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Effect of elevation on soil quality under bamboo (*Bambusa teres* Buch.-Ham. ex Munro) stands outside forest areas in Eastern Nepal

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ABSTRACT

Bamboo dynamics in non-forest areas remain relatively underexplored, despite over 50 % of the global bamboo population being found in degraded, marginal or agricultural lands outside forests. To address this, we investigated soil quality dynamics under isolated bamboo stands (*Bambusa teres*) across three elevation regions: lower (0–400 m), middle (400–800 m), and higher (800–1200 m) in Katari, Udayapur, Nepal. Stratified sampling, followed by purposive sampling, was used to account for elevation variation and bamboo's scattered distribution. A total of thirty 100 m^2 circular plots (10 per elevation stratum) were sampled at two soil depths (0–15 cm and 15–30 cm) to assess soil quality, using various indicators based on published literature from Nepal. At middle elevation, organic carbon, nitrogen and potassium were significantly higher at 0–15 cm, while phosphorus and pH were higher at 15–30 cm ($p \leq 0.05$). A fair soil quality rating (SQI: 0.48 –0.57) was observed in the study area. Elevation significantly ($p \leq 0.05$) affected SQI at 0 –15 cm depth, with higher SQI at middle elevation (0.57) and lower SQI at lower elevation (0.48). For effective bamboo management and land-use planning, it is important to consider elevation-specific zoning. Middle and higher elevations should be prioritized for bamboo plantations, incorporating management activities and agroforestry integration to enhance soil productivity. Further studies with larger samples and broader geographic coverage, incorporating additional soil indicators and environmental variables is recommended.

1. Introduction

Bamboos, fast-growing evergreen perennials from the *Bambusoideae* subfamily of the *Poaceae* family, are categorized into the *Olyreae* (herbaceous), *Bambuseae* (tropical) and *Arundinarieae* (temperate) tribes (Akinlabi et al., 2017; Ahmad et al., 2021). Globally, bamboo covers at least 35 million hectares (about 1 % of the world's forest), with over 50 % growing outside official forests on degraded, marginal or agricultural lands (FAO, 2020). It is predominantly found in Southeast and South Asia, with China hosting the most species (Pandey et al., 2023; Sharma, 1980). Bamboo plays a crucial role in ecosystem services by improving soil quality, reducing erosion, enhancing carbon (C) sequestration and providing essential resources for construction, crafts and rural livelihoods (Paudyal et al., 2019; Ayer et al., 2023). Due to its versatility and ecological benefits, bamboo is often referred to as "green gold" or "poor man's lumber" (Tripathi et al., 2003; Lobovikov et al., 2007; Nirala, 2017).

Soil quality is integral not only to agricultural productivity but also to ecosystem services such as air and water purification, making it crucial for environmental sustainability and human well-being (Haryuni et al., 2020). This is particularly significant in developing countries where soil quality directly influences food security and economic stability (Wiebe, 2003). Assessing soil quality requires an understanding of its physical, chemical and biological properties, which inform its

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capacity to perform essential functions (Karlen and Stott, 1994; Doran and Parkin, 2015). However, soil quality is a complex and dynamic concept that cannot be directly measured in the laboratory or field but is inferred through a soil quality index (SQI) using various soil indicators (Stocking, 2003). An SQI can be estimated using a statistical model, through a soil fertility index (categorical) or through an additive method (simple and weighted system) based on common soil parameters (Mukherjee and Lal, 2014). Abdu et al. (2023) compared these three SQI methods and found that the additive method based on common soil parameters provided consistent assessments, making it valuable for soil quality evaluation. In Nepal, Bajracharya et al. (2006) developed a soil quality rating guide based on an assigned range of values for commonly used soil parameters such as organic carbon, nitrogen (N), potassium (K), phosphorus (P), pH and soil texture. This method was subsequently used to study the dynamics of soil quality under different land uses in Nepal. Nepal and Mandal (2018) studied soil quality and a nutrient index in Badekhola and Brindaban catchments. Ghimire et al. (2018) studied how soil quality varies with different land uses such as forest, agroforest and agricultural land in the Chure region of Central Nepal. Another comparative assessment of the soil nutrient status and SQI according to soil depth was conducted by Ghimire et al. (2020) in sub-watersheds in Udayapur, Nepal. Similarly, Poudel et al. (2024) applied an SQI method to understand the effects of silvicultural interventions on community managed Sal (*Shorea robusta* C.F.Gaertn.) forest soil in the Central Terai region of Nepal. Kandel et al. (2024) assessed soil quality of different forest stand and management regime types using a similar SQI method for the whole Terai region of Nepal. Recently, Maharjan et al. (2024) investigated the impact of agroforestry interventions on soil quality using an SQI approach in the Mid hill region of central Nepal. However, there is no well-established methodology for estimating SQI for bamboo-based ecosystems such as bamboo forest, bamboo stands outside forest area, plantations and agroforestry.

Elevation plays a significant role in influencing climate, temperature, precipitation and other environmental factors, all of which can affect soil characteristics such as pH, organic matter content, nutrient levels and soil texture (Alves et al., 2010; Bennie et al., 2008; Luizão et al., 2004; Lin et al., 2012;). Many bamboo species are highly adaptable and can thrive in various soil conditions, and their growth has the potential to modify soil properties (Li et al., 2017: Li et al., 2018; Liu et al., 2019; Ouyang et al., 2022; Zhou et al., 2022). For instance, bamboo cultivation decreases soil pH, total N and organic matter content, and mulching can induce further soil acidification (Qian et al., 2021). Bamboo species can improve soil properties such as hydraulic conductivity, water stable aggregates and mean weight diameter (Kaushal et al., 2020). Extensively managed Moso bamboo (*Phyllostachys edulis* (Carrière) J.Houz.) can significantly increase total organic C content, C mineralization rate, soil pH, total N, aggregate stability and amorphous and organically complexed Fe contents in the soil (Zhou et al., 2022). The interaction between bamboo growth and soil characteristics, however, varies with elevation, as demonstrated by several studies. For instance, Fang et al. (2018) and Guan et al. (2015) reported positive and negative correlation of SOC with altitude and soil depth, respectively in Moso bamboo forests in China. Huang et al. (2014) also reported higher levels of soil C and N in high-elevation bamboo plantations (1200 and 1400 m) than at lower elevations (600, 800 and 1000 m). Furthermore, Ayer et al. (2024) studied elevation-aspect influence on *Bambusa teres* Buch.-Ham. ex Munro C stocks outside forest areas with higher SOC stocks being found in the middle elevation zone (400–800 m). While these studies have investigated soil quality indicators in managed bamboo ecosystems, such as plantations and agroforestry systems, research on soil properties in unmanaged or minimally managed bamboo stands remains scarce (Ayer et al., 2024). Additionally, studies examining the interaction between elevation and soil quality in bamboo-based ecosystems are also limited. Understanding this interaction is essential for assessing bamboo's potential as a sustainable land management tool, particularly in regions with diverse topography and climatic conditions where bamboo plantations are widely used for land restoration.

