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Research Article

# Carbon sequestration potential of a sal (*Shorea robusta*) dominated community forest in central Nepal

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## ABSTRACT
This study assessed the biomass and carbon stocks above and below ground in a community forest in central Nepal that is dominated by Sal (*Shorea robusta*). A basic random sample design with a 2% sampling intensity and 500 m² circular plots was used to gather field data from Block 1 of the Piple Pokhara Community Forest, Makawanpur District, between October 2021 and March 2022. Tree height and diameter at breast height (DBH) were measured, and standard allometric equations were used to determine biomass. A total of 78 individual trees were measured across the eight sample plots. With a mean height of 13.18 m and a mean DBH of 20.66 cm, the forest showed moderate structural variability. The average total biomass per tree was 315.63 kg, with mean above-ground and below-ground biomass of 263.03 kg and 52.61 kg, respectively. Above-ground components accounted for the highest share of the corresponding mean carbon stocks, which were 0.12 tons above-ground, 0.02 tons below-ground, and 0.15 tons overall per tree. Plot-to-plot variations in carbon stocks ranged from 0.11 to 0.20 tons per tree, primarily due to variations in tree size. The findings highlight the role of community forests in Nepal's efforts to mitigate climate change and account for carbon emissions. They show that the community forest serves as an efficient local carbon sink and that better forest management that focuses on stand structure could further enhance its carbon sequestration potential.
**Keywords:** Climate change mitigation, biomass, carbon, forest management

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## INTRODUCTION
Carbon sequestration is the process by which plants and other systems capture atmospheric $CO_2$ and store it in long-term sinks. In forests, this involves the accumulation of carbon in trees and soils (Selin *et al.*, 2021). About 60% of the world's terrestrial carbon is stored in these forest reservoirs, making them critical for climate regulation (Bajracharya *et al.*, 2018). Forest activities such as afforestation are key to enhancing this sequestration potential (Vance, 2018; Batjes, 2014; Wannasingha *et al.*, 2023). In particular, soil organic carbon (SOC) is a highly influential pool, and increasing SOC levels is a recognized strategy for climate change mitigation (Hu *et al.*, 2018; Alidoust *et al.*, 2018; Gautam *et al.*, 2023). To standardize the accounting of such efforts, international frameworks like the UNFCCC and the Kyoto Protocol, guided by IPCC (2006) guidelines, identify five key terrestrial carbon pools: soil, litter, belowground biomass, aboveground biomass, and deadwood. National inventories under these

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agreements must account for carbon changes from forestry and land-use activities, including afforestation (Di Cosmo *et al.*, 2022).

In Nepal, community forestry plays a central role in this landscape. Currently, 22,682 community forest user groups manage approximately 2.4 million hectares. These forests hold significant potential for enhanced carbon sequestration and climate change mitigation. With the emergence of the REDD+ mechanism, the carbon storage role of forests has gained paramount importance, and community forestry is widely seen as a model approach. Consequently, integrating community forests into REDD+ and carbon-trading frameworks is a policy priority for the Nepalese government and NGOs. This integration, however, depends on accurate and reliable measurement of forest carbon stocks.

Accurately quantifying carbon stocks requires attention to all pools, particularly below-ground biomass (BGB), which accounts for 20–26% of total forest biomass (Cairns *et al.*, 1997). Its accumulation mirrors above-ground patterns, with the highest density in the top 30 cm of soil (Jackson *et al.*, 1996). However, while above-ground biomass assessment is well-established, methods for BGB are less standardized, more costly, and less frequently applied in practice (IPCC, 2006), often leading to the combined reporting of live and dead roots. Common estimation techniques, like allometric equations, introduce uncertainties, and field measurements are complicated by the disturbance and potential loss of root biomass during sampling. Furthermore, forest carbon dynamics are influenced by human activities such as harvesting and fuel use, which can shift a forest from a carbon sink to a source (Nowak & Crane, 2002). As a result, BGB remains a significant yet often overlooked component, with estimates for Nepalese community forests frequently relying on generalized conversion factors that may not reflect local conditions, introducing uncertainty into carbon assessments. Given Nepal's increasing engagement with REDD+ and carbon financing, developing accurate, localized forest carbon data is crucial. This study aims to address this need by measuring the above- and below-ground carbon stocks in a Sal (*Shorea robusta*)-dominated community forest. Specifically, it focuses on Block 1 of the Piple Pokhara Community Forest in Makawanpur District, central Nepal, to provide a detailed assessment.

