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Assessing Tree Biomass and Carbon Stock Differences Between Sacred Groves in Kathmandu District, Nepal

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Abstract

Sacred groves, which are maintained over a long period of cultural and religious practices, are important ecological reserves that play a great role in conserving biodiversity and managing climate change. The objective of this study is to measure and compare the biomass and carbon stock in two sacred groves in Kathmandu District Swayambhu Sacred Grove (SSG) and Dakshinkali Sacred Grove (DSG) to determine the relative contribution of the two groves in the local carbon sequestration. Systematic random sampling was done to determine 89 circular plots of area 10 m radius with the help of Google Earth Image and 77 of the accessible plots were sampled (30 in SSG and 47 in DSG). Systematic records were made on diameter of tree at breast height (DBH), tree height, and species identity. Overground biomass was determined as the Chave et al. (2005) allometric model, whereas the below-ground biomass was estimated by using a standard root to shoot ratio. The total biomass was then divided into carbon stock with the IPCC carbon fraction of 0.47. Species-wise Carbon contribution was conducted to find out structural and ecological disparities between the groves. It is found in the results that there are evident differences in biomass accumulation and carbon storage between the two sites. Compared to DSG, SSG had significantly greater above-ground biomass (201.7 t/ha) and below-ground biomass (40.3 t/ha). Total carbon stock was also considerably high in SSG (113.76 ± 1.687 t/ha) compared to DSG (79.87 ± 1.113 t/ha) and statistical analysis showed that there was a significant difference between them ($p = 0.021$). Species composition analysis also indicated that SSG was even and rich in carbon with *Schima wallichii* as the dominant one, and DSG had *Pinus roxburghii* and *Alnus nepalensis* as the best dominating species. All in all, the paper emphasizes that SSG is a more developed, structurally further and efficient carbon reservoir in comparison with DSG that depicts less carbon storage since the forest structure is more homogenous.

Keywords: Allometric analaysis, carbon stock, kathmandu district, sacred groves, tree biomass estimation,

Introduction

Global warming has become one of the most topical environmental issues of the twenty-first century, which are mainly caused by the increasing levels of greenhouse gases (GHGs) emitted by anthropogenic sources, including the burning of fossil fuels, the rapid industrialization process, and deforestation, as well as the massive change in land use (Creamer & Gao, 2015; Nunes, 2023). Carbon dioxide (CO_2) is the biggest contributor of these gases since it occupies almost 76% of all anthropogenic GHG emissions (Pachauri et al., 2014). Forest ecosystems have a significant place in the global carbon cycle as they are among the largest carbon sinks, which absorb atmospheric CO_2 by photosynthesis and retain it on tree biomass and soils (Psistaki et al., 2024). Forests in the world have higher potential to store carbon than the whole atmosphere (Zhu et al., 2024), and this is why they are indispensable in climate change mitigation efforts. Nevertheless, the continued destruction of forests and their degradation are still emitting huge amounts of carbon into the atmosphere, increasing global warming and disturbing the balance of the ecological situation. Consequently, the knowledge of the distribution and amount of forest biomass and carbon stocks has become vital in the development of efficient climate alleviation and forest protection policies (Rajasugunasekar et al., 2023).

In this wider environmental scenario, a concept of sacred groves forest patches traditionally conserved by local people through indigenous cultural and religious values has come into the limelight as the ecologically important refuges that promote conservation and increase the resilience of the climate conditions (Khumbongmayum et al., 2006). Cultural norms and taboos also control these groves to limit extractive activities like timber harvesting, fuelwood gathering, and hunting so that they can preserve the features of old forests and maintain their ecological processes (Rath & Ormsby, 2020). As nature-based solutions, sacred groves are important ecosystem performers, which offer essential services such as carbon sequestration, watershed control, soil preservation, and microclimate control (Kondhalkar, 2025). Their protection over the long-term enhances the ability of regions to sequester carbon, as they have been determined to be of importance as ecological resources in combating climate change (Moradi & Shabanian, 2023).

