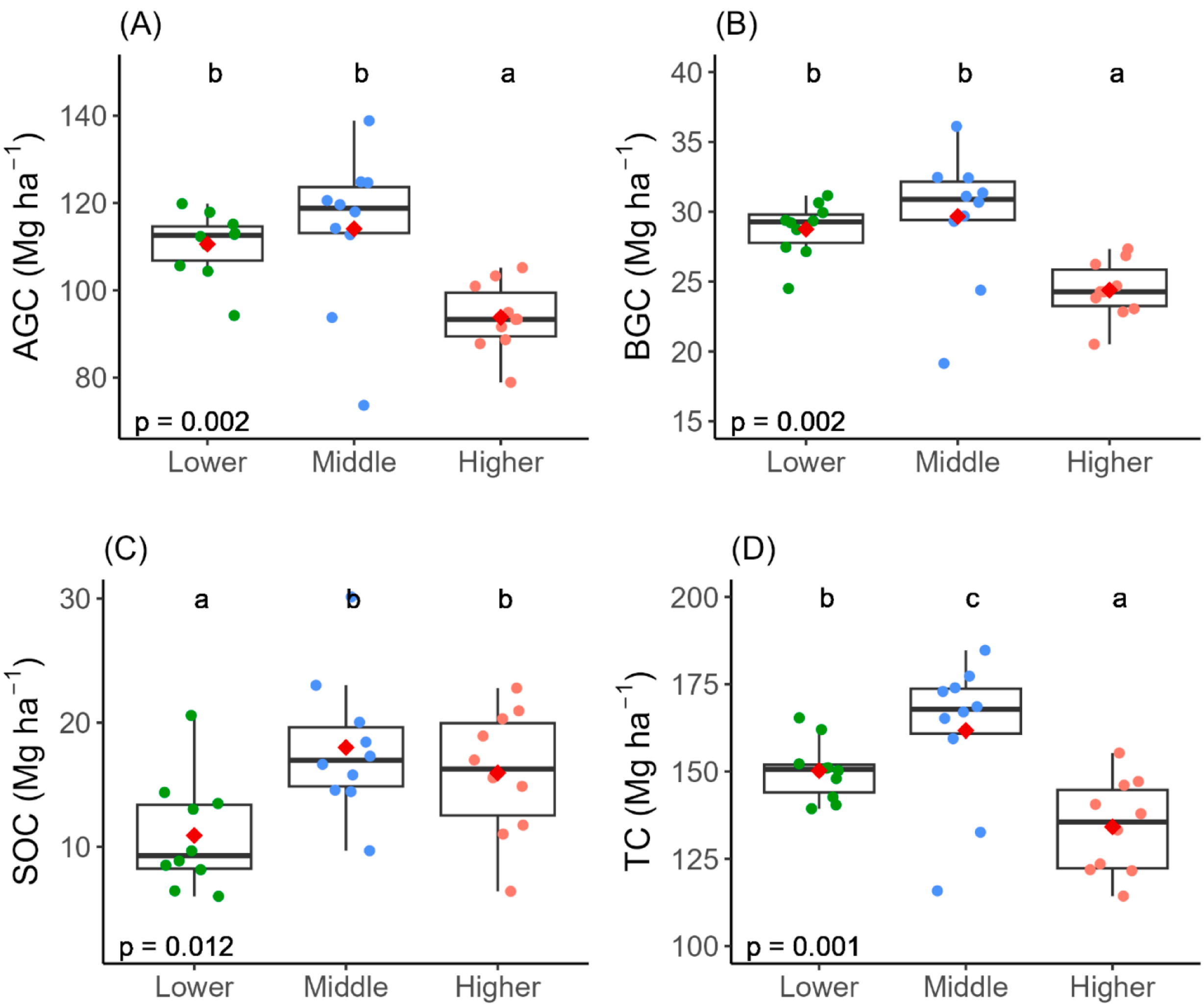

Fig. 4. Distribution of C stock across elevation categories. Different lowercase letters indicate significant differences ($p < 0.05$) between elevation categories and red dot represents mean value. AGC, BGC, SOC and TC stands for Aboveground C, Belowground C, Soil Organic C, Total C respectively.

