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Effect of assisted natural regeneration on forest biomass and carbon stocks in the Living Mountain Lab (LML), Lalitpur, Nepal

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ABSTRACT

Various environmental, management and biotic and abiotic factors determine forest types, regeneration, biomass, carbon and tree composition, structure, and diversity. Diachronic analysis of forest biomass and carbon stocks of 2014 and 2022 was carried out to assess the effect of assisted natural regeneration in the Living Mountain Lab (LML) of International Center for Integrated Mountain Development (ICIMOD), Nepal. A total of thirty permanent sample plots were laid in the natural dense and sparse forest stands following stratified random sampling. The site was enriched with 17,472±100.2 seedlings ha^{-1} indicating the excellent natural regeneration with the average tree density 1337±80.5 ha^{-1} and mean basal area 28.69±6.9 m^2ha^{-1}. The average forest biomass in 2022 was 200.73±65.2 t ha^{-1} and the most contribution was from trees (96 %). The mean net annual biomass increment was found to be 6.80 $tha^{-1}yr^{-1}$ and the open tree canopy with sparse strata contributed the most. The mean vegetation carbon was 98.31±10.3 t Cha^{-1} significantly contributed by trees. Thus, the large trees with open canopy contain significant amount of forest biomass and store more carbon as woody components and support species dynamics. Similar assessment of forest biomass and carbon has a potential to be linked with forest restoration with reference to regeneration, carbon sequestration and climate change mitigation.

Introduction

Forests play a vital role in the global carbon cycle (Houghton et al., 2009). Throughout the past three decades, there has been discussion on the effects of human influence on the forest ecosystems in the Himalayas (Singh and Singh, 1987; Thadani, 1999). The leading cause of forest degradation in the Himalayas is immediate need-based and small-scale (Singh, 1998). In contrast to acute human-induced forest disturbance, chronic disturbances are associated with removing small amounts of biomass from many different plants or trees at frequent and often regular intervals and interrupting regeneration (Thadani, 1999; Kunwar and Sharma, 2004). Typically, these disturbances are in the form of firewood, loping for fodder and litter removal, and, to a lesser extent, extraction of various non-timber forest products (NTFPs) such as lichens, mosses, and medicinal plants. Such disturbances lead to a gradual degradation of the forest (Singh, 1998). Within the forest ecosystem, such troubles are subject to the kind of management interventions (DeFries et al., 2007). The change in altitude, aspect, topography, climatic and biotic factors, and management practice are always associated with the forest vegetation composition (Kunwar et al., 2020). The elements are also used to explain forest management patterns (Rohde, 1999).

Forest vegetation properties, such as tree composition and structure, tree biomass, tree diversity, and soil carbon changes with management practice, are determined by various environmental, abiotic, and abiotic factors (V.C. Joshi et al., 2021). Recent findings regarding the unpredictability of biomass stocks and carbon sinks in the terrestrial ecosystem are worrying (Houghton, 2005; Oli and Shrestha, 2009; Baral et al., 2022). These findings have made the work of terrestrial ecologists interested in biomass research and the carbon cycle much more urgent. There is a growing demand for accurate rates of biomass stocks and carbon sequestration in the warming World. Forests are the World's most significant carbon sink and play a vital role in climate change mitigation through carbon sequestration; thus, assessing carbon stock in

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the forests is essential for policy prescription and management planning (Burman et al., 2021).

Various environmental, abiotic, and biotic factors at a given site influence many ecosystem attributes, including tree composition and structure, biomass, diversity, evenness, and soil carbon (Southon et al., 2018). These characteristics might alter with management practices. Given the background, an effort was made to complement the knowledge base of the forest biomass and carbon stock of the differently regenerated and managed sites of Living Mountain Lab (LML) of International Center for Integrated Mountain Development (ICIMOD), Nepal. This study was carried out in examining the structure, composition, diversity, and biomass of forest and tree species, as well as their relationships and how these parameters change with management and silvicultural treatments. In addition, tree regeneration, density, carbon stock and the associated disturbances in the two sample forest stands were assessed.