Forests, including holy groves, are central to the process of climate mitigation by absorbing CO_2 the process of atmospheric CO_2 capture and storage in plant tissue and soils (Hurteau, 2021). Even though most sacred groves may be relatively small, they are unique ecological and cultural landscapes which are centuries old since they have been kept as sacred spaces. Sacred groves in Nepal and in particular the Kathmandu District are known to act as important sanctuaries to biodiversity, cultural heritage and environmental balance with the growing urbanism (Dhakal et al., 2021). Their carbon stocks are important to measure both local and regional carbon processes and to place these groves in new climate mitigation and carbon-finance models like the REDD+ (Sapkota et al., 2022). Moreover, the quantification of aboveground biomass and carbon storage will also add value to ecosystem service and make community more involved in conservation efforts.

Although such sacred groves are of ecological and cultural significance, there are limited studies on the scientific aspects of the carbon sequestration potential of sacred groves in Nepal (Shrestha et al., 2020; Paudel et al., 2022). Most research on the topic has concentrated on the community forests, national parks, and plantation systems (Pandey et al., 2014; Gautam et al., 2020), which is why a significant knowledge gap is seen concerning culturally preserved forest patches. This disparity is further increased in the Kathmandu District, where urbanization, fragmentation of forests, and land-use transformation are posing a great threat to available green cover areas (Shrestha et al., 2019). Nevertheless, the sacred groves like Swayambhu and Dakshinkali remain as the relics of the ancient forest due to the religious practices; hence it is in these areas that comparative ecological analysis can be carried out.

It is against this backdrop that the current study will involve a comparative study of tree biomass and tree carbon stock of two sacred groves in Kathmandu District, namely Swayambhu and Dakshinkali. The carbon storage potential of these groves is also a crucial parameter to assess the role of these groves in the urban carbon balance (Joshi et al., 2023). The objective of the study is to measure the aboveground biomass of trees and the corresponding carbon stocks as well as to compare the carbon sequestration potential of the two sites. Through the process of combining the past conservation methods with modern carbon accounting methods, the study identifies sacred groves as significant natural carbon reserves that connect cultural heritage with climate mitigation.

Materials and Methods

Study Area

The present study was carried out in Kathmandu district of Central Nepal at the Swayambhu sacred grove (SSG) and Dakshinkali sacred grove (DSG) (Figure 1). SSG is one of the holiest Chaitya of Buddhism, located to the northwest of Kathmandu, with a latitude of 27°43'1.19"N and a longitude of 85°17'15.90"E, and a height of approximately 1350 to 1405 meters. The area of the SSG is approximately 31.38 hectares (including monuments) with UNESCO declaring it a World Heritage Site in 1979. The government body that oversees SSG management is Federation of Swayambhu Management and Conservation (FSCM). DSG lies 22 kilometers south of Kathmandu at 27°37' 11"N and 85°15'04"E and 1550 meters above sea level. This is an indigenous image of the Goddess Kali, who is a caring mother and protects her devotees and children against accidents and tragedies. It is the "Dakshinkali Area Development Committee" of the local community that manages its 56 hectares. The average rainfall is 1503.11 mm annually, and the climate of the research area is 1503.11 mm, which is subtropical to lower temperate. June recorded the highest average temperature of between 19.93°C to 30.57°C, and January recorded the lowest average temperature of between 2.69°C to 20.27°C.

