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# Contribution of deadwood and forest soil to carbon sequestration in Chitwan National Park, Nepal

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**Abstract.** *Lamichhane U, Ghimire P. 2024. Contribution of deadwood and forest soil to carbon sequestration in Chitwan National Park, Nepal. Asian J For 8: 158-164.* Deadwood and forest soil are essential components of forest ecosystems, significantly contributing to carbon (C) sequestration and climate change mitigation. This study evaluated the condition of deadwood in Chitwan National Park (CNP) and assessed the carbon sequestration potential of both deadwood and forest soil. Using the line transect method, we assessed standing and fallen deadwood, along with soil analysis. Soil samples were collected by incremental depth (0-15 and 16-30 cm). Deadwood classes were categorized into three density classes—sound, intermediate, and rotten—based on wood hardness. The study found that the total volume and biomass of deadwood were 24.66 $m^3$ $ha^{-1}$ and 12.84 t $ha^{-1}$, respectively, with a total carbon stock of 6.43 t $ha^{-1}$. Carbon stock was primarily concentrated in the intermediate class for both standing (40.57%) and fallen deadwood (43.01%). A significant difference was found between total carbon stocks in standing and fallen deadwood ($p<0.003$) in CNP forest. Total soil organic carbon (SOC) in CNP was measured at 69.64 t $ha^{-1}$ up to a 30 cm soil depth. An independent t-test revealed a significant difference in average SOC between the two soil layers ($p<0.001$). Thus, the development and implementation of regional plans for deadwood management are necessary in Chitwan National Park.

**Keywords:** Carbon sink, climate change, deadwood carbon, forest ecosystem, soil organic carbon

**Abbreviations:** C: Carbon, CNP: Chitwan National Park, $CO_2$: Carbon dioxide, GHGs: Greenhouse gases, SOC: Soil organic carbon

## INTRODUCTION

There is a global consensus that climate change is a real and rapidly advancing threat in this century, with world temperatures increasing by 0.11°C per decade since 1850 (IPCC 2023). Since 1982, this warming rate has accelerated to 0.20°C per decade, with widespread agreement that an increase above 2°C could trigger runaway climate change, severely impacting weather systems and biodiversity (USGCRP 2017; IPCC 2023). Forests play a crucial role in the global carbon (C) cycle, storing a significant proportion of atmospheric C. In forest ecosystems, biomass C and soil C are key components of C storage (Lal et al. 2015; Ghimire 2022). Depending on management practices, forests can either act as C sinks or sources. Notably, green forests have been identified as a cost-effective solution for C sequestration, aiding in the mitigation of global warming (Gren and Aklilu 2016; Raihan et al. 2019). In this context, Nepal's forests are of particular importance, and quantifying C stored across various pools contributes to global management efforts.

Deadwood, including fallen trees, branches, fragmented wood, stumps, and standing dead trees (snags), represents an essential component of forest ecosystems (Neumann et al. 2023; Stokland and Alfredsen 2024). Historically, deadwood was often misperceived as a vector for tree diseases, insect infestations, and forest fires (Kafle et al. 2019; Paletto et al. 2021; Seibold et al. 2021). However, recent studies on nutrient cycling and global warming emphasize that deadwood is critical to ecosystem biodiversity, stability, and balance (Blonska et al. 2017; Paletto et al. 2021; Neumann et al. 2023). Numerous studies have highlighted the vital role of deadwood in C storage, nutrient cycling, energy flow, and soil fertility improvement, among other benefits (Kafle et al. 2019; Seibold et al. 2021).

Soils also represent a vital C sink, significantly contributing to climate change mitigation (Lal et al. 2015; Blonska et al. 2019). Soil C sequestration captures atmospheric carbon dioxide ($CO_2$) and stores it as organic matter, which plays a critical role in reducing atmospheric $CO_2$ levels (Lal et al. 2015; Ghimire et al. 2018). In addition to offsetting anthropogenic emissions, soil C sequestration strengthens terrestrial C sinks. Globally, soil is the largest reservoir of terrestrial organic C, containing three times more C than the atmosphere and 3.8 times more than the biotic pool (Lal et al. 2015; Boubehziz et al. 2024). Consequently, soil organic carbon (SOC) stocks have a vital role in mitigating climate change as a key component of the terrestrial C cycle.