## METHODOLOGY

### Study Area

The study site is Piple Pokhara Community Forest in Hetauda Sub-Metropolitan City, Makawanpur District, Central Nepal. The duration of the study is from October 2021 to March 2022. The community forest is approximately 110 hectares in size and is divided into four management blocks for administrative purposes. Our study focused on Block 1, which is relatively easily accessed and has relatively similar stand structure, which helped us conduct our fieldwork as constrained by logistics. The location of Block 1 is at the western boundary of this forest, at approximately 512 m above mean sea level, and has slopes of about 10 degrees (Figure 1).

*Shorea robusta* is more dominant, with relatively few individuals of *Schima wallichii* and *Albizia procera*. This forest is representative of a Sal-dominated community forest found within the mid-hills of Nepal. Although socio-demographic data has been recorded during the

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initial socio-reconnaissance visits, the focus of the study has remained only on biophysical data.

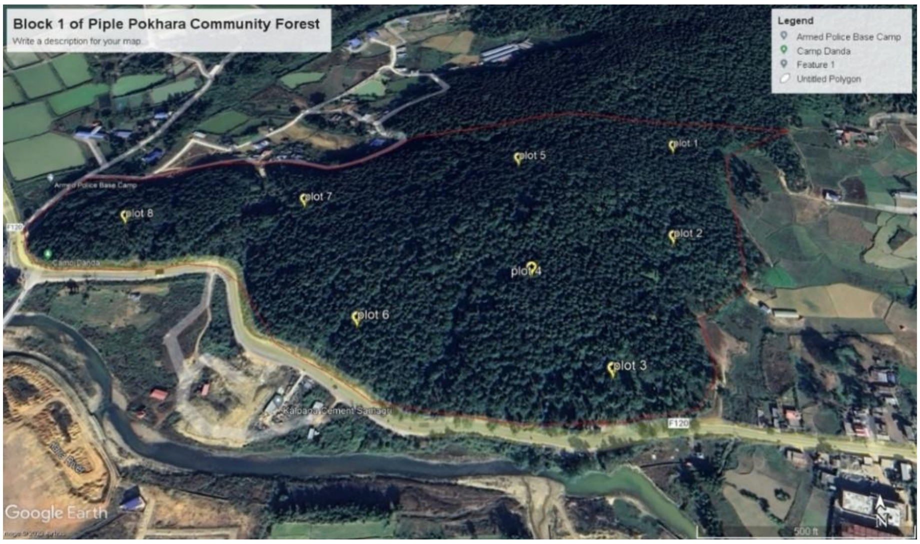


**Figure 1: Google Earth imagery showing study area and sample plots**

### Sampling Design

Tree biomass and carbon stocks were estimated by adopting a simple random sampling design. We adopted the guidelines for national forest inventory and community forest carbon assessment, and used a 2% sampling intensity since the stands are relatively even. Within Block 1, circular sample plots of 500 m² were laid out with a radius of 12.62 m. Considering the total area of the block of 18.9 ha, eight plots were placed randomly throughout this block. This placement was decided so as to have good spatial coverage and to minimize edge effects.

### Data Collection

For each sample plot, we found and marked in the field all the living trees with a diameter greater than the minimum measurable size. We measured DBH at a height of 1.3 m from the ground using a diameter tape. Tree height was determined by clinometer. For each plot, we determined species composition, total number of trees, and stand structure. All assessments are standard forest inventory methods with plots adjusted to reflect the slope to provide precise plot area.

### Stand Structure Measurements

Stand structural parameters including basal area (m²/ha), stem density (stems/ha), and mean diameter at breast height (DBH) and height were calculated at the plot level and scaled to per-hectare values. These parameters provide essential context for interpreting carbon stock estimates.

### Biomass Estimation

Above-ground tree biomass (AGTB) was estimated using the allometric equation developed by Chave *et al.* (2005) for moist tropical forests, which is widely applied in South Asian forest carbon studies:

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$AGTB=0.0509 \times \rho \times D^2 \times H$……………..Eq. 1

Where;
ρ = species-specific wood density (g/cm³),
D = diameter at breast height (cm), and
H = total tree height (m).

Wood density values were adopted from published literature and standard references for dominant tree species. Biomass estimates were first calculated at the individual tree level and then aggregated at plot and block levels.