Nepal harbours 12 bamboo genera and over 53 bamboo species in non-forest areas, ranging from the lowland Terai (50 m) to the high altitudes (3500 m) (Ayer et al., 2023; Das, 2004; Das and Thapa, 2011; Ghimire, 2008). While studies on bamboo in Nepal have predominantly focused on its socioeconomic benefits (Bajracharya et al., 2012; Jha and Yadav, 2015) and its role in providing ecosystem services (Ayer et al., 2023; Ayer et al., 2024; Gautam et al., 2018), research on soil dynamics in bamboo stands outside forest areas remains limited (Ayer et al., 2024; Ghale et al., 2020). Although Pandey et al. (2023) examined the interaction between planted bamboo species and soil properties in the Pan Kholsi Micro-Watershed, the influence of elevation on these interactions has yet to be fully explored. Given that bamboo is predominantly found on degraded and marginal lands across Nepal, understanding its impact on soil quality is crucial for effective plantation management. Therefore, this study evaluated the effect of elevation on soil properties and overall soil quality across soil depths under *B. teres* stands outside forests. We selected *B. teres* for this study due to its widespread use by farmers in plantations and its concentrated natural distribution in Eastern Nepal, as demonstrated by Kharel et al. (2024), who used Maximum Entropy (MaxEnt) modelling to analyze its potential distribution across Nepal. We hypothesized that soil quality declines with increasing elevation, driven by reduced organic matter accumulation, lower microbial activity and harsher climatic conditions. Additionally, we expected that topsoil (0–15 cm) would show higher nutrient content and better soil quality indicators compared to subsoil (15–30 cm) due to greater organic input and biological activity in the upper soil layers. We believe that this study will guide bamboo plantation and management decisions in Nepal due to the widespread bamboo presence in degraded, marginal and agricultural lands. Furthermore, the study will provide valuable insights into bamboo research in isolated or scattered patches, an area where information is currently limited in global literature (Canavan et al., 2017; Fang et al., 2018).

2. Materials and methods

2.1. Study area

This study was carried out across the elevation gradient of Katari municipality (26.8372 °N and 86.3213 °E) in Udayapur district, within Koshi Province, Nepal (Fig. 1). Katari municipality is located at elevations reaching up to 2100 m above sea level (Fig. 1). The climate of the study area is tropical to subtropical with an annual minimum temperature, maximum temperature, and average annual rainfall of 16.8 °C, 28.1 °C, and 1349.2 mm, respectively (DoHM, 2017). The study site encompassed four distinct forest types: Hill Sal (*Shorea robusta*) Forest, Chir Pine (*Pinus roxburghii* Sarg.) Forest, Chir Pine-Broadleaved Forest, and Lower Temperate Oak Forest. These forests supported a diverse assemblage of tree species, including *Shorea robusta*, *Terminalia chebula* Retz., *Adina cordifolia* (Roxb.) Hook.f. & Benth., *Senegalia catechu* (L.f.) P.J.H.Hurter & Mabb., *Terminalia bellirica* (Gaertn.) Roxb., *Bombax ceiba* L., *Dalbergia sissoo* Roxb. ex DC., *Schima wallichii* (DC.) Korth., *Castanopsis indica* (Roxb. ex Lindl.) A.DC., *Pinus roxburghii, Alnus nepalensis* D. Don, *Rhododendron arboretum* Sm., *Lyonia ovalifolia* (Wall.) Drude and *Myrica esculenta* Buch.-Ham. ex D.Don (Ayer, 2023; Khamcha et al., 2023; Lamichhane and Karna, 2009). In Nepal, farmers often lack awareness of the benefits that bamboo plantations can provide for shade-loving crops (Ayer et al., 2023; Ayer et al., 2024). As a result, bamboo is commonly planted in marginal, degraded or sloping areas. Furthermore, a prominent common misconception exists among farmers that bamboo needs little maintenance for growth (Ghimire, 2008). Therefore, the study plots in our research consisted of scattered bamboo clumps across marginal, degraded and sloping fields, without any specific management practices or the presence of other plant species. Bamboo plant population characteristics, including clumps per hectare, culms per hectare and mean DBH across elevation regions (0–1200 m),