Materials and methods

Study area

The ICIMOD's Living Mountain Lab is located at Godavari municipality of Bagmati province in the Pulchowki watershed, approximately 15 km southeast of Kathmandu (Fig. 1). The park has a total area of about 30 hectares (ha). The Godavari-Kunda Community Forest surrounds it to the northeast, and the Diyale Community Forest to the southwest. The site has an altitude range of 1540–1800 m above sea level (m.a.s.l) and a gradient ranging from almost 0° to more than 60° in parts of the upper forest zone. Vegetation in the study area comprises a mixture of deciduous and evergreen broadleaved species. The soil texture varies from clay loam to sandy and silty clay loams rich in forest humus. Soil types include sandy alluvial soil in the lower areas and shallow dry soil on the ridge tops. The climate is subtropical to warm temperate, with a mean annual temperature of 17.2 °C. The annual temperature ranges from −0.5 °C to 33.8 °C with an annual mean relative humidity of 76 %. The region's average annual rainfall is 2062 mm, with around 80 % of this total falling during the monsoon season from June to September (Southon et al., 2018).

ICIMOD's LML has three primary functions; first, it serves as a platform to showcase and demonstrate simple and easily replicable technologies, techniques, and innovations that can sustainably improve mountain communities' ecological and economic conditions. Secondly, it serves as a place to conduct field research and test and verify scalable solutions. Third, it serves as a place for training, reflection, and experience sharing and a repository of faunal and floral resources. The LML has been actively managed for the last 30 years to restore its originally highly degraded condition, characteristic of the surrounding hillsides.

Sample plot design and data collection

This study was carried out in a series of stratified-randomly distributed permanent sample plots in the LML at Godavari. A total of thirty permanent sample plots each measuring 10×10 m^2 were laid in the forest with different aspects, altitude, canopy cover, and canopy densities. These plots were subjected to a survey of tree species composition and forest structure. The sub-plots, each measuring from 1 m^2 (1×1 m^2) to 25 m^2 (5×5 m^2), were nested inside the 100 m^2 plots to appraise the frequency and density of herbs and grasses and seedlings, respectively. Similarly, the sapling and tree biomass were measured from the 25 m^2 and 100 m^2 plots. The stratified-random sampling with nested plots