Hu et al., 2021). The locations receiving well-distributed and higher rainfall support a greater diversity and growth of bamboo species (Bajracharya, 2008). Similarly, cooler temperatures at higher elevation can slow down decomposition processes, leading to the accumulation of biomass over time (Huang et al., 2014). This slower decomposition rate at higher elevations may result in a build-up of organic matter, contributing to increased SOC stock. Several studies have reported a decrease in aboveground C (Fan et al., 2013; Ghale et al., 2020; Masisi et al., 2022) and increase in SOC stock with increasing elevation (Chang et al., 2016; Ghale et al., 2020; Huang et al., 2014) which was explained by lower temperature and higher precipitation in higher elevation. However, our study observed higher C stocks across all C pools in bamboo stands at middle elevations (Fig. 4) which contrast with established findings from previous studies from outside forest areas in Nepal (Ghale et al., 2020) and bamboo forest in China (Fang et al. 2013; Fang et al., 2018; Tang et al., 2017) and Africa (Masisi et al., 2022). This difference could be explained by difference in location of our study plots which is outside the forest area. Although lower temperatures and higher precipitation in higher elevations generally favor aboveground biomass growth, areas outside of forests at increasing elevations present challenging conditions for bamboo due to rocky and shallow soils with poor nutrient availability (McIntire et al., 2016). Forest soils are often rich in organic matter from decaying leaves and other plant material (Osman and Osman, 2013). However, outside forest areas, especially at higher elevations, soils may lack this organic input, further reducing nutrient availability (Saeed et al., 2019). In addition, increasing precipitation may lead to soil erosion and nutrient leaching due to the absence of canopy cover outside the forest area, especially where bamboo clumps are distributed scatteredly (McDonald et al., 2002). In this context, middle elevations outside the forest might represent a transitional zone in terms of environmental conditions. They may offer a more moderate and stable microclimate compared to higher elevations, where conditions can be cooler and more extreme, and lower elevations, which may experience higher temperatures and more arid conditions (Pan et al., 2023). These moderate conditions at middle elevations could provide an optimal environment for bamboo biomass growth and SOC accumulation. Another possible reason could be difference in species in previous studies such as Ghale et al. (2020) (*Bambusa Nepalensis, Himalayacalamus Fimbriatus, Melocanna baccifera*), Masisi et al. (2022) (*Oxytenanthera abyssinica, Bambusa vulgaris*) and Fan et al. (2013) (*Phyllostachys edulis*), Tang et al. (2017) (*P. edulis*), Fan et al. (2018) (*P. edulis*). Masisi et al. (2022) in Africa found aboveground C variation across elevation gradients as species-dependent, with *O. abyssinica* storing higher amounts of aboveground C compared to *B. vulgaris*, even though both were lowland bamboo species. While research on the relationship between bamboo biomass C stock and elevation is limited, Masisi et al. (2022) suggested that variation often correlates with individual species' adaptability to the environment of locality. Therefore, our study highlights the significance of mid-level elevations as pivotal areas for C stock for bamboo. Considering the role of elevation in