The global forest C reservoir is larger than that in the atmosphere (Lal et al. 2015; IPCC 2023). Soils worldwide contain approximately 1,500 billion tonnes of organic C, making them the second-largest active C sink after oceans, which store around 4,000 billion tonnes. Soil stores more C than vegetation (560 billion tonnes) and the atmosphere (760 billion tonnes) combined (Kafle et al. 2019; Mo et al. 2023). Thus, forestry initiatives have significant potential for reducing net greenhouse gas emissions by preventing C release from standing forests, enhancing soil management, or promoting natural regeneration of degraded areas. Deadwood is increasingly recognized as critical in C stock conservation (Seibold et al. 2015; Kafle et al. 2019; Liu and Fan 2023). For example, deadwood in the USA stores 14% of the nation's total forest C pool (Woodall et al. 2008). In Nepal's forests, out of the total C stock, tree components (live, dead standing, deadwood, and below-ground biomass), forest soils, and litter and debris account for 61.53, 37.80, and 0.67%, respectively (DFRS 2016). Kafle et al. (2019) reported 10.741 t ha$^{-1}$ of total C stock in dead wood in Parsa National Park, Nepal. According to, Subedi et al. (2015), forests in Nepal's Chitwan-Annapurna Landscape (CHAL) region have a total C stock of 540.1 million $tCO_2e$ with an average of 725.9 tCO2e ha$^{-1}$. Of the various carbon pools, the live C pool stored above and below ground is 399.6 $tCO_2e$ ha$^{-1}$, the soil is also an important pool of C with an average of 320.3 $tCO_2e$ ha$^{-1}$. Thus, deadwood contributes to sustainable forest management and mitigates climate change due to its C storage capacity (Senhofa et al. 2020; Stokland and Alfredsen 2024). In Nepal, studies focusing on non-living biomass C sequestration are very limited, yet they are critical for understanding the true C potential of these ecosystems. Given Nepal's commitment to sustainable forest management and climate mitigation under the Paris Agreement of United Nations Framework Convention on Climate Change, it is essential to assess all C pools in order to inform national and regional climate policies. This study aimed to explore the potential of deadwood and forest soil in C storage, contributing to climate change mitigation.

## MATERIALS AND METHODS

### Study area

This study was conducted in Chitwan National Park (CNP), located in south-central Nepal, spanning an area of 952.63 km² in the tropical lowlands of the Inner Terai (Figure 1). Elevations range from approximately 100 m in the river valleys to 815 m in the Siwalik Hills. Established in 1973 as Nepal's first national park, CNP holds unique ecosystems of global significance. In 1996, a 750 km² buffer zone surrounding the park, consisting of forests, private lands, and cultivated areas, was designated to enhance conservation efforts. The park contains tropical and subtropical forests, with *Shorea robusta* (Sal) forests covering around 70% of its area. Grasslands make up 20%, riverine forests 7%, and *Shorea robusta* mixed with Chirpine 3%. The riverine forests, largely in the floodplains, consist mainly of *Acacia catechu*, *Dalbergia sissoo*, and *Bombax ceiba*, while *Pinus roxburghii* is found at higher elevations. The park experiences average winter temperatures of 25°C, reaching up to 43°C during the summer (CNP 2022).

### Sampling and data collection

Deadwood sampling was conducted using a line transect method, with a total of 158 transect lines randomly laid for inventory, following methods by De Meo et al. (2019) and Neumann et al. (2023). Each transect line measured 100 m in length. Every piece of wood intersecting the line had its diameter measured, and decomposition class recorded. Only fallen deadwoods with a minimum diameter of 10 cm were measured. Wood samples were classified into three decomposition classes—sound (very hard), intermediate (hard), and rotten (soft)—determined by striking the wood with a sharp blade. If the blade rebounded, the wood was categorized as sound; if it slightly penetrated, intermediate; and if it split apart, rotten (Pearson et al. 2007).