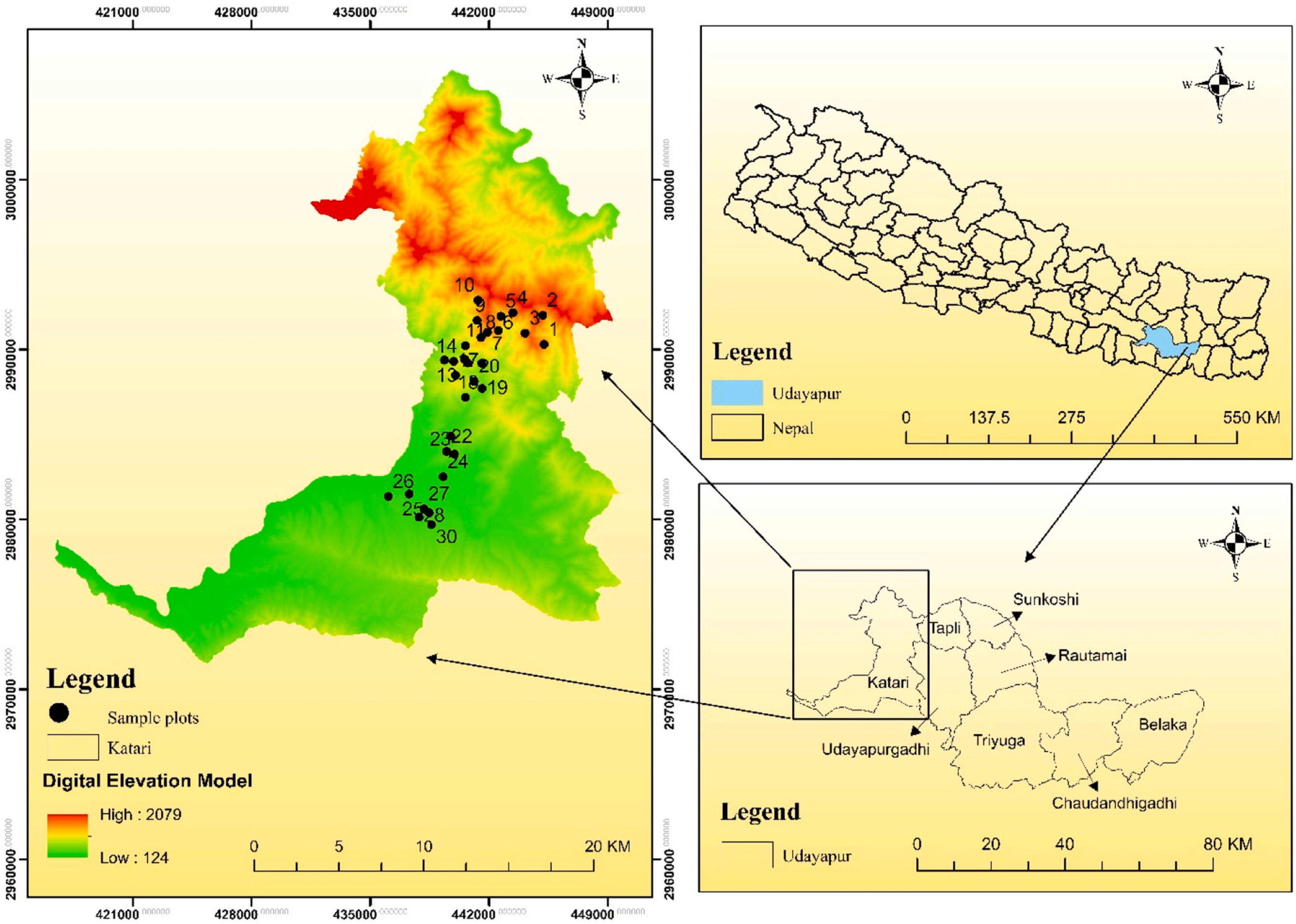

Fig. 1. Map of the study area; Katari Municipality, Udayapur District.

have been previously documented by Ayer et al. (2024) (Appendix 1).

2.2. Study design and soil sampling

Following Ghale et al. (2020) and Ayer et al. (2024), stratified sampling was initially applied to ensure representation of the three elevation strata: lower (0–400 m), middle (400–800 m) and higher (800–1200 m; Fig. 1). This enabled the variation across elevation gradients to be captured (Ghale et al., 2020; Ayer et al., 2024). Due to budget constraints and plot inaccessibility, as well as the scattered distribution of bamboo stands, the sample sizes were small, particularly at higher elevations. Moreover, bamboo stands along roadsides, residential areas and rivulets were excluded, as these locations are often subject to disturbances such as traffic, construction and water flow impacts, which could influence soil quality and introduce confounding variables. Additionally, bamboo clumps in agricultural lands were excluded to avoid potential confounding effects from fertilizer use or agricultural practices. Following stratification, we purposively selected bamboo stands from accessible areas with varying clump densities within each elevation zone, ensuring that sites with both high and low bamboo density were represented. This approach allowed us to balance logistical constraints while focusing on capturing the variation in soil quality across elevation zones.

Thirty circular sample plots (10 per elevation zone/stratum, each 100 m^2) were established (Ayer et al., 2024). Soil properties were studied at two different depths (0–15 cm and 15–30 cm) as the shallow soils and subsurface rocks limited sampling beyond 30 cm (Subedi et al., 2010). We assumed that sampling the top 30 cm of soil would sufficiently answer our research questions as bamboo generally has a shallow root system that extends down to a depth of about 30 cm (although some species can go deeper). Soil samples were taken from the four corners of each plot at each depth using a soil auger and a 3 cm diameter and 30 cm deep core sampler. The sub-samples from each corner of the plot at different depths were mixed and were expected to provide a representative overview of the soil properties within the sample plot. In addition, it is critical to space sampling locations from bamboo clumps to reduce the impact of roots and canopy on soil characteristics. Thus, on average, we kept the bamboo clumps and the plot's sampling locations 3 m apart. In this way, a total of 60 soil samples (3 elevations × 10 replications × 2 depths) representing the various combinations of elevations and depths were collected. For further examination, these soil samples were placed in zip-lock plastic bags, securely sealed, and transported to the Koshi Province Soil and Fertilizer Testing Laboratory in Sunsari district, Nepal for subsequent analysis.

2.3. Soil analysis

A digital pH meter was used for determining soil pH (McLean, 1982), and the hydrometer method for soil texture (Bouyoucos, 1962). SOC was assessed by the Walkley and Black method (Walkley and Black, 1934); total N by the Kjeldahl method (Bremner and Mulvaney, 1982); available P by Olsen's and Somers method (Olsen and Sommers, 1983); and available K by flame photometer method (Thomas, 1982).

2.4. SQI assessment

Due to the absence of a specific methodology for calculating soil quality for bamboo, we used the SQI approach (Eq. 1) due to its simplicity and consistency of the outcomes for different soil types, as recommended by Abdu et al. (2023). This process followed three main steps: (i) identifying relevant soil indicators, (ii) transforming indicators into scores, and (iii) integrating the scores into an index. In this study, we focused on commonly used and accessible indicators such as SOC, pH, soil texture, total N, available P and available K, which are widely recognized as key factors influencing soil quality. These indicators have been well-documented in previous studies in Nepal (Bajracharya et al., 2006; Ghimire et al., 2018; Poudel et al., 2024; Kandel et al., 2024; Maharjan et al., 2024) as reliable measures for assessing soil health and fertility. Given the limited access to advanced laboratory resources and budget constraints, we prioritized indicators that can be measured using standard field techniques and laboratory procedures, ensuring practical feasibility within the scope of this study. The formula for SQI is given as Eq. 1.

$$SQI = (a \times R_{STC}) + (b \times R_{pH}) + (c \times R_{OC}) + (d \times R_N \times R_P \times R_K) \quad (1)$$

where,

SQI = soil quality index,
R_{STC} = assigned ranking values for soil textural class
R_{pH} = assigned ranking value for soil pH,
R_{OC} =assigned ranking value for SOC,
R_N=assigned ranking value for total N,
R_P=assigned ranking values for available P,
R_K =assigned ranking value for available K.
a= 0.2, b= 0.1, c= 0.4, and d= 0.3 (weighted values corresponding to each parameter).