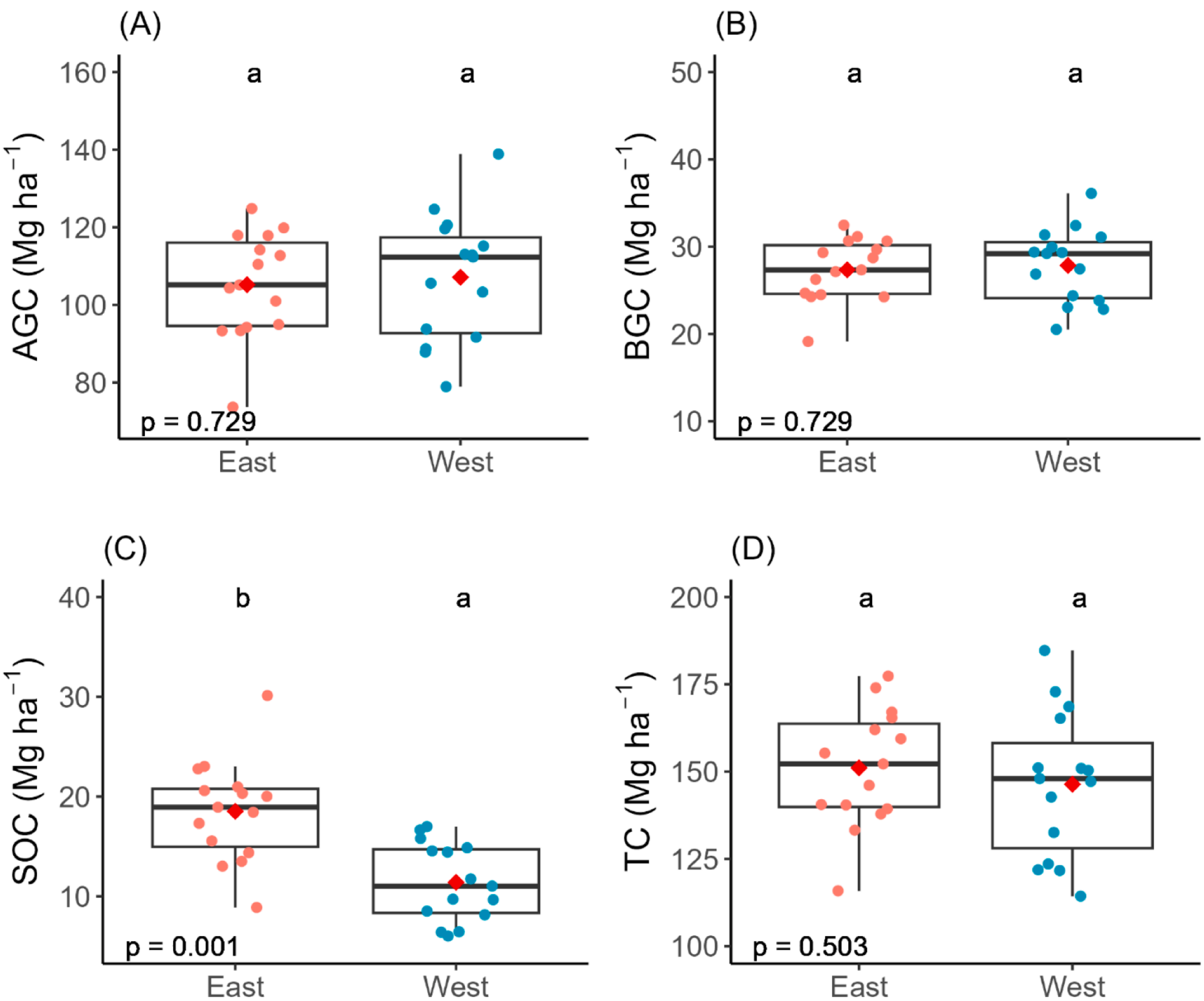

Fig. 5. Distribution of C stock across aspect categories. Different lowercase letters indicate significant differences ($p < 0.05$) between aspect categories and red dot represent mean values. AGC, BGC, SOC and TC stands for Aboveground C, Belowground C, Soil Organic C, Total C respectively.

bamboo's biomass production and C stock outside forest area, middle-elevation regions hold significant potential for bamboo plantations, particularly on marginal lands outside forests.

4.4. Influence of aspect on carbon stock

Our study reported slightly higher aboveground and belowground C stock in West aspect than East aspect (Fig. 5) which contradicts with Niu et al. (2020). Niu et al. (2020) reported higher aboveground C stock in East aspect than West aspect in Moso bamboo plantation forest in China which was explained by higher incidence of solar radiation compared to the other aspects. Another study by Deng et al. (2016) in China also revealed better bamboo growth in sunny slopes compared to the shady slopes. This difference could be due to difference in studied species as well as environmental conditions between inside and outside the forest area. *B. nutans*, the species studied in our research, may have different physiological responses to sunlight and temperature variations compared to Moso bamboo as different species have different growth characteristics, environmental requirements, and responses to external factors that can impact carbon sequestration (Sharma et al., 2024). Additionally, outside forest area, *B. nutans* stands may benefit from reduced competition and increased sunlight exposure due to minimal canopy cover from surrounding trees. This can positively affect their growth rates and carbon sequestration capacity since the spatial arrangement of vegetation including vegetation density and spacing in a forest or non-forest area—strongly influences resource allocation and ultimately, their biomass growth (Forrester, 2019). However, no significant difference in aboveground and belowground C stocks was found between East and West aspects, which may be due to the lack of intensive bamboo management practices in study area. The absence of management interventions such as irrigation, fertilization, selective thinning, etc. could have minimized the potential effects of aspect-caused microclimatic variations, such as differences in soil moisture, air and soil temperature, and precipitation, on C stocks (Lv et al., 2020). For example, farmers harvest bamboo shoots and bamboo culms once they mature but do not employ any additional silvicultural management techniques (Ayer et al., 2023a), because farmers in Nepal believe that bamboo requires minimal care and management practices (Ghimire, 2008). This general lack of intensive bamboo management might have dampened the expected differences in carbon sequestration between East and West. On the other hand, our study revealed that SOC was significantly higher (Fig. 5) in East than West aspect which is consistent with Niu et al. (2020). This might be because the East aspect is called the half-sunny slope which receives a higher incidence of solar radiation leading to higher rates of plant decomposition, and soil organic matter accumulation compared to the West aspect (Qian et al., 2019). Prior studies also suggest that aspects with lower solar radiation exhibit lower C and nutrient dynamics in soil (Kato et al., 2006; Zhang et al., 2011; Bangroo et al., 2017). Furthermore, due to the scattered clumped distribution of *B. nutans* outside the forest, we can find reduced canopy cover which increases probability of receiving higher solar radiation, resulting in higher SOC stock accumulation.