Standing dead trees and stumps were sampled within 158 circular plots of 100 m² each, following carbon measurement guidelines by ANSAB (2010). For each plot, diameter at breast height (DBH) and height were measured. Standing dead trees were identified based on criteria from ANSAB (2010): (a) trees with branches and twigs but no leaves, (b) trees with no twigs but with small and large branches, (c) trees with only large branches, and (d) trunks without branches. These samples were classified by decomposition state using methods by Pearson et al. (2007).

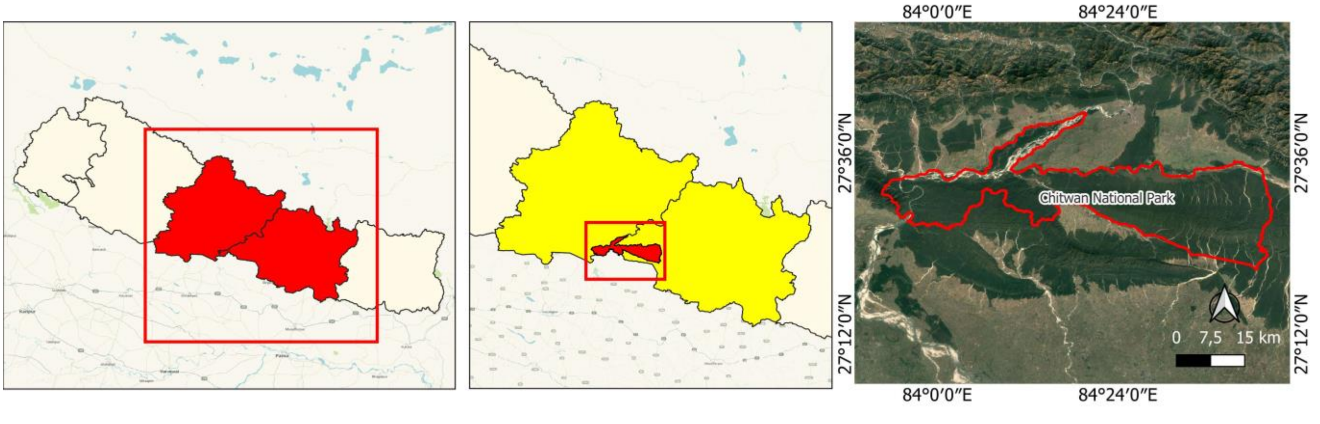

**Figure 1.** Location map of Chitwan National Park, Nepal and its buffer zone area

Soil samples were collected from 40 soil pits, with two samples taken per pit (depths of 0-15 and 16-30 cm). Each soil core sample, approximately 200 cm³, was collected using a cylindrical metal core (5 cm diameter and 5 cm length). Additional soil samples (100 g each) were taken from each depth for bulk density and organic carbon analysis. Samples were labeled and sent to a soil laboratory for further analysis (ANSAB 2010).

### Estimation of biomass and carbon stock in fallen deadwoods

The volume of fallen deadwoods per unit area was estimated for each decomposition class using the following formula (Kafle et al. 2019):

Volume ($m^3 ha^{-1}$) = $\pi^2 * [(d1^2 + d2^2 + d3^2 \ldots\ldots\ldots + dn^2)/8L]$

Where:

d1, d2, d3,…, dn: The diameter (cm) of each of the n pieces intersecting the transect line

L: The transect line length (100 m)

Average dry density of deadwoods was calculated for each class, adjusting by a proportion factor: 90% for sound, 70% for intermediate, and 40% for rotten wood (ANSAB 2010; Kafle et al. 2019). Biomass and carbon stocks were then estimated using the formula suggested by Pearson et al. (2007):