2.5. Statistical analysis

We used the Shapiro-Wilk's test for normality and Barlett's test for homogeneity of variance to ensure that our data satisfied the prerequisites for parametric tests before moving on with the statistical analysis. The criteria of equal variance and normality were met given both tests produced non-significant p-values ($p > 0.05$). We then used the Paired Samples *t*-test to compare soil properties between two depths, and one-way ANOVA to evaluate significant differences in soil properties across different elevation categories. All statistical analyses were conducted at a significant level of 0.05. Differences between means were considered significant if $p \leq 0.05$ and non-significant if $p > 0.05$. These statistical analyses were conducted using R software (version 4.2.3).

Table 1
Common soil parameters and ranking values for SQI in Nepal.

Parameters	Ranking Values 0.2	0.4	0.6	0.8	1
Soil Textural Class	C, S	CL, SC, SiC	Si, LS	L, SiL, SL	SiCL, SC
Soil pH	< 4	4–4.9	5–5.9	6–6.4	6.5–7.5
SOC%	< 0.5	0.6–1	1.1–2	2.1–4	> 4
Fertility (NPK)	Low	Mod Low	Moderate	Mod. High	High
SQI	Very Poor	poor	Fair	Good	Best

Source: (Bajracharya et al#, 2006)
where,
C- Clay, Si- Silt, S- Sand, LS- Loamy sand, CL- Clay loam, SiL- Silty loam, SC- Sandy Clay, SiCL -Silty clay loam, SiL- Silty loam, SiC- Silty Clay, SL- Sandy loam, SCL- Sandy Clay loam, LS- Loamy Sand, SQR- Soil Quality Rating

Table 2
N, P and K interpretation of soil in context of Nepal.

Total N (%) Range	level	Available P (kg ha^{-1}) Range	level	Available K (kg ha^{-1}) Range	level
< 0.1	Low	< 31	Low	< 110	Low
0.1–0.2	Medium	31–55	Medium	110–280	Medium
> 0.2	High	> 55	High	> 280	High

Source: (NARC, 1999)

3. Results

3.1. Effect of soil depth on soil properties

Table 3 presents the soil properties at various soil depths. We found significant differences in only SOC, total N and available K across both soil depths. The soil pH was acidic and showed no significant difference at the two different depths. Both SOC and total N content were higher at 0–15 cm compared to the 15–30 cm depth. Interestingly, available P increased with depth, from 5.56 ± 0.76 kg ha^{-1} at 0–15 cm to 8.72 ± 2.24 kg ha^{-1} at 15–30 cm. Conversely, available K was higher at the 0–15 cm depth level (398.78 ± 43.44 kg ha^{-1}) and decreased to 279.46 ± 32.80 kg ha^{-1} at the 15–30 cm depth.

3.2. Effect of elevation on soil properties at different soil depths

Fig. 2 presents soil properties across depths and elevation categories. At 0–15 cm, soil pH was highest at the middle elevation (5.84 ± 0.26), followed by the lower (5.40 ± 0.06) and higher elevations (5.30 ± 0.06), although the differences were not significant. A sandy clay loam texture was consistent across elevations. SOC and total N were significantly higher in the middle elevation (2.62 ± 0.21 % SOC, 0.23 ± 0.02 % N) than in the higher (2.35 ± 0.23 % SOC, 0.20 ± 0.02 % N) and lower elevations (1.62 ± 0.2 % SOC, 0.14 ± 0.02 % N). Available P increased with elevation but was not significant, with the highest levels at the higher elevation (7.19 ± 1.19 kg ha^{-1}), followed by the middle (5.57 ± 1.49 kg ha^{-1}) and lower elevations (4.27 ± 1.19 kg ha^{-1}). Available K was significantly higher at the middle elevation (543.04 ± 75.71 kg ha^{-1}) than at the higher (384 ± 77.45 kg ha^{-1}) and lower elevations (269.31 ± 48.07 kg ha^{-1}).

At the 15–30 cm depth, soil pH was significantly higher at the middle elevation (5.99 ± 0.29) than at the higher elevation (5.31 ± 0.09) (Fig. 2). The sandy clay loam soil texture was consistent across all elevations. SOC content was highest at the higher elevation (2.15 ± 0.28 %), followed by the middle (1.74 ± 0.28 %) and lower elevations (1.29 ± 0.25 %), although these differences were not statistically significant. Total N showed a similar trend, increasing from 0.11 ± 0.02 % at the lower elevation to 0.15 ± 0.02 % at the middle and 0.18 ± 0.02 % at the higher elevation. In contrast, available P was significantly higher at the higher elevation (17.12 ± 5.75 kg ha^{-1}) than at the middle (5.03 ± 1.20 kg ha^{-1}) and lower elevations (4.01 ± 1.54 kg ha^{-1}). Similarly, available K was significantly higher at the middle elevation (435.25 ± 48.44 kg ha^{-1}) compared to the higher

Table 3
Soil properties at different depths (mean± standard error). Different letters represent significant differences at 95 % confidence level.