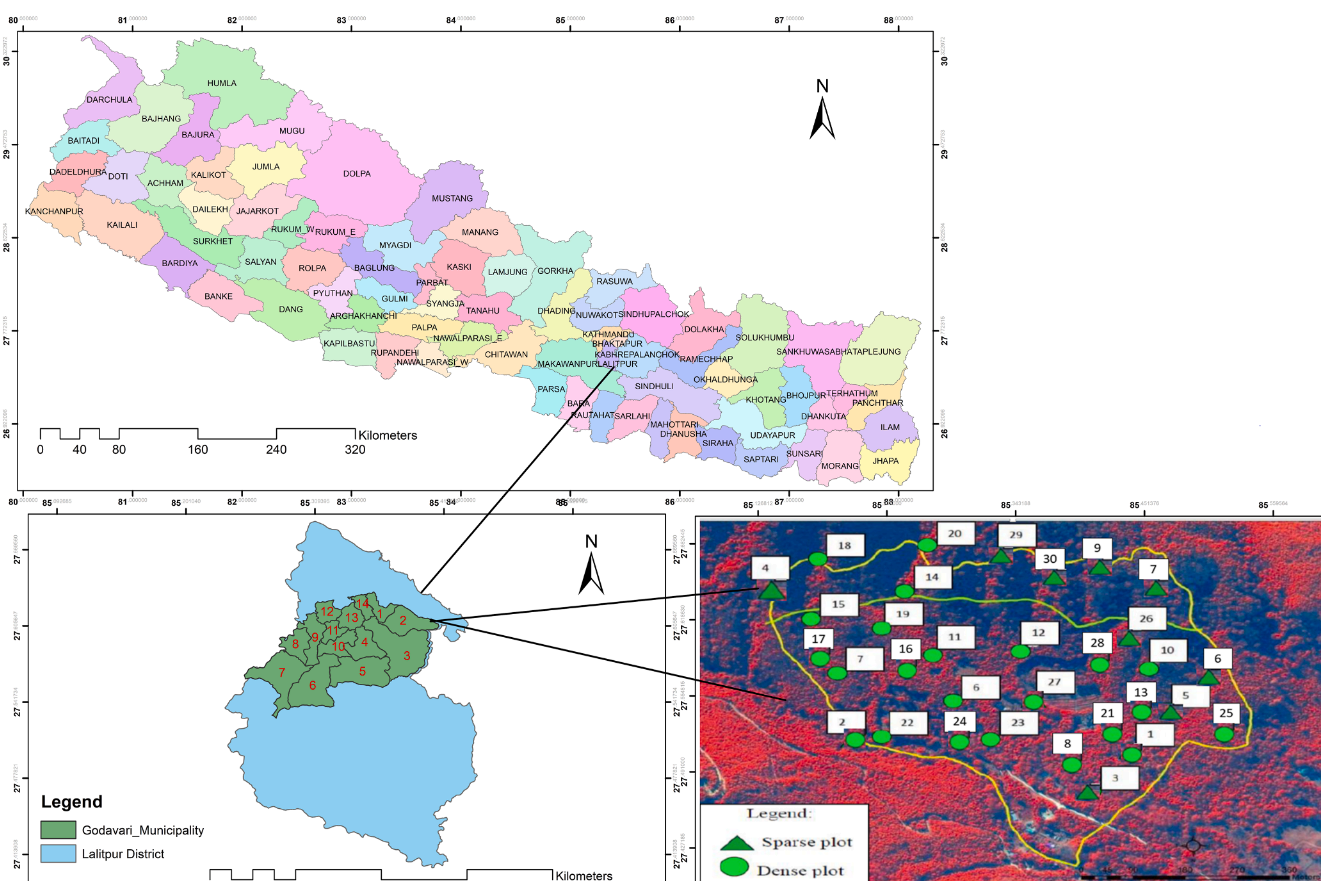

Fig. 1. Study area map showing sample plots.

method was used in the sampling design because of its simplicity for long-term monitoring (ICIMOD 2013).

Tree vegetation analysis, biomass estimation, and annual biomass production

Within each sample plot, tree DBH and height were measured using diameter tape for diameter measurement, and vertex IV and transponder were used for height measurement (Ravindranath and Ostwald, 2008). Tree density is simply the number of trees per unit area and is generally reported as the number of trees per hectare. We calculated tree density following Zobel et al. (Zobel et al., 1987; Zobel and Singh, 1997). Disturbances such as signs of fire, fodder collection, firewood collection, timber collection, grazing, human trampling, soil erosion were recorded and indexed subjectively from 0 (no impact) to 7 (presence of all four factors) following Miehe et al. (Miehe et al., 2015) and Kunwar et al. (Kunwar et al., 2020). Allometric equations developed previously by Chave (Chave et al., 2005) were applied to mean DBH, height, and wood-specific gravity of each tree species to calculate the biomass stock of individual tree components. Likewise, the allometric equation developed by the Department of Forest Research and Survey (DFRS) Government of Nepal for saplings was used to calculate the sapling biomass (Tamrakar, 2000). The below-ground biomass (BGB) was calculated following the formula BGB = Above ground biomass AGB × 0.2 MacDicken (MacDicken, 1997) and the biomass of herbs, grasses and

Table 1
Biomass estimation method of different biomass pools.

Biomass Pool	Equations	Description of symbol	Reference
Above ground tree biomass (AGTB)	$AGTB = 0.0509 * \rho\ D^2H$	ρ: wood specific gravity (kg m^{-3}), D: tree DBH, H: tree height (m)	(Tamrakar, 2000)
Below ground biomass (BGB)	BGB = AGTB*20 %	AGTB: meaning above ground tree biomass	(MacDicken, 1997)
Above ground sapling biomass (AGSB)	$\log(AGSB) = a + b\ \log(D)$	Log: natural log, a: intercept of allometric relationship for sapling, b: slope allometric relationship for saplings, D: over bark at DBH	(Tamrakar, 2000)
Leaf litter, herbs and grasses (LHG)	$LHG = \frac{W_{field}}{A} \cdot \frac{W_{subsample,dry}}{W_{subsample,wet}} \times 10$	W_{field}: weight of the fresh field sample of LHG, destructively sampled within an area of size A [kg]; A: size of the area in which LHG were collected [m^2]; $W_{subsample\ dry}$: weight of the oven-dry sub-sample of LHG taken to the laboratory to determine moisture content [g]; and $W_{subsample\ wet}$: weight of the fresh sub-sample of LHG taken to the laboratory to determine moisture content [g].	(Subedi et al., 2010)
Total Biomass (TB)	TB=AGTB+BGB+SB+LHG		(Subedi et al., 2010)

total forest was calculated following Subedi et al. (Subedi et al., 2010) as provided in (Table 1).