Biomass stock ($t\ ha^{-1}$) = ∑ (average dry wood density × volume of deadwoods for each decomposition class)

Carbon stock of fallen deadwoods ($t\ ha^{-1}$) = Biomass stock/2

### Estimation of biomass and carbon stock in standing dead trees and stumps

The biomass of each dead tree or stump was estimated using the allometric equation by Chave et al. (2005):

$B = 0.112 \times (\rho D^2 h)^{0.916}$

Where:

B: The biomass (kg)

ρ: The wood specific gravity ($g\ cm^{-3}$)

D: DBH (cm)

h: Tree height (m)

Biomass density for each plot was calculated, then converted to tons per hectare ($t\ ha^{-1}$) by multiplying by 10. Carbon stock densities were derived by applying the IPCC (2006) default carbon fraction of 0.47 (ANSAB 2010).

### Soil organic carbon analysis

Soil bulk density was calculated using core sampling method (ANSAB 2010). Samples were oven-dried at 105°C to adjust for moisture, then calculated as follows:

Bulk density ($g\ cm^{-3}$) = Oven dry weight of soil (g)/ Volume of the soil ($cm^3$)

Soil organic carbon (SOC) per unit area ($t\ ha^{-1}$) was measured using the Walkley-Black wet oxidation method (Walkley and Black 1934), involving oxidation by potassium dichromate and sulfuric acid, with titration of excess dichromate by ferrous ammonium sulfate. SOC stock was calculated with Chhabra et al. (2003) equation:

$SOC = \rho \times * d \times \%C$

Where:

ρ: The bulk density

d: Soil horizon depth (cm),

%C: The organic carbon percentage.

To assess variations in deadwood C stocks among decomposition classes, a one-way ANOVA was performed at a 5% significance level. Differences in SOC between soil depths were evaluated with an independent t-test at the same significance level.

## RESULTS AND DISCUSSION

### Volume of standing and fallen deadwoods

In Chitwan National Park (CNP), the volume of standing deadwoods across three decomposition classes—rotten, intermediate, and sound—was calculated. The total volume of standing deadwoods was found to be 13.40 $m^3\ ha^{-1}$. The intermediate class had the highest volume of standing deadwood at 5.44 $m^3\ ha^{-1}$, followed by the sound class at 4.92 $m^3\ ha^{-1}$, and the rotten class at 3.05 $m^3\ ha^{-1}$. Similarly, the total volume of fallen deadwoods was measured at 11.26 $m^3\ ha^{-1}$. Among the decomposition classes for fallen deadwoods, the intermediate class again had the highest volume at 4.76 $m^3\ ha^{-1}$, followed by the sound class at 3.62 $m^3\ ha^{-1}$, and the rotten class at 2.88 $m^3\ ha^{-1}$. Table 1 presents the descriptive statistics for the volume of standing and fallen deadwoods in each decomposition class within the CNP forest.

**Table 1.** Statistics of standing and fallen deadwoods volume in Chitwan National Park, Nepal

| Deadwoods category | Decomposition classes | Volume ($m^3 ha^{-1}$) | | | |
|---|---|---|---|---|---|
| | | Mean±SE | Maximum | Minimum | Total |
| Standing | Rotten | 0.163±0.044 | 0.82 | 0.02 | 3.05 |
| | Intermediate | 0.130±0.020 | 0.88 | 0.01 | 5.44 |
| | Sound | 0.082±0.018 | 0.65 | 0.00 | 4.92 |
| | Total | 0.125±0.028 | | | 13.40 |
| Fallen | Rotten | 0.082±0.015 | 0.50 | 0.02 | 2.88 |
| | Intermediate | 0.089±0.017 | 0.58 | 0.04 | 4.76 |
| | Sound | 0.117±0.022 | 0.52 | 0.01 | 3.62 |
| | Total | 0.960±0.018 | | | 11.26 |