Soil properties	Soil depth 0–15 cm	15–30 cm	p value
pH	5.51 ± 0.1^a	5.63 ± 0.12^a	0.446
Soil texture	Sandy Clay Loam	Sandy Clay Loam	
SOC (%)	2.2 ± 0.14^a	1.73 ± 0.16^b	0.035 *
Total N (%)	0.19 ± 0.01^a	0.15 ± 0.01^b	0.037 *
Available P (kg ha^{-1})	5.67 ± 0.76^a	8.72 ± 2.24^a	0.206
Available K (kg ha^{-1})	398.78 ± 43.44^a	279.46 ± 32.8^b	0.033 *

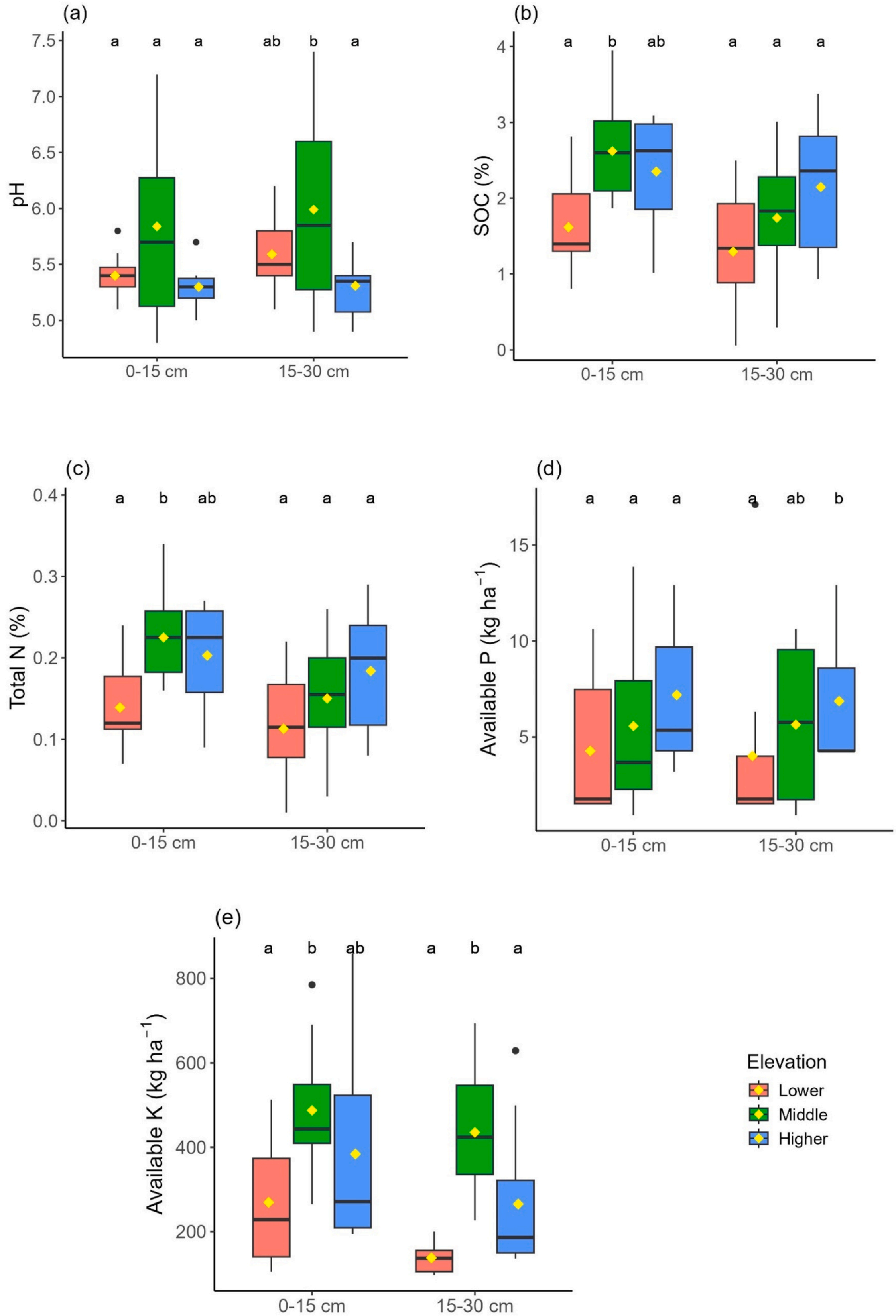

Fig. 2. Soil properties at different depths across different elevations. Different letters represent significant differences at 95 % confidence level. Yellow dot refers to mean value. Pink, green and blue box represent lower, middle and higher elevation categories respectively.

(265.35 ± 54.62 kg ha^{-1}) and lower elevations (137.78 ± 11.02 kg ha^{-1}).

3.3. Effect of depth and elevation on soil quality

Higher SQI was observed at 0–15 cm depth (0.53) than at 0–30 cm depth (0.49), although this difference was not statistically significant. Elevation-wise, the middle elevation (0.57) had a higher SQI followed by the higher (0.54) and lower elevations (0.48) at 0–15 cm depth (Fig. 3). However, the SQI showed an increasing trend with increasing elevation at the 15–30 cm depth (Fig. 3). The SQI values at the lower, middle and higher elevations at 15–30 cm depth were 0.46, 0.51 and 0.54, respectively. One-way ANOVA showed a significant difference in SQI across elevation category at the 0–15 cm depth only where the Post hoc Tukey test revealed only a pair lower-middle as significant.

4. Discussion

4.1. Effects of soil depth on soil properties

We found moderately acidic (5.51–5.63) soil pH with no significant difference between the studied depths (Table 1). This could be due to the similar soil texture throughout the profile, which resulted in an even distribution of organic matter and nutrients, limiting variations in pH (Ge et al., 2019). This aligns with Kumari (2017), who reported no significant differences in soil pH at different depths in different bamboo species plantations in the Mid hills of Himachal Pradesh, India. The acidic soil pH across the study area could be due to increased leaching in open areas with less vegetation. In such areas, more rainfall reaches the soil, potentially leading to higher leaching of base cations and lower retention of organic matter, which could result in more acidification and a lower pH (Reuss, 1980). This aligns with Pandey et al. (2023) who observed acidic soil pH under various bamboo species (*Bambusa teres, Bambusa balcooa* Roxb., *Dendrocalamus* species) outside forest areas in the Pani Kholsi Micro-Watershed, Nepal. Soil pH influences nutrient availability and is a key indicator of soil fertility (Black, 1968; Saha et al., 2018). The observed acidic pH under bamboo stands outside forest areas could negatively impact bamboo growth as well as overall soil fertility (Qian et al., 2021). Low soil pH can limit bamboo productivity by reducing nutrient availability (NPK) and increasing toxic levels of aluminum and manganese (Li et al., 2022; Zong et al., 2023). Additionally, low pH can disrupt soil microbial activity, impairing nutrient cycling. This results in poor growth, stunted development and reduced biomass production, with extreme acidity potentially causing bamboo withering (Gui et al., 2013). For bamboo management, understanding the impact of soil pH is critical, as it informs practices such as soil amendment and fertilization strategies to optimize bamboo growth. While certain bamboo species may thrive in these conditions, other crops or plants that require a more neutral pH might struggle (Dewangan et al., 2023). This suggests that soil management practices may need to be tailored when bamboo is involved, especially if the land is later used for different agricultural purposes. However, bamboo species that can thrive in unfavourable conditions may be suitable for use in afforestation or agroforestry in regions where soil acidity is a challenge (Ngaba et al., 2024). This would help to utilize land that might otherwise be less productive for conventional crops. We observed sandy clay soil texture at both depths (Table 1) which aligns with Tripathi and Singh (1996) in Indian dry tropical *Dendrocalamus strictus* (Roxb.) Nees forests, Huang et al. (2014) and Chang et al. (2016) in *Phyllostachys edulis* plantation in central Taiwan, and Abebe et al. (2021) in *Oxytenanthera abyssinica* (A.Rich.) Munro bamboo forests of Ethiopia. A similar soil texture at the depths studied was anticipated, as differences in texture are typically driven by variations in parent material, vegetation type and pedogenic processes (Hailemariam et al., 2023), all of which were consistent in our case. Furthermore, sandy clay loam soils are ideal for the growth and productivity of bamboo species because they offer a balanced mix of drainage, moisture retention and nutrient availability (Othman, 2001).