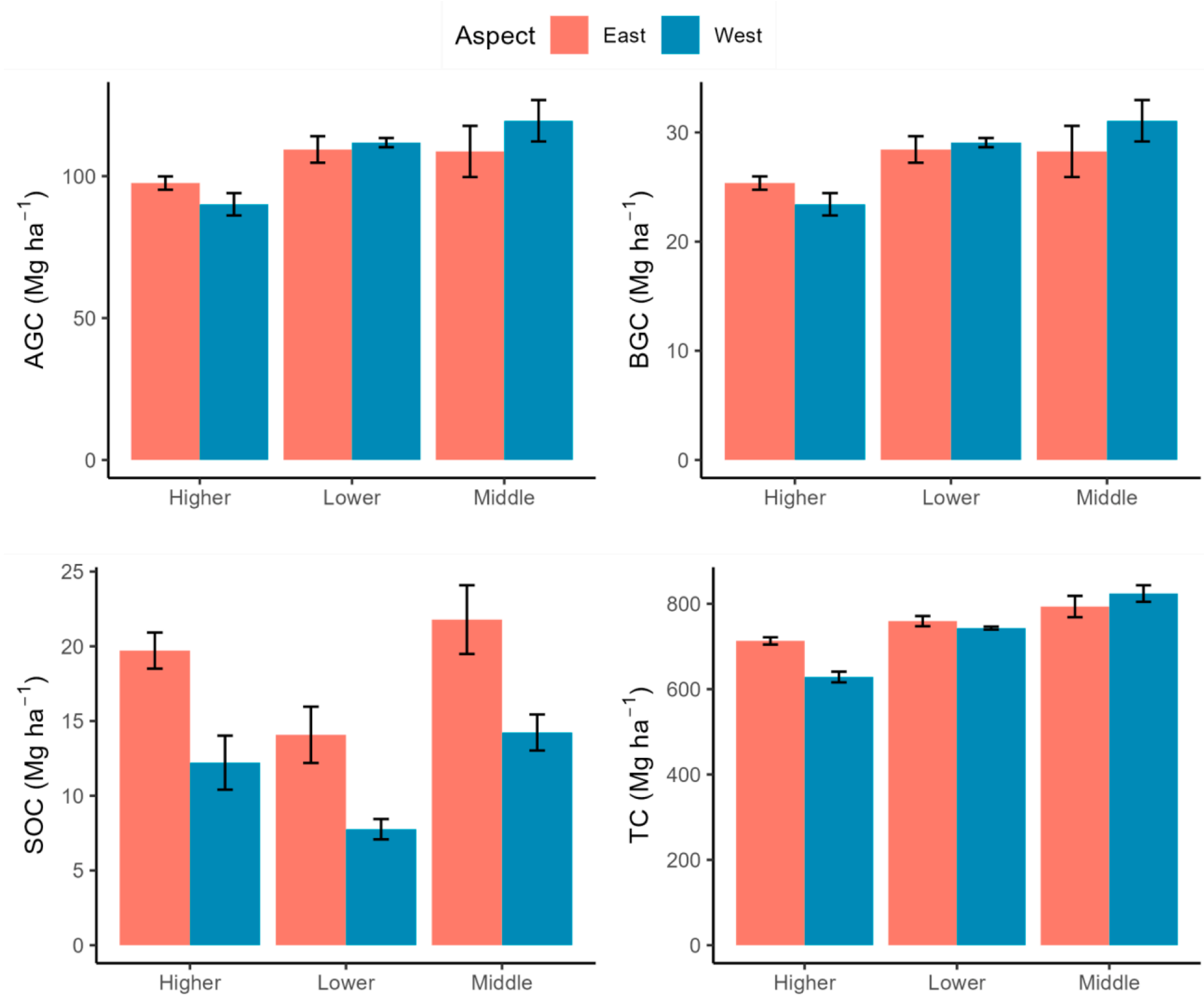

Fig. 6. Interaction influence of elevation and aspect on C stock distribution.