This allometric equation was selected due to its development for moist tropical forests and widespread application in comparable South Asian studies, though we acknowledge that species-specific equations for *Shorea robusta* remain limited.

**Below-Ground Biomass Estimation**

Below-ground tree biomass (BGTB) was estimated using the root-to-shoot ratio approach proposed by MacDicken (1997), whereby below-ground biomass is assumed to be 15% of above-ground biomass:

$BGTB=0.15 \times AGTB$ ………………..Eq. 2

This simplified approach aligns with IPCC Tier-1 recommendations and is commonly applied where destructive root sampling is impractical, though it introduces uncertainty as root-to-shoot ratios can vary with species, age, and site conditions.

**Carbon Stock Calculation**

Tree biomass was converted to carbon stock using standard biomass-to-carbon conversion factors. Above- and below-ground carbon stocks were estimated separately and then summed to obtain total tree carbon stock at the block level. Carbon density (t/ha) was calculated by scaling plot-level estimates to the total area of Block 1.

This study focused exclusively on tree biomass carbon**;** soil organic carbon, litter, and deadwood pools were not assessed, consistent with our objective of quantifying tree carbon stocks**.**

**Data Analysis**

All field data were compiled and analysed using SPSS. Biomass and carbon stocks were calculated at plot, block, and per-hectare scales. Results are presented as total and mean carbon stocks for above- and below-ground tree biomass. Due to the study's descriptive and inventory-based nature, the analysis focused on carbon stock estimation rather than statistical inference.

## RESULTS

**The tree structure attributes**: The details of descriptive statistics are presented in Table 1. The average diameter at breast height (DBH) of sampled trees was 20.66 cm, with values ranging from 11.15 cm to 28.03 cm. This indicates a moderate variation in stem size, as reflected by the standard deviation of 4.25 cm. Tree height averaged 13.18 m, with a minimum

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of 9.00 m and a maximum of 23.00 m, suggesting a relatively heterogeneous stand structure. Wood density was fairly consistent across samples, with a mean of 0.87 gm/cm³ and a narrow range between 0.68 gm/cm³ and 0.88 gm/cm³, highlighting the uniformity of species composition or wood quality.

**Biomass distribution**: Above-ground tree biomass (AGTB) exhibited considerable variability, averaging 263.03 kg per tree, but ranging widely from 55.69 kg to 492.69 kg**.** Below-ground tree biomass (BGTB) followed a similar pattern, with a mean of 52.61 kg and values spanning 11.14 kg to 98.54 kg. Consequently, the total biomass averaged 315.63 kg**,** with a minimum of 66.82 kg and a maximum of 591.23 kg**.** The relatively high standard deviations (109.10 kg for AGTB and 130.92 kg for total biomass) underscore the variability in tree size and productivity within the sampled population.

**Carbon stock estimates:** Carbon storage followed the biomass distribution trends. Above-ground carbon averaged 0.12 tons, ranging from 0.03 tons to 0.23 tons, while below-ground carbon averaged 0.02 tons, with a narrower range of 0.01–0.05 tons. The total carbon stock per tree was 0.15 tons, with values between 0.03 tons and 0.28 tons. These figures highlight the significant contribution of above-ground biomass to overall carbon sequestration, accounting for the majority of stored carbon.

**Table 1**: Descriptive statistics of variables

| Variables | Mean | SD | Minimum | Maximum |
|---|---|---|---|---|
| DBH(cm) | 20.66 | 4.25 | 11.15 | 28.03 |
| Height (m) | 13.18 | 2.37 | 9.00 | 23.00 |
| Density (gm/cm$^3$) | 0.87 | 0.03 | 0.68 | 0.88 |
| AGTB (kg) | 263.03 | 109.10 | 55.69 | 492.69 |
| BGTB (kg) | 52.61 | 21.82 | 11.14 | 98.54 |
| Total Biomass (kg) | 315.63 | 130.92 | 66.82 | 591.23 |
| Above ground carbon (t) | 0.12 | 0.05 | 0.03 | 0.23 |
| Below ground Carbon (t) | 0.02 | 0.01 | 0.01 | 0.05 |
| Total Carbon (t) | 0.15 | 0.06 | 0.03 | 0.28 |

The estimated stem density for Block 1 was 195 stems/ha. The total carbon density for the tree pool was calculated at 28.93 t C/ha.