SOC and total N were significantly higher at the upper depth (0–15 cm) compared to the lower depth (15–30 cm) (Table 1). This aligns with previous studies in *B. teres* forests in the North Eastern Himalayan region of India (Venkatesh et al., 2005), in managed *D. strictus, B. vulgaris, B. balcooa* and *B. teres* plantations in North India (Tariyal et al., 2013), in *P. edulis* plantations in China (Fang et al., 2018; Guan et al., 2015); in *P. edulis* plantations in central Chinese Taipei (Wang et al., 2017), in a *P. edulis* plantation in Italy (Chiti et al., 2024), and in

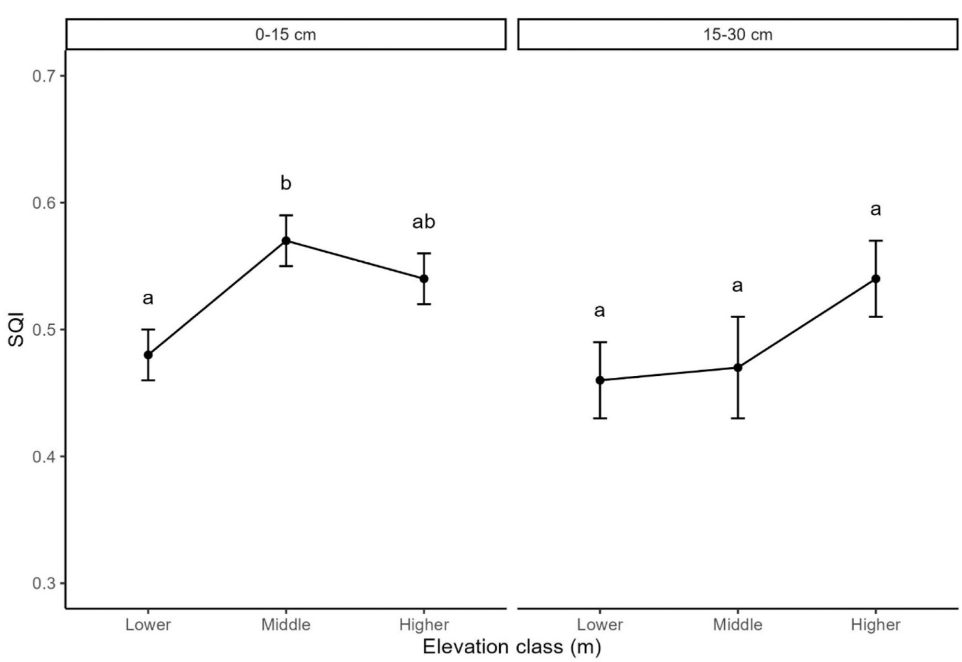

Fig. 3. Soil quality index across different elevation class at each depth. The point indicates the mean value and bar indicates the standard error. Different small letters indicate significant differences whereas similar letters represent no significant difference at 95 % confidence level.

subtropical bamboo plantations in India (Nath et al., 2015). The decline in SOC and total N with increasing soil depth may be attributed to the rapid utilization of nutrients in the upper layers due to the more fibrous root system of bamboo in topsoil layer (Tang et al., 2024; Qin et al., 2017). This can be linked to increased microbial activity and higher litter input from bamboo, which accelerates soil fertility and decomposition (Pan et al., 2024; Tariyal et al., 2013; Venkatesh et al., 2005; Sharma et al., 2024).

Higher available P was observed with increasing soil depth (Table 1). This finding aligns with Guan et al. (2017) in Moso bamboo forests in China where they observed higher available P in deeper soil. The accumulation of P in the deeper layers in our study could be a result of natural leaching over time, especially in the absence of management practices that could alter this process (Fetzer et al., 2022; Jin et al., 2023). However, Tariyal et al. (2013), working with *D. strictus, B. vulgaris, B. balcooa* and *B. teres* plantations in North India, reported higher P content at 0–15 cm depth. This could be because they conducted the study in managed plantations in the Terai region of Uttarakhand, India whereas our sites were completely unmanaged. In contrast to available P, lower available K was observed at lower depth (Table 1) which aligns with managed bamboo plantations in India (Tariyal et al., 2013). The depletion of K in the lower soil layers may be explained by its higher mobility and uptake by bamboo roots concentrated in the upper soil strata (Riekerk, 1971; Sharma et al., 2024). Available K is often more available in surface soils where organic matter decomposition releases it into the soil solution, making it readily accessible to plants (Marschner and Rengel, 2023). In unmanaged bamboo stands, the absence of external K inputs could lead to its gradual depletion at depth, as bamboo roots continue to extract this essential nutrient from the upper soil layers (Kaushal et al., 2020; Ni and Su, 2024).