**Table 2.** Biomass of standing and fallen deadwood in Chitwan National Park, Nepal

| **Deadwoods category** | **Decomposition classes** | **Biomass stock (t ha$^{-1}$)** | | | |
|---|---|---|---|---|---|
| | | **Mean±SE** | **Maximum** | **Minimum** | **Total** |
| Standing | Rotten | 0.085±0.016 | 0.28 | 0.01 | 1.61 |
| | Intermediate | 0.0.68±0.005 | 0.21 | 0.01 | 2.83 |
| | Sound | 0.0493±0.004 | 0.30 | 0.00 | 2.54 |
| | Total | 0.125±0.028 | | | 6.98 |
| Fallen | Rotten | 0.043±0.016 | 0.27 | 0.01 | 1.46 |
| | Intermediate | 0.046±0.008 | 0.30 | 0.03 | 2.52 |
| | Sound | 0.058±0.012 | 0.28 | 0.01 | 1.88 |
| | Total | 0.960±0.018 | | | 5.86 |

**Table 3.** Bulk density and organic carbon content on different soil depths in Chitwan National Park, Nepal

| **Attributes** | **Soil depths (cm)** | | | |
|---|---|---|---|---|
| | **0-15** | | **16-30** | |
| | **Mean** | **SE** | **Mean** | **SE** |
| Bulk density (gm cm$^{-3}$) | 1.19 | 0.01 | 1.27 | 0.01 |
| Organic carbon content (%) | 2.14 | 0.02 | 1.64 | 0.01 |

**Table 4.** Total soil organic carbon stock at different soil depths in Chitwan National Park, Nepal

| **Soil depths (cm)** | **Mean SOC (t ha$^{-1}$)** | **SE** | ***p*-value (t-test)** |
|---|---|---|---|
| 0-15 | 38.20 | 1.72 | 0.001* |
| 16-30 | 31.24 | 1.30 | |
| Total | 69.64 | | |

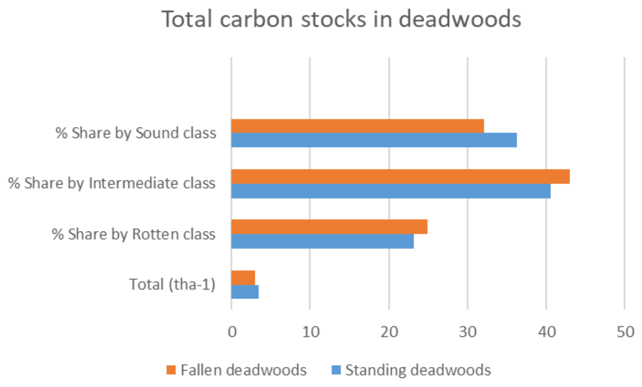

**Figure 2.** Total carbon stock in deadwoods in Chitwan National Park, Nepal

### Biomass of standing and fallen deadwoods

A total of 6.98 t ha⁻¹ of biomass was recorded in standing deadwoods and 5.86 t ha⁻¹ in fallen deadwoods. The intermediate decomposition class had the highest biomass in both standing (2.83 t ha⁻¹) and fallen deadwood (2.52 t ha⁻¹) categories. Conversely, the lowest biomass was observed in the rotten class for both standing and fallen deadwood categories (Table 2).

ANOVA results indicated no significant difference in the mean biomass stock across decomposition classes for both standing deadwood ($p>0.05$) and fallen deadwood ($p>0.05$). This suggests that the mean carbon stocks for each decomposition class contributed approximately equally within the CNP forest (Table 2).