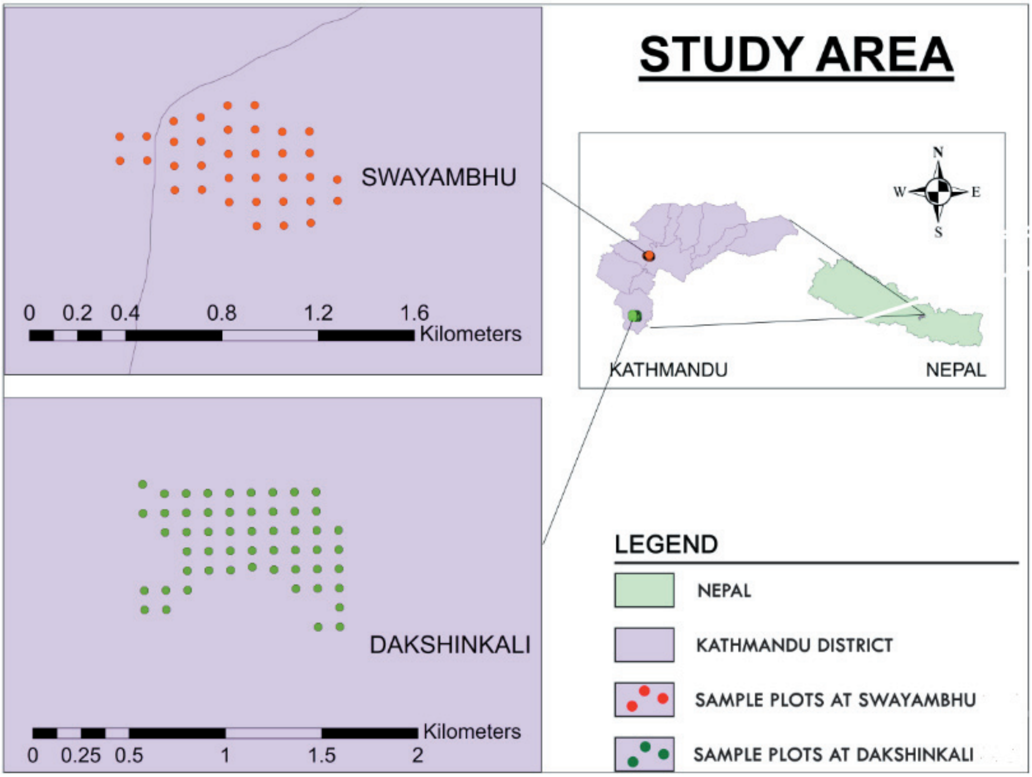

Figure 1: Study area map with sampling plots displayed.

Sampling Design and Data collection

Using the systematic random sample method, data was collected from circular plots with a radius of 10 m (area 314.2857 m2) (Shrestha et al., 2020). A total of 89 sample plots were established, 35 in SSG and 54 in DSG, across parallel transects that ran north-south at intervals of 100 meters. At SSG, there were nine parallel transects, while at DSG, there were ten. To minimize edge impact, the first plot was randomly positioned 25 meters within the forest margin (Shrestha et al., 2019). Other plots were then set 100 meters apart using Google Earth images. Using GPS coordinates that were uploaded to Garmin GPS Map64s (FRA/DFRS, 2014), 77 of the 89 sample plots (30 in SSG and 47 in DSG) were sampled by navigating the Plot Centre. Twelve plots were unreachable. To avoid counting a tree twice, the diameter of each tree within each plot was measured at breast height (1.37 m) using DBH tape. This was done starting from the eastern boundary and working inwards. A Silva clinometer and a measuring tape were used to measure each tree's height. Using standard references (Rajbhandari and Rai, 2017; Shrestha, 1998) and comparing them to specimens from the National Herbarium and Plant Laboratories, Godawari (KATH), the collected plant species were identified. Specimens were named using an annotated checklist of Nepal's blooming plants (Press et al., 2000).

Data Analysis

Above-ground tree biomass (AGTB) was estimated by using the allometric models created by Chave et al. (2005), as stated in Eq. (1).

$AGTB = 0.0509 \rho D^2 H$ Eq. (1)
Where, AGTB = above ground tree biomass (kg)

ρ = wood specific gravity (g/cm^3)
D = diameter of tree at breast height (cm)
H = height of tree (m)

Trees having a DBH of less than 5 cm were not included in the measurement of the carbon stock (Chave et al., 2005). (Zanne et al., 2009) The wood specific gravity was taken from the global database. According to Mac Dicken (1997), below-ground biomass was determined using a root to shoot ratio of 1:5 (20% of AGTB). Carbon stock densities (weight of carbon in the tree) were calculated from biomass stock densities using the IPCC (2006) carbon fraction of 0.47. The sum of above-ground and below-ground carbon stock was used to determine the total carbon stock density (in kg/m2) of trees in the sacred grove. By multiplying this figure by 10, it was transformed to tons per hectare (GoN, 2011). The carbon stock (t/ha) of all species in a forest was divided by the total carbon stock of a specific species on the same forest, as indicated in Eq. (2), to get the percentage contribution of C-stock of each species in the forest.

Carbon stock (%) = Eq. (2)
R software, the Statistical Package for Social Sciences (SPSS) version 25.0, and Microsoft Excel 2010 were utilised for all statistical analyses. Using the SPSS 25.0 edition of the program, the data was initially examined for normality (Shapiro test). The data's normality was assessed using the Shapiro-Wilk test ($p > 0.05$), and non-normal data was converted using the log transformation method prior to normality being mentioned.