4.2. Effect of elevation on soil properties at different soil depths

We observed significantly higher soil pH at middle elevation, followed by lower and higher elevations in lower depth only (15–30 cm) (Fig. 2). This could be because middle elevations might experience more moderate temperatures and moisture levels, creating conditions that favour a more balanced soil pH (Ayer et al., 2024). Extreme conditions at higher and lower elevations such as precipitation and temperature could promote processes that either acidify or alkalize the soil (Rengel, 2011). For instance, higher rainfall at higher elevations increases leaching and reduces soluble base cations, leading to lower pH levels (Yimer et al., 2006). We observed similar soil textures of sandy clay loam across all elevations outside the forest area (Fig. 2). A similar type of soil texture was found in mixed open and dense forests in the Northeastern Himalayan region of India (Choudhury et al., 2015), in a *P. edulis* plantation in Chinese Taipei (Wang et al., 2016), and in thorny bamboo (*Bambusa spinosa* Roxb. [syn. *Bambusa stenostachya* Hack.]) forests of southern Chinese Taipei (Shiau et al., 2017). This could be due to similar parent material, vegetation, climate or the extent of erosion or deposition processes (Charan et al., 2013; Yang et al., 2008). Furthermore, due to the absence of bamboo management interventions in the study area, the soil might have been allowed to develop and maintain a stable soil texture (Choudhury et al., 2015).

Elevation has a major influence on temperature, precipitation patterns, soil properties and other environmental factors that affect bamboo growth and dispersal (Ayer et al., 2023; Fang et al., 2018; Zhu et al., 2019). Similarly, a recent study by Ayer et al. (2024) reported higher bamboo biomass and carbon stock at middle elevation (400–800 m) outside the forest area due to the favourable environmental conditions for bamboo growth. This explains why higher SOC and total N at middle elevation were observed in our study (Fig. 2). Higher bamboo biomass leads to increased litter and root inputs, which boost SOC through organic matter accumulation and enhance total N levels through improved decomposition and nitrogen fixation processes (Yuen et al., 2017). Additionally, SOC and total N tend to be higher in undisturbed bamboo plantations compared to managed ones (Yang et al., 2020). Given that the study area lacked specific bamboo management practices, we expected that SOC and total nitrogen levels would be elevated. However, we observed no such significant difference at the lower depth (15–30 cm) (Fig. 2). While elevation affects surface soil conditions through temperature, moisture and vegetation types, its impact might be less pronounced in the deeper soil layers where the influence of elevation-related factors diminishes. Furthermore, decomposition rates and nutrient turnover might be similar across elevations in the deeper layers due to slower microbial activity and reduced organic matter input at these depths, leading to uniform SOC and N levels (Pries et al., 2018).

Available P increased with elevation at both depths (Fig. 2) which aligns with Saha et al. (2018) in the Himalayan temperate forests of India and Li et al. (2023) in the Lijiang Alpine Botanical Garden of Yunnan, southwest China. This can be convincingly attributed to enhanced microbial activity driven by the distinct soil and climatic conditions found at higher elevations. Lin et al. (2015) reported a higher diversity of soil bacterial communities in bamboo plantations at higher elevations (1000–1200 m). Similarly, Chang et al. (2016) reported increased soil microbial biomass, enzyme activities and community structure due to an increase in elevation in Moso bamboo plantations in Taiwan. Cooler temperatures and higher precipitation at higher elevations create a favourable microclimate for specific microbial communities that may play a crucial role in the mineralization of organic P (Siles et al., 2016). As these microorganisms thrive, they convert organic phosphorus into forms more readily available for plant uptake, leading to higher P levels in the soil. However, Guan et al. (2017) reported no significant spatial variability of P in Moso bamboo forests in China. The difference between their findings and ours could be due to the lack of intensive stand management activities such as frequent fertilization treatments, annual bamboo harvest and digging bamboo shoots in our study area; these activities were prevalent at the site studied by Guan et al. (2017). At both depths, the middle elevation showed higher available K concentrations followed by the higher and lower elevations (Fig. 2). This could be due to the higher density and biomass of bamboo at middle elevation which can significantly influence potassium availability (Ayer et al., 2024). Middle elevations often support denser vegetation with higher biomass, which leads to greater P uptake by plants and accumulation in plant tissues. When this biomass decomposes, potassium is returned to the soil, potentially increasing its availability. Our results, however, differ from those of Guan et al. (2017) in the Moso bamboo forests of China, Saha et al. (2018) in the Himalayan temperate forests of India, and Hailemariam et al. (2023) in the natural forest of Southern Ethiopia. As mentioned above, the difference may be attributed to the absence of bamboo management in our study area.

4.3. Effect of depth and elevation on soil quality

Soil chemical and physical properties, along with management-induced changes, soil depth and topography are factors influencing forest soil quality (Schoenholtz et al., 2000; Shao et al., 2020). Therefore, we investigated their effect on bamboo stands outside forest areas across different depths and elevation categories. We observed a soil quality range of 0.46–0.57 (Fig. 3) which is considered fair according to the soil rating by Bajracharya et al. (2006). This observed SQI under bamboo stands outside the forest is lower than the Terai *Shorea robusta* forest (0.66) (Poudel et al., 2024) and agricultural land (0.64) in the Chure region of Central Nepal (Ghimire et al., 2018). Maharjan et al. (2024) also reported higher SQI in agroforestry systems with different management regimes (0.6–0.8) in the mid-hills of Kaski district, Nepal. Furthermore, Chen et al. (2024) also reported higher SQI in oak forests invaded by Moso bamboo (0.6) in the northern subtropics of China. The observed lower SQI under bamboo stands outside forest areas could be due to the absence of bamboo management activities such as managed harvesting of bamboo shoots, application of chemical fertilizer and organic amendments, or other activities. However, the higher SQI in unmanaged bamboo stands than Ghimire et al. (2018) found in degraded land (0.4) suggests that bamboo plantations not only stabilize soil and prevent erosion but also improve soil quality. An investigation into the SQI of managed bamboo stands could provide valuable insights into how different management practices affect soil quality while maintaining or enhancing bamboo productivity. For instance, it could provide valuable guidance on sustainable harvesting intervals, the impact of using organic versus chemical fertilizers, and the effects of different irrigation practices on soil quality. Therefore, we recommend assessing soil quality in bamboo stands under various management interventions.

Our study observed no significant difference in SQI across the studied depth ($p > 0.05$). This could be useful information for bamboo land management, as it indicates that practices aimed at improving soil quality could be applied uniformly across these depths. However, Kamal et al. (2023) reported a decrease in SQI with depth due to the decline in essential soil properties that support soil health and fertility. Therefore, it is necessary to examine SQI in deeper soil layers (up to 1 m) to better understand the vertical distribution of soil quality.