### Total carbon stocks of deadwoods in CNP

In the CNP forest, the total carbon stock in deadwood was 6.43 t ha⁻¹, with 3.5 t ha⁻¹ contributed by standing deadwood and 2.93 t ha⁻¹ by fallen deadwood. Within the standing deadwood category, 40.57% of the carbon stock was attributed to the intermediate decomposition class, followed by 36.29% in the sound class and 23.14% in the rotten class (Figure 2). Similarly, in the fallen deadwood category, the intermediate class accounted for 43.01% of the carbon stock, followed by 32.08% in the sound class and 22.91% in the rotten class. The total carbon stock in standing deadwood was thus 1.20 times higher than in fallen deadwood. Additionally, the study found a significant difference between the total carbon stocks in standing and fallen deadwood ($p<0.003$) in the CNP forest.

### Bulk density and organic carbon content

The average bulk density in the CNP forest was 1.23 g cm$^{-3}$, with an average bulk density of 1.19 g cm$^{-3}$ in the 0-15 cm soil profile depth and 1.27 g cm$^{-3}$ in the 16-30 cm profile depth (Table 3). The highest bulk density was recorded in the 16-30 cm profile depth at 1.63 g cm$^{-3}$, while the lowest value was recorded in the 0-15 cm profile depth at 0.80 g cm$^{-3}$.

Similarly, the average organic carbon content in the CNP forest was 1.89%, with 2.14% in the 0-15 cm soil profile depth and 1.64% in the 16-30 cm profile depth (Table 3). The highest organic carbon content was found in the 0-15 cm profile depth at 2.39%, while the lowest was recorded in the 16-30 cm profile depth at 0.35%.

### Soil organic carbon stock

The distribution of mean soil organic carbon (SOC, t ha⁻¹) in both soil profile depths is shown in Table 4. The total SOC in CNP was found to be 69.64 t ha⁻¹. The average SOC was higher in the 0-15 cm soil depth, with 38.20 t ha⁻¹, while the 16-30 cm depth had a lower average of 31.24 t ha⁻¹. The quantity of SOC decreased with increasing soil depth (Table 4). The independent t-test indicated a significant difference in the mean SOC between the two soil profile depths ($p<0.001$).

Deadwoods are an important carbon (C) pool and a significant source of carbon that must be accounted for (Wijas et al. 2024). They are a vital component of forest ecosystems, contributing significantly to carbon storage and cycling, thus aiding in climate change mitigation (Moreno-Fernández et al. 2020; Liu and Fan 2023). In this study, the total biomass and C stock of standing deadwoods were higher than those of fallen deadwoods (Figure 2). The total C stock in standing deadwoods was found to be 1.20 times higher than that of fallen deadwoods. In both standing and fallen deadwoods, the proportion of biomass and C stock was predominantly dominated by the intermediate decomposition class. The intermediate class shared 40.57% of the total C in standing deadwoods, while in fallen deadwoods, it contributed 43.01%. These results are consistent with those of Kafle et al. (2019), who reported higher biomass and C stock in standing deadwoods than fallen deadwoods in Parsa National Park, Nepal. Kafle et al. (2019) also found that the intermediate class contributed the highest biomass and C stock for both standing and fallen deadwoods. Furthermore, a study by Kirby et al. (1998) in the USA reported that the volume of fallen deadwoods in British broadleaved forests was less than 20 $m^3$ $ha^{-1}$. Alberdi et al. (2020) also reported deadwood biomass of 2.92 Mg $ha^{-1}$ in the mixed forests of southwestern Europe, which is double the stock found in conifer and broadleaved forests. Understanding and preserving the role of deadwoods in carbon dynamics is crucial for sustainable forest management and global climate regulation.