The net biomass production (ΔB) in 2014 (B1) and 2022 (B2) were taken as annual biomass accumulation (ΔB = B2-B1). The sum of ΔB values for different components was taken for adding the biomass in trees and other pools (Rana et al., 1989; Singh et al., 2011). The plot level biomass (kg m^{-2}) was converted to (t ha^{-1}), and finally, tree biomass stock was converted into tree carbon stock after multiplying it with the IPCC default carbon fraction of 0.47 (IPCC 2006).

Statistical analysis

We used Redundancy Analysis (RDA) to investigate the relationship between plot-level vegetation characteristics, environmental variables, and total carbon stock. RDA is the canonical extension of principal component analysis and is intended to display the main trends in the variation of a multidimensional dataset in a reduced space of a few linearly independent dimensions (Legendre and Legendre, 1998). In RDA, the canonical axes differ from the principal components in that they are constrained to be linear combinations of supplied environmental variables (ter Braak, 1994). As there are two types of forest sites (sparse-human managed forest and dense-natural forest), which forest type contributes the most forest carbon was assessed and validated statistically.

Results

Vegetation parameters

A total of 70 tree species belonging to 44 families were recorded in the plots and measured to estimate biomass and carbon stock. There was a dominant canopy of tree species *Castanopsis tribuloides, Castanopsis indica, Fraxinus floribunda, Machilus odoratissima, Zizyphus recurva, Quercus glauca, Magnolia kisopa* and *Schima wallichii*. The vegetation type is mixed broad-leaved with an average of 72.5 % crown cover, 15 % shrub cover, and about 75 % grasses in the natural forest on steep slopes. While the tree crown cover was about 56 %, shrub cover 24 %, and herb cover over 75 % in shrubland at LML, Godavari. Schima-Castanopsis, Oak-laurel, and mixed Oak were the dominant forest types of the site.

Diameter and height characteristics of trees

Based on the data analysis, we estimated that the overall average DBH of trees falls between 15.07±2.3 cm, and the precision average height of trees falls between 10.65±1.4 m. Moreover, we estimated that the average density of trees ranges between 1337±80.5 trees ha^{-1}, and the average basal area of the tree falls between 28.69±6.9 m^2 ha^{-1} (Supplementary file 1). It can be concluded that the tree species in the forest stand are in the ideal state regarding tree density stocking. In the present study, a decreasing concave up curve has been observed while plotting a diameter distribution curve, showing the number of smaller diameter class trees with higher proportion and the higher diameter classes in decreasing order Fig. 2 on the left side. Fig. 2 on the right side showed a positive correlation between tree diameter and height with an adjusted r^2 value of 0.578 and a p-value of 0.05.

Natural regeneration

The status of natural regeneration in LML forests was found to be excellent, and we estimated that the overall precision average of seedlings was 17,472±100.2 seedlings ha^{-1}. The regeneration in the ICIMODs LML is in the ideal state, and it might be due to the timely silvicultural treatments and practices adopted at Godavari and better timely forest protection measures (restriction on open grazing, lopping, fodder collection, illicit felling, and encroachment to the forest land).