Elevation gradients can lead to variations in temperature and moisture, which directly influence soil properties and quality (Li et al., 2022; Ngaihte et al., 2024). At lower elevations, higher temperatures can accelerate leaching processes, leading to nutrient depletion and reduced nutrient retention in the soil (Costa et al., 2022). In contrast, higher elevations experience cooler temperatures that can slow microbial activity, thereby limiting nutrient cycling and organic matter decomposition (Kaštovská et al., 2022). We found significantly higher SQI values at middle elevations (400–800 m) (Fig. 3), which may be attributed to more moderate climatic conditions. These moderate conditions likely support favourable microbial activity and better nutrient cycling, resulting in improved soil quality. Supporting studies by Lin et al. (2017) and Li et al. (2022) highlight the influence of temperature and moisture on microbial processes, bacterial diversity and soil quality, further reinforcing the observed trend in our study. Similarly, Ayer et al. (2024) reported higher bamboo density and biomass at middle elevations outside the forest area in the Udayapur district of Nepal. This increase in bamboo density and biomass could lead to greater organic matter input into the soil, thereby contributing to improved soil quality. However, we did not find a significant difference in SQI across elevation categories at the lower depth (15–30 cm) (Fig. 3). This could be because nutrient availability and soil properties might vary in depth. At lower depths, soil properties may be less variable or less responsive to elevation changes compared to surface layers. This can lead to less significant differences in SQI at lower depths. Furthermore, organic matter tends to accumulate in the upper soil layers (0–15 cm). Therefore, changes in soil quality with elevation might be more pronounced at these shallower depths than at deeper layers (15–30 cm) where organic matter is less concentrated.

This study enhances our understanding of bamboo ecosystems in non-forest areas of Nepal, particularly how elevation impacts soil quality. Our study suggests that unmanaged bamboo systems may have different effects on soil quality than managed systems outside forest areas, raising questions about the influence of management practices (e.g., thinning, pruning, fertilization). Furthermore, it shows that elevation affects soil properties such as SOC, pH and nutrient levels, offering valuable insights for land-use decisions in reforestation, afforestation and agroforestry. These findings highlight the need to incorporate elevation factors into bamboo management to improve soil health and carbon sequestration.

4.4. Limitations of this study

This study has several important limitations that may affect the interpretation and generalizability of the findings. One primary limitation is the small sample size within each elevation zone due to the scattered distribution of bamboo clumps in non-forest areas of Nepal, which may not adequately represent broader bamboo ecosystem conditions. A larger sample size would have enhanced the statistical power of the study. Additionally, the research was constrained by limited resources typical of a resource-poor country, resulting in a narrower range of soil quality indicators assessed. Including more comprehensive indicators, such as microbial biomass, enzyme activities and soil aggregation, could provide a better understanding of bamboo soil health dynamics (Cao et al., 2024; Wang et al., 2024).

Furthermore, the study's focus on specific regions may not reflect the ecological diversity across Nepal. Bamboo ecosystems can vary widely based on climate, soil type and management practices, limiting the applicability of the findings to other areas. Another limitation is the relatively few environmental variables (i.e. elevation) considered. Similarly, while key soil properties like pH, organic carbon, nitrogen, phosphorus and potassium were measured, important factors such as moisture content and soil fauna were not included, potentially overlooking their influence on soil quality. Finally, the absence of managed bamboo stands restricts our ability to understand how management practices such as selective thinning and fertilization impact soil quality. Future research should aim for a broader geographic scope, larger sample sizes and a more diverse range of variables to confirm these findings and enhance their applicability.

5. Conclusion

This study is, to my knowledge, the first to investigate the effect of elevation on soil quality under bamboo stands outside forest areas. Most soil quality indicators were significantly influenced by elevation, highlighting its role in determining site suitability for bamboo. The observed fair soil quality (0.48–0.57) suggests that, despite the lack of intensive management, bamboo plantations could be strategically utilized on degraded and marginal lands for restoration projects. While elevation significantly affects soil quality in scattered bamboo stands, soil depth does not, indicating that middle and higher elevations are more suitable for bamboo plantations. Targeted strategies, such as sustainable harvesting, organic amendments and site-specific species selection, could further enhance soil health and productivity in these areas. In contrast, lower elevations may not yield substantial soil improvements but could be prioritized for industrial and commercial applications. By integrating bamboo into land restoration projects and agroforestry systems in middle and higher elevations, both ecological and economic benefits could be maximized. Considering the limitations of our study, future research should expand the geographic scope, increase the sample size and incorporate a broader range of soil quality indicators, including deeper depths, along with additional environmental variables. This will be necessary to confirm our findings and provide more widely applicable conclusions.

CRediT authorship contribution statement

Ayer Santosh: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Poudel Sandip:** Writing – original draft. **Adhikari Kishor:** Writing – original draft. **Shapkota Jun:** Writing – original draft. **Bhatta Kishor Prasad:** Writing – review & editing, Writing – original draft, Supervision. **Gautam Jeetendra:** Supervision. **Maraseni Tek:** Writing – review & editing, Supervision. **Maharjan Menuka:** Writing – review & editing, Writing – original draft, Supervision.

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.

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Declaration of competing interests

The authors have no relevant financial or non-financial interests to disclose.

Appendix 1. Stand structure of bamboo stands outside forest area in Katari, Udayapur, Nepal. Different letters represent significant differences, and similar letters represent no significant difference at 0.05 significance level

Category	Clump (ha^{-1})	Culm (ha^{-1})				DBH (cm)
		1–2 Yrs	3–4 Yrs	5–6 Yrs	Total	
Elevation						
Lower (0–400 m)	367^a	19389	1133	9044	29567^a	6.79 ± 0.25^a
Middle (400–800 m)	400^a	28520	2200	11760	42480^a	6.82 ± 0.41^a
Higher (800–1200 m)	300^a	2440	1180	1120	4740^b	6.21 ± 0.34^b
Aspect						
East	374^a	18507	1440	6500	26447^a	6.59 ± 0.26^a
West	335^a	14750	1600	8050	24400^a	6.62 ± 0.31^a

Source: Ayer et al. (2024)

Data Availability

Data will be made available on request.

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