Across the eight plots, the mean diameter at breast height (DBH) ranged from 17.42 cm (Plot 5) to 24.04 cm (Plot 2). Plot 2 recorded the largest trees in terms of DBH, while Plot 5 had the smallest. Tree height varied between 12.27 m (Plot 8) and 14.33 m (Plot 7), showing moderate variation across plots. Taller trees were generally observed in Plots 6 and 7, whereas shorter trees dominated Plots 1, 5, and 8. Similarly, Wood density remained relatively stable across most plots, averaging 0.88 gm/cm³, except for Plot 4, which showed a slightly lower mean density of 0.81 gm/cm³. This suggests that species composition or wood quality was largely uniform, with Plot 4 standing out as an exception. Plot 4 has a mean wood density of 0.81 g/cm$^3$ while all other plots are 0.88 g/cm$^3$. This is due to the presence of species like *Schima wallichii* or *Albizia procera* in that specific plot. Above-ground tree biomass (AGTB) was highest in Plot 2 (355.66 kg) and lowest in Plot 5 (192.27 kg), reflecting differences in DBH and height. Below-ground biomass (BGTB) followed similar trends, ranging from 71.13 kg in

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Plot 2 to 38.45 kg in Plot 5. Consequently, total biomass was greatest in Plot 2 (426.80 kg) and lowest in Plot 5 (230.73 kg). Intermediate values were observed in Plots 3, 6, 7, and 8, indicating moderate productivity. In addition, the carbon storage mirrored biomass distribution. Above-ground carbon ranged from 0.09 tons (Plot 5) to 0.17 tons (Plot 2). Below-ground carbon was relatively consistent, between 0.02–0.03 tons across plots. Total carbon stock per plot varied from 0.11 tons (Plot 5) to 0.20 tons (Plot 2). Plots 1, 3, and 8 showed similar values (~0.16 tons), while Plots 4, 6, and 7 averaged around 0.14 tons.

**Table 2:** Comparison of mean differences among the plots from one to eight

| Plot | DBH (cm) | Height (m) | Density (gm/cm$^3$) | AGTB (kg) | BGTB (kg) | Total Biomass (kg) | Above ground carbon (t) | Below ground Carbon (t) | Total Carbon (t) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 22.16 | 12.30 | 0.88 | 289.65 | 57.93 | 347.58 | 0.14 | 0.03 | 0.16 |
| 2 | 24.04 | 13.75 | 0.88 | 355.66 | 71.13 | 426.80 | 0.17 | 0.03 | 0.20 |
| 3 | 21.56 | 13.11 | 0.88 | 278.83 | 55.77 | 334.59 | 0.13 | 0.03 | 0.16 |
| 4 | 21.29 | 13.67 | 0.81 | 256.66 | 51.33 | 307.99 | 0.12 | 0.02 | 0.14 |
| 5 | 17.42 | 12.38 | 0.88 | 192.27 | 38.45 | 230.73 | 0.09 | 0.02 | 0.11 |
| 6 | 18.98 | 14.20 | 0.88 | 243.04 | 48.61 | 291.65 | 0.11 | 0.02 | 0.14 |
| 7 | 19.96 | 14.33 | 0.88 | 254.38 | 50.88 | 305.25 | 0.12 | 0.02 | 0.14 |
| 8 | 22.29 | 12.27 | 0.88 | 277.59 | 55.52 | 333.11 | 0.13 | 0.03 | 0.16 |

**Carbon Density per Hectare:** Based on Plot 2 (highest mean carbon per tree at 0.20 tons and 8 trees), the carbon density is approximately 32 tC/ha for that specific stand structure.

## DISCUSSION

Table 1 showed the sampled Sal trees exhibited moderate variation in diameter at breast height (DBH, 20.66 cm ± 4.25) and height (13.18 m ± 2.37), reflecting a heterogeneous stand structure typical of community-managed tropical forests (Shrestha et al., 2024). Wood density was relatively uniform (0.87 g/cm³ ± 0.03), indicating species consistency and stable wood quality. Above-ground biomass (AGTB, 263.03 kg/tree) and below-ground biomass (BGTB, 52.61 kg/tree) varied considerably among trees, leading to a total biomass of 315.63 kg per tree.