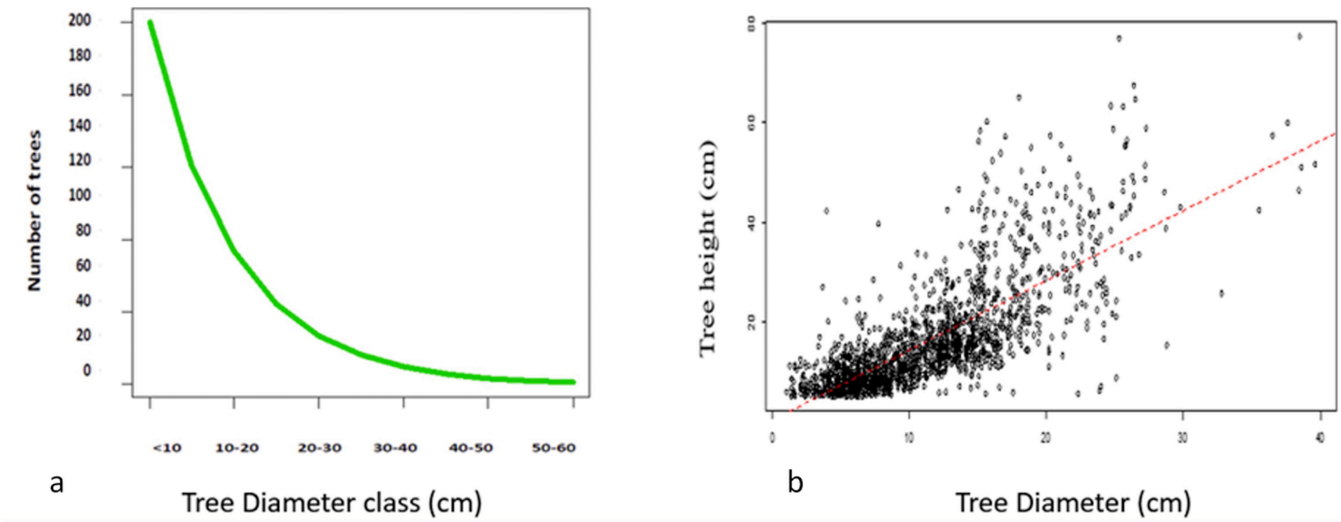

Fig. 2. Association of tree diameter with tree height and number of trees.

Forest biomass and carbon

The current estimation of forest biomass in the LML showed that the mean forest biomass was 194.33 t ha^{-1}, contributed by trees, saplings, herbs, and leaf litter biomass pools. The tree biomass pool contributed about 93.5 %, the sapling pool contributed only 0.64 %, the herb and grasses biomass pool contributed 1.90 % of the total biomass, and the leaf litter biomass pool contributed about 3.96 % (Table 2).

The net biomass production (ΔB) between the biomass of 2014 (B1) and the biomass of 2022 (B2) was taken as annual biomass accumulation (ΔB = B_2-B_1). The herb biomass values taken during peak production were used as herb biomass accumulation annually. The average forest biomass in the dense strata was 193.5 t $ha^{-1,}$ and sparse strata had a bit higher biomass 217.6 t $ha^{-1,}$ respectively (Fig. 3). The average forest biomass in LML at Godavari was 139.52 t ha^{-1} in 2014, which increased to about 200.73±65.2 t ha^{-1} during the monitoring period 2022. This hinted that the net biomass production in the monitoring plot of LML, Godavari was found to increase per year by 6.80 t ha^{-1}. Likewise, the open canopy sparse strata showed slightly higher (107.44 t Cha^{-1}) as compared to the dense canopy strata (94.39 t Cha^{-1}) with ($p = 0.04$, $t = 1.80$). This might be due to the open canopy, which allows more sunlight into the forest floor and provides more favorable conditions for vegetation growth than the closed canopy.

Factors influencing biomass and carbon

The RDA exhibited the effect of the nine variables on total carbon (Tot_C). As shown in Fig. 4, the first axis (RDA1) significantly ($p = 0.014$, $F = 41.96$) explained the variables. Interpreted from the figure, botanical variables tree density (T_Density) and species richness and non-botanical variables (Elevation, Disturbance, and Slope) significantly correlated with total carbon. Other variables (tree crown, height, and diameter) showed positive but insignificant correlations (Table 3). However, all these variables accounted for less than half the proportion (Adj. $R^2 = 42$ %) of the variability in total carbon with significant global RDA significance ($p = 0.01$, $F = 3.33$) (Table 3). Human-managed sparse forests significantly contributed to forest carbon (p = 0.04, t = 1.80).