4.5. Interaction effect of elevation and aspect on carbon stock

The influence of elevation on C storage remains relatively consistent across different aspects (East and West) (Fig. 6 and Table 2) suggesting that elevation-related patterns are robust and not highly dependent on aspect. This consistency indicates that elevation serves as a dominant driver of C dynamics within these bamboo ecosystems (Fang et al., 2018). While aspect significantly impacts SOC, it does not exhibit a similar influence on aboveground C, belowground C, and total C (Fig. 6 and Table 2). This highlights the specific role of aspect in shaping SOC stock. It implies that factors related to slope orientation, such as solar radiation exposure, may have a more pronounced effect on SOC accumulation and decomposition processes (Zhang et al., 2011). However, this study revealed that interaction between elevation and aspect does not have a significant interaction effect on any of the C pools (Fig. 6). For land managers and conservationists, considering the impact of elevation and aspect when modeling the SOC stock is valuable (Fang et al., 2018). These findings further encourage research to explore the mechanisms driving elevation-related patterns in C dynamics and the unique role of aspect in influencing SOC stock. Understanding these factors in more detail can enhance our ability to manage and conserve bamboo-dominated ecosystems effectively (Yuen et al., 2017).

5. Conclusion

This study affirms the potential of bamboo stands (*B. nutans*) outside the forest in C storage (148.73 Mg ha^{-1}), emphasizing their significance in climate change mitigation. Additionally, they demonstrated noteworthy C storage in aboveground biomass (106.17 Mg ha^{-1}), belowground biomass (27.60 Mg ha^{-1}), and soil (14.96 Mg ha^{-1}) respectively. Middle elevations outside forest area demonstrated significantly higher C stocks (161.77 Mg ha^{-1}) than other elevation ranges due to moderate and stable microclimates. Additionally, areas with an East slope (18.52 Mg ha^{-1}) exhibit notably higher SOC compared to the West aspect (11.4 Mg ha^{-1}). By recognizing the significance of elevation and aspect outside forest area in carbon dynamics, policymakers and land managers can make more informed decisions to enhance C sequestration and contribute to broader climate change mitigation efforts. In-depth explorations into the complex interplay of elevation, aspect, and other environmental factors outside forest area, including leaf litter C, are necessary to better understand the nuanced relationships affecting C dynamics in bamboo ecosystems. Given the focus on *B. nutans* in this study, future research should explore the carbon capacity of other bamboo species outside forest area as well. This study also call for incorporating bamboo C into Nepal's REDD+ initiative which can be crucial for optimizing opportunities to earn C credits. (Eq. (1)-(5)).

CRediT authorship contribution statement

Santosh Ayer: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Sachin Timilsina:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation.

Table 2
Two-way ANOVA on the combined effect of elevation and aspect on carbon stock of different carbon pool.

Carbon pools	Source of Variation	Df	Sum Sq	Mean Sq	F value	Pr(>F)
AGC (Mg ha^{-1})	Elevation	2	2349	1174.70	7.84	0.002**
	Aspect	1	28	27.80	0.19	0.670
	Elevation x Aspect	2	419	209.60	1.40	0.266
	Residuals	24	3595	149.80		
BGC (Mg ha^{-1})	Elevation	2	158.89	79.44	7.84	0.002**
	Aspect	1	1.89	1.89	0.19	0.670
	Elevation x Aspect	2	28.34	14.17	1.40	0.266
	Residuals	24	243.15	10.13		
SOC (Mg ha^{-1})	Elevation	2	266.4	133.20	10.34	0.001***
	Aspect	1	380.4	380.40	29.54	0.000***
	Elevation x Aspect	2	2.5	1.20	0.10	0.910
	Residuals	24	309.1	12.90		
TC (Mg ha^{-1})	Elevation	2	3843	1921.70	8.33	0.002**
	Aspect	1	165	165.40	0.72	0.406
	Elevation x Aspect	2	669	334.50	1.45	0.255
	Residuals	24	5539	230.80		

*** and.
** represents significance level at 0.001 and 0.05 respectively.

Rajeev Joshi: Writing – review & editing, Writing – original draft. **Prakash Chaudhary:** Writing – original draft, Investigation. **Jeetendra Gautam:** Writing – review & editing, Formal analysis. **Menuka Maharjan:** Writing – review & editing. **Himlal Baral:** Writing – review & editing. **Kishor Prasad Bhatta:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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