In this study below-ground carbon was relatively consistent, between 0.02–0.03 tons across plots. Total carbon stock per plot varied from 0.11 tons to 0.20 tons (Table 2). This value appears well below the national average of 176.96 t/ha reported by the Department of Forest Research and Survey (2015). Mandal *et al.* (2013) found that sal-dominated forests, above-ground biomass is the most prominent carbon pool. The below-ground carbon content of 16.4% contributes to the total and agrees with the value estimated to be within the normal ranges of tropical forests (Cairns *et al.*, 1997). Aryal *et al.* (2013) found higher carbon storage in a single-species dominated forest compared to mixed forests in Gwalinidaha Community Forest, Lalitpur. Mandal *et al.* (2013) reported above-ground carbon stocks of 274.66 tC/ha in three collaborative Sal forests of Mahottari district. In hilly regions, Nepal (2006) reported carbon stock density of 186.95 t/ha in a Sal-dominated community forest of Palpa district, while Shrestha (2008) recorded 235.95 t/ha in a similar forest type. The lower values observed in the present study can be attributed to the immature forest structure, smaller DBH of trees, lower

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stand density, and the site's physiographic characteristics. There is a strong positive correlation between DBH and carbon storage; even a 4 cm increase in mean DBH (as seen between Plot 5 and Plot 1) resulted in a nearly 45% increase in carbon per tree. Factors that influence carbon cycling in forest soils include microclimate, the type of life that constitutes fauna, soil type, aridity of the environment, and forest management practices (Shrestha, 2008; Shrestha & Singh, 2008). The primary organic carbon inputs to soil come from leaf litter and root turnover that range from 50 to 200 Mg per hectare per year, depending on forest age, vegetation, and climate (Ostrowska *et al.*, 2010). Indeed, in the case of the Piple Pokhara Community Forest, it may be that the comparatively low carbon levels are due to the increased utilization of litter and residues, which will lead to reduced accumulation of organic matter in the soil, as suggested by observations made by Pandey and Bhusal (2016). Moreover, it is possible that the topography, characterized by shallow alluvial soil, may limit the development of biomass and carbon. Although the carbon density is lower compared with the national averages, the Piple Pokhara Community Forest also makes a contribution to local carbon sequestration and is part of Nepal's efforts to mitigate climate change. The management of community forests helps with the conservation of forests and improvement of carbon density. Improving management practices of forests, including enrichment planting, management of litter, and improvement of soil fertility, would also increase the potential of carbon sequestration of Sal-dominated community forests.

**Methodological Considerations**

The use of generalized allometric equations and a constant root-to-shoot ratio introduces an element of error into our calculations, although it is traditional in a cursory evaluation of carbon. Direct comparisons between the tree-specific carbon density in this study and the national average (176.96 t/ha) should be made with caution, as the latter likely incorporates additional carbon pools such as soil organic carbon (SOC) and litter, which were not within the scope of this assessment. The low value in this study is partly because it accounts only for tree biomass carbon and excludes Soil Organic Carbon (SOC) and Litter/Deadwood, which typically make up over 50% of the 176.96 t/ha national figure.

## CONCLUSION

With a mean DBH of 20.66 cm and a mean height of 13.18 m, the forest stand showed moderate structural heterogeneity. This led to an average total biomass of 315.63 kg per tree and a mean total carbon stock of 0.15 tons per tree, with above-ground components contributing the largest share (263.03 kg biomass and 0.12 tons carbon). Plot-level variation revealed that whereas smaller trees in Plot 5 (DBH 17.42 cm) stored the least biomass (230.73 kg) and carbon (0.11 tons), larger trees in Plot 2 (DBH 24.04 cm) stored the most biomass (426.80 kg) and carbon (0.20 tons). These results suggest that forest management should prioritize protecting and promoting larger-diameter trees, implement site-specific silvicultural interventions to improve growth in underperforming plots, and conduct routine monitoring to increase biomass productivity and carbon sequestration potential. Thinning operations in over-stocked areas are recommended to allow remaining Sal trees to reach higher DBH classes more rapidly, thereby maximizing the sequestration rate per individual.

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**Authors' Contribution**
R. Ojha designed the research, conducted the field work, and analyzed the data. R. Ojha, J. Shapkota and G. Kafle prepared the manuscript. G. Kafle supervised the overall research, report, and article preparation. All authors read and approved the final manuscript.

**Conflicts of Interest**
The authors declare that there is no conflict of interest regarding the publication of this manuscript.

**Ethics Approval Statement**
This study in forest ecosystems did not involve human or animal subjects. All necessary approvals for site access, and experimental activities were obtained from the appropriate authorities, in compliance with institutional and national regulations.

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