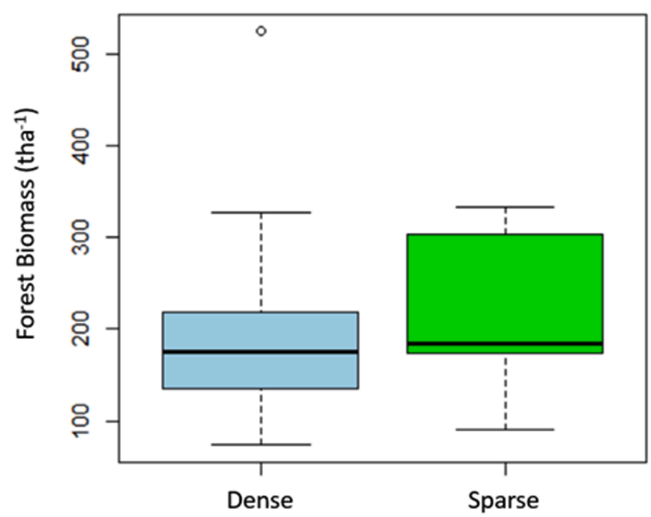

Fig. 3. Box and whisker plot of the forest biomass in LML. The box represents interquartile (IQ) range (25th–75th percentile), whiskers represent the highest and lowest forest biomass value, and outliers are represented by hollow circle.

Discussion

The LML is a specular area with three ecological zones containing varied habitats and plant species. We observed three types of forest, Schima-Castanopsis, Oak-Laurel, and Mixed-Oak in and around the LML site. Both research sites were enriched with the dominant trees of these forest types, resulting in the forests having a high potential for present and future forest biomass stock. As most of the trees belong to the small diameter classes as attributed by an inverse J shaped diameter distribution curve, the site is a potential forest tree biomass and carbon sequestration. It has been argued that primary forests, especially very old forests, are unimportant in addressing the climate change problem because their carbon exchange is at an equilibrium state (Melillo et al.,

Table 2
Sample precision and statistical coefficient of two sites.

SN	Strata	District	No. of plots	Mean	Std. dev	Half width at 95 %	Max.	Min.	Sampling precision
1	Dense (D)	Lalitpur	21	193.5	95.3	43.4	525	73.3	10.0
2	Sparse (S)	Lalitpur	9	217.6	87.0	66.9	334	91.0	8.8

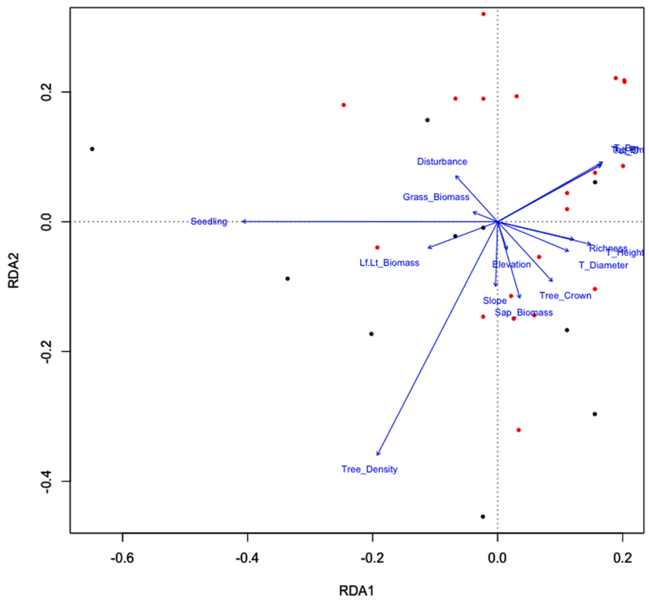

Fig. 4. Effect of Tree and Vegetation Characteristics and Environmental Factors on forest biomass and carbon. Longer arrows mean this variable strongly drives the variation in the community. Arrows pointing in opposite directions have a negative relationship and those pointing in the same direction have a positive relationship. Dotted lines are axes. Blue lines are explanatory variables.

Table 3
Summary Statistics of Redundancy Analysis (RDA) between tree carbon and tree characteristics and environmental factors.

Parameters	Variance	F	Pr(>*F*)
Elevation	238.24	6.513	0.020*
Disturbance	281.54	7.696	0.015*
Slope	107.89	2.949	0.099
T_Height	13.21	0.361	0.567
T_Diameter	39.56	1.081	0.288
T_Density	199.49	5.453	0.031*
T_Crown	53.25	1.455	0.215
Seedling	42.15	1.152	0.296
Richness	121.12	3.311	0.089.