Results

Contribution of Species in Tree Carbon Stock

Table 1 demonstrates the distribution of carbon stocks by species that have evident structural and ecological variations in the Swayambhu Sacred Grove (SSG) and the Dakshinkali Sacred Grove (DSG). In SSG, the major carbon-storing species is *Schima wallichii* with a contribution of 47.23 t/ha (41.51%) of total carbon stock, then *Pinus roxburghii*, with a contribution of 21.15 t/ha (18.59%). Several broadleaf species like *Ficus benjamina*, *Pyrus pashia*, *Stranvaesia nussia*, and *Grewia optiv*a, have a more balanced and diverse distribution of carbon with a contribution of between 2 to 7%. The abundance of many species with smaller yet significant proportions implies that SSG has a mixed and mature forest structure of high ecological complexity. This multi-species contribution pattern shows that the grove is long-term safe and in quite undisturbed state, which helps to accumulate biomass in a stable condition.

Conversely, two species dominate the pattern of carbon stock in DSG with *Pinus roxburghii* alone having a carbon stock of 41.49 t/ha (51.96%), and *Alnus nepalensis* having a carbon stock of 16.23 t/ha (20.32%). These two species have a percentage of over 70 of the total carbon stored in the grove, which implies a more uniform composition of the forest. The rest of the species contribute less than 2% each with a low biomass distribution among other species. Some of the species like *Castanopsis indica*, *Celtis Australis*, *Choerospondias axillaris*, and *Zizyphus incurva* play minor roles but bring out some ecological contrasts of SSG. All in all, DSG has a focused carbon stock structure mainly represented by rapid growing or structurally dominant species, which implies that it has different regeneration patterns, management effects, and ecological regimes than SSG.

Table 1: Species-wise Tree carbon stock (t/ha) and percentage contribution in SSG and DSG.

S.N	Name of species	SSG C stock (t/ha)	CS (%)	DSG C stock (t/ha)	CS (%)
1	*Pinus roxburghii* Sargent	21.15	18.59	41.49	51.96
2	*Schima wallichii* (DC.) Korth.	47.23	41.51	9.52	11.92
3	*Alnus nepalensis* D. Don	–	–	16.23	20.32
4	*Pyrus pashia* Buch-Ham.ex D.Don	7.44	6.54	0.36	0.44
5	*Castanopsis indica* (Roxb.) Miq.	–	–	2.85	3.57
6	*Myrsine capitellata* Wall.	–	–	0.66	0.83
7	*Rhododendron arboreum* Sm.	–	–	0.24	0.3
8	*Ficus benjamina* L.	8.1	7.12	–	–
9	*Lyonia ovalifolia* (Wall.) Drude	–	–	0.22	0.27
10	*Grewia optiva* J. R. Drumm. ex Burret	2.49	2.18	–	–
11	*Stranvaesia nussia* (D. Don) Decne.	7.37	6.48	–	–
12	*Syzygium cumini* (L.) Skeels	3.38	2.97	0.01	0.01
13	*Prunus cerasoides* D. Don	1.04	0.92	0.01	0.01
14	*Fraxinus floribunda* Wall.	3.38	2.97	0.04	0.05
15	*Choerospondias axillaris* (Roxb.) B. L. Burtt & A. W. Hill	3.45	3.03	1.2	1.5
16	*Zizyphus incurva* Roxb.	0.63	0.56	1.22	1.53
17	*Sapium insigne* (Royle) Benth. ex-Hook. f.	–	–	0.21	0.26
18	*Osmanthus fragans* Lour.	2.27	2	–	–
19	*Pinus patula* Scheide. ex Schltdl&Cham.	–	–	1.04	1.3
20	*Rhus succedanea* L.	–	–	0.01	0.01
21	*Ficus benghalensis* L.	0.37	0.33	–	–
22	*Castanopsis tribuloides* (Sm.) A. DC.	–	–	0.27	0.34