Soil organic carbon (SOC) is a critical component of soil health and plays a pivotal role in forest productivity, ecosystem resilience, and the global carbon cycle (Lal et al. 2015). This study quantified SOC stocks up to a depth of 30 cm. SOC content ranged from 0.35 to 2.39% in the study area. The higher SOC content in the upper soil layers may be attributed to increased organic matter content and reduced influence of parent materials (Lal et al. 2015; Ghimire et al. 2018). The average SOC stock up to 30 cm depth was found to be 34.82 t $ha^{-1}$. The SOC stock was higher in the upper soil layers than in the lower layers. Pandey and Bhusal (2016) reported that SOC decreases with increasing soil depth in *Shorea robusta* forests of Nepal's hills and Terai regions. Ghimire et al. (2018) found SOC stocks of 24.65 t $ha^{-1}$ up to 40 cm in the *Shorea robusta*-dominated lowland forests of Makawanpur District, Nepal. In addition, SOC in the Terai and Chure regions of Nepal was estimated to be 33.66 t $ha^{-1}$ and 31.44 t $ha^{-1}$, respectively, within 30 cm depth (DFRS 2016), which aligns with the current findings of 34.82 t $ha^{-1}$. This similarity may be due to comparable physiographical locations and forest types. Bono et al. (2024) reported that temperate old-growth forests in the Dinaric Alps contain some of the largest carbon stocks in Europe, with 67 Mg C $ha^{-1}$ in dead biomass and 96 Mg C $ha^{-1}$ in soil to a depth of 60 cm. Similarly, Seedre et al. (2015) estimated 15 Mg C $ha^{-1}$ and 171 Mg C $ha^{-1}$ of C stock in dead biomass and soil, respectively, in a montane Norway spruce (*Picea abies* Karst.) old-growth forest in the Bohemian Forest, Czech Republic. Chhabra et al. (2003) found 70 Mg $ha^{-1}$ of SOC in tropical deciduous forests in India at a 1-meter soil profile depth. Compared to IPCC estimates for European mountain temperate primary forests (IPCC 2019; Yona et al. 2020), the total C stock of 328 Mg C $ha^{-1}$ is much higher than our estimate of 75.87 Mg C $ha^{-1}$, which excludes living biomass. Healthy SOC levels support diverse soil life, reduce erosion and pollution, and contribute to sustainable land management and global food security (Ghimire et al. 2023; Mo et al. 2023).

Moreover, the findings from this study consistent with global research emphasizing the significance of non-living carbon pools in forest carbon accounting. For instance, in a comprehensive study of carbon stocks across global forests, Pan et al. (2011) reported that deadwood and soil together contribute approximately 40% of the total forest carbon pool in boreal and tropical forests. Similarly, Poudel et al. (2019) reported that community managed forest of tropical area of Nepal exhibited higher carbon stock (176. 8 t $ha^{-1}$) than agricultural land (73.42 t $ha^{-1}$). The carbon stored in the forest biomass was found to be 1.5 times higher than in the forest soils. This substantial proportion under importance of including deadwood and soil carbon pools in forest carbon inventories and management strategies. By expanding the focus of carbon sequestration studies beyond live biomass, we can gain a more accurate picture of carbon storage potential, as seen in this study on Chitwan National Park.

In conclusion, this study highlights the critical roles of deadwood and forest soil in carbon sequestration within Chitwan National Park, Nepal. Deadwood, a critical component of forest biomass, serves as both a carbon sink and a reservoir, storing carbon over long periods as it decomposes slowly. Forest soils also hold large amounts of carbon through organic matter accumulation, making them essential for long-term carbon storage. Together, deadwood and forest soil are vital contributors to mitigating climate change by reducing atmospheric carbon levels. This study found that standing deadwoods contributed more carbon stock than fallen deadwoods, with the former being 1.20 times greater. Furthermore, the average carbon stock in both standing and fallen deadwoods was higher in the sound class compared to the intermediate and rotten classes. As significant carbon pools, deadwood and soil contribute meaningfully to the total carbon stock, providing long-term storage that is crucial in mitigating climate change. Findings of this study are consistent with existing research in Nepal, reinforcing the importance of incorporating deadwood and soil organic carbon into national carbon accounting. For policymakers, this study offers valuable insights for developing holistic approaches to carbon management, which are essential as Nepal targets its climate goals under the Paris Agreement. By recognizing the roles of deadwood and soil, conservation efforts can prioritize these components to maximize carbon sequestration, support forest resilience, and contribute to mitigating the effect of global warming.

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