Note = * significant within 95 % confidential, and, significant within 90 % confidential.

1995); the present carbon offset investments are focused on growing young trees as their rapid growth provides a higher sink capacity than old trees (Keith et al., 2009).

Eight tree species viz. *Castonopsis tribuloides, C. indica, Quercus glauca, Schima wallichii, Myrica esculenta, Celtis australis, Eurya cerasifolia*, and *Fraxinus floribunda* were the dominant tree species in both forest stands in terms of density and biomass stock. Consistent with our findings, Godavari area was reported to be covered by Schima-Castanopsis, Oak-Laurel, and Mixed-Oak forest types (Kattel et al., 2015) and populated by dense tree species of Rosaceae (species of *Prunus*), Rutaceae (species of *Citrus* and *Zanthoxylum*) and Fagaceae (species of *Castanopsis, Quercus*) (Devkota and Kunwar, 2008). *Q. glauca* and *Q. incana* are often gregarious on the southern slopes between 1000 and 2000 m (N.R. Joshi et al., 2021). The Godavari area is enriched with about 100 medicinal plants, including 694 species of other plants (ICIMOD 2008).

The overall growing stock at the natural forest stands on steep slopes, and shrubland on the valley of biomass monitoring plots at Godavari was excellent and comparable with other previous studies conducted in various forest regimes of middle hills of Nepal and abroad (Tripathi et al., 2018; Verma and Garkoti, 2019; Gosain et al., 2015). The mean forest biomass in the ICIMODs LML was slightly higher than the national weighted forest biomass (176.86 t ha^{-1}) (DFRS 2015). Oak forests of Garhwal, Nainital, Almora, and Kumaon, India, were reported to have a forest biomass of range 145–225 t ha^{-1} (V.C. Joshi et al., 2021; Verma and Garkoti, 2019; Gosain et al., 2015). The DBH distributions follow a left-skewed trend in forest plots of natural forests on steep slopes. A reversed decreasing concave up-shaped curve was obtained, indicating most of the trees in all the strata are smaller and pole-sized, and there is a high potential to enhance tree biomass and carbon stock in the future. The larger the DBH, the larger the tree trunk and branch surface, resulting in higher tree biomass (Adhikari et al., 2021). In general, the size class distribution of undisturbed or less disturbed forests should fit the reverse decreasing concave up-shaped pattern, with most of the trees in smaller classes and fewer in larger ones (Whitmore, 1990). This means that the forest in the project site is in regenerative conditions and facing minimum anthropogenic disturbances from the ecological point of view.

The precision average tree density of the forest stand was found to be 1337±80.5 trees ha^{-1} in the biomass monitoring period 2022. The status of the natural regeneration in the forests of Godavari was found to be excellent as the overall precision average of the seedlings was found to be 17,472±100.2 seedlings ha^{-1}. The mean tree basal area at natural forest stand was found to be 28.69±6.9 m^2 ha^{-1}. The forest in the ICIMODs LML is considered good as the average number of seedlings is more than 5000 ha^{-1} (MoFSC/CPFD 2000). In the present study, the number of seedlings ha^{-1} is comparable and slightly higher than the mean seedling density in the forests of Nepal, 10,095 seedlings ha^{-1} (DFRS 2015). The total tree density of 910 ha^{-1} to 1680 ha^{-1} reported by Joshi and Tewari (Joshi and Tewari, 2011) for different central Himalayan oak and pine forests is comparable with our study in ICIMODs LML. The mean tree density values obtained in this study were higher (more than double) than the mean tree density (430 stems ha^{-1}) in the county's forests. Likewise, the mean tree basal area was also higher in the ICIMODs LML compared to the mean basal area in the forests of Nepal (20.57 m^2 ha^{-1}) (DFRS 2015).

The current estimation of forest biomass in LML showed that the precision average forest biomass was included between 200.73±65.2 t ha^{-1}, contributed by trees (96 %), saplings (1.0 %), herbs (0.8 %), and leaf litter biomass pools (2.2 %). The precision average forest biomass was included between139.52±10.4 t ha^{-1} in 2014. The net biomass production in the biomass-monitoring plot of LML was found to be 6.80 t ha^{-1}yr$^{-1.}$ The total tree biomass in the undisturbed pine forest in central Himalaya ranges between 280 and 405 t ha^{-1} (Raikwal, 2009), Pine and Oak mixed forest in Kumaun Himalaya was 179–486.6 t ha^{-1} (Rawat et al., 2011), and the tree biomass under the forest fire disturbance area was ranged between 9.47 and 62.54 t ha^{-1} in the central Himalayan forest (Joshi et al., 2013; Woodall and McCormick, 2022). The average forest carbon without considering soil carbon in LML, Godawari, was about 98.31±10.3 t ha^{-1}, less than that from the study carried out in the same area a decade ago (Karki et al., 2016). We reported slightly higher carbon stock in the sparse strata 107.44 t C ha^{-1}, compared to the dense strata, where 94.39 t C ha^{-1} was reported. Less carbon (50.8 - 87.13 t ha^{-1}) was reported from the community-managed Schima-Castanopsis forest (Tripathi et al., 2018; Gurung et al., 2022), and this could be due to semi-protected management strategy. Community forests are protected by the local communities and, for the certain days in a year the local communities are allowed to access forests for collecting firewood, fuelwood, forage, fodder and logs, following community forest operational plan. They are relatively moderately-disturbed than the protected forest like LML, Lalitpur. Moderately open canopy in the human-managed and relatively disturbed forest led to the crown cover gaps (Pandey et al., 2020) that let growing abundant seedlings and saplings. Despite dense seedling and saplings grown, their contribution forest carbon was found to be less significant (only 2.5 %), as was observed in community forests of low lands Tarai (Sunar, 2020) and abroad (Hu et al., 2015). The mixed Sal (*Shorea robusta*) forest of Tarai with contributed higher forest carbon (120 t C ha^{-1}) (Thapa-Magar and Shrestha, 2015). Large tropical trees store significant amounts of carbon in woody components (Meyer et al., 2018) and the open canopy plays an important role in forest carbon stocks and dynamics.

Of the nine explanatory variables tested, the number of trees, elevation, and disturbance explained more variation in tree carbon than other variables. Tree characteristics tree density, crown cover, diameter, and height exhibited a positive correlation with carbon; however, only the former one was significant. As we observed, carbon stock was positively associated with crown cover in the Sal forest (Meyer et al., 2018). Density and diameter were positively associated with carbon in a study in the Chure region of Nepal (Poudel et al., 2022). DFRS report (2015) stated that the main factors influencing carbon loss are disturbance intervened by grazing and illegal logging (DFRS 2015). Physiological and environmental factors affect forest tree carbon, tree height, and tree diameter (Sharma and Kakchapati, 2018; Mäkelä, 2002). Physiographic factor slope exhibited a negative association as reported in other countries (Egeta et al., 2023; Maggi et al., 2005), and this could be because higher slope areas contain little vegetation compared to the lower slope areas.

Conclusions

The knowledge of forest dynamics is essential for resource management. This study focused on the dynamics of assisted natural regeneration, forest biomass production, and carbon stock in the institution-managed forest of Lalitpur, Nepal. Result showed that the research site is rich in biodiversity, and the site offers opportunities to restore carbon and other values that aid the sustainable forest ecosystem. Large tropical trees store significant amounts of carbon as woody components and their open canopy habitat boasts higher forest carbon stocks and dynamics. Our findings helps develop discussions regarding the roles of conservation, sustainable management of forests, and enhancement of forest carbon stocks. We recommend setting a framework for assessing the trade-offs between naturally regenerated forests and in the future to adopt the best forest management regime that brings conservation and carbon trade together.

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CRediT authorship contribution statement

Nabin Raj Joshi: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Surendra Raj Joshi:** Writing – review & editing, Supervision, Funding acquisition. **Erica Udas:** Writing – review & editing, Supervision, Project administration, Methodology. **Bhaskar Singh Karky:** Writing – review & editing, Supervision, Methodology. **Durga Hari Kutal:** Writing – review & editing, Writing – original draft, Formal analysis. **Ripu Mardhan Kunwar:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envc.2024.100858.

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