23	*Sapindus mukorossi* Geartn.	0.08	0.07	–	–
24	*Cinnamomum tamala* (Buch.Ham.) Nees & Eberm.	0.05	0.05	–	–
25	*Saurauia napaulensis* DC.	–	–	0.05	0.06
26	*Morus macroura* Miq.	0.19	0.17	–	–
27	*Ilex excelsa* (Wall.) Hook. f.	0.37	0.32	0.19	0.24
28	*Acer oblongum* Wall. ex-DC.	1.49	1.31	–	–
29	*Ficus lacor* Buch-Ham.	1.36	1.19	–	–
30	*Ligustrum* sp.	0.03	0.03	–	–
31	*Flacourtia* sp.	1.31	1.15	–	–
32	*Myrica esculenta* Buch-Ham. ex D. Don	–	–	0.13	0.16
33	*Albizia procera* (Roxb.) Benth.	–	–	0.11	0.14
34	*Melia azederach* L.	0.17	0.15	0.06	0.07
35	*Grevillea robusta* A. Cunn. ex R. Br.	0.26	0.23	0.08	0.1
36	*Celtis australis* L.	0.01	0.01	1.49	1.86
37	*Jacaranda mimosifolia* D. Don	–	–	0.15	0.18
38	*Maclura cochinchinensis* (Lour.) Corner	0.09	0.08	–	–
39	*Pinus wallichiana* A. B. Jacks.	–	–	0.02	0.02
40	*Ficus religiosa* L.	0.01	0.01	–	–
41	*Lagerstroemia indica* L.	0.01	0.01	–	–
42	*Bauhinia variegata* L.	0.02	0.02	0.02	0.02
43	*Xylosma controversum* Clos	0.01	0.01	–	–
44	*Michelia champaca* L.	0.002	0.001	–	–
45	*Persea duthiei* (King ex Hook. f.) Kosterm.	–	–	0.44	0.55
46	*Phyllanthus emblica* L.	–	–	0.74	0.92
47	*Eucalyptus* sp.	–	–	0.19	0.24
48	*Betula alnoides* Buch-Ham. ex D. Don	–	–	0.41	0.51
49	*Eurya acuminata* DC.	–	–	0.04	0.06
50	*Alangium chinense* (Lour.) Harms	–	–	0.1	0.13
51	*Casuarina equisetifolia* L.	–	–	0.05	0.07
52	*Quercus glauca* Thunb.	–	–	0.03	0.04
53	*Rhus* sp.	–	–	0.01	0.01
54	*Cedrus deodara* (Roxb. ex D. Don) G. Don	–	–	0.01	0.01
55	*Albizia lebbeck* (L.) Benth.	–	–	0.004	0.01
56	*Rhus javanica* Miller	–	–	0.003	0.003
57	*Maesa chisia* Buch-Ham. ex D. Don	–	–	0.003	0.003
	Total	**113.76**	**100**	**79.87**	**100**

(Source: Field Study,2022)

Tree Biomass and Carbon Stock

Figure 2 represents comparison of above-ground, below-ground and total tree biomass at the Swayambhu Sacred Grove (SSG) and Dakshinkali Sacred Grove (DSG). The findings indicate that SSG has significantly higher storage of biomass in all its parts. In the case of above-ground biomass, SSG measures about 201.7 t/ha, which is quite significant compared to 141.6 t/ha in DSG. It means that SSG can sustain bigger or thicker tree stands, which may reflect the state of mature forests and a lesser level of anthropogenic disturbance. The same trend is reflected in underground biomass. About 40.3 t/ha is contained in SSG and 28.3 t/ha in DSG, indicating that the root biomass is also higher in SSG and the size and complexity of its trees are larger. The total biomass is 242.05 t/ha in SSG and 169.93 t/ha in DSG when above-ground and below-ground values are added together. This disparity indicates a much greater overall biomass accumulation in SSG and, therefore, greater ecological stability, greater productivity, and greater ability to sequester carbon as opposed to DSG.

Total tree carbon stock measured from this study was 113.76±1.687 t/ha for SSG and 79.87±1.113 t/ha for DSG (Table 1). The mean value of tree carbon stock was 3.792 t/ha and 1.997 t/ha respectively in SSG and DSG. There was significant difference ($p = 0.021$) in mean values of tree carbon stock between two sacred groves.

Figure 2: Above-ground tree biomass, below-ground tree biomass and total tree biomass of Swayambhu sacred grove (SSG) and Dakshinkali sacred grove (DSG).

Discussion

The distributions of the carbon stocks of species in the two sacred groves show some glaring ecological differences that are related to the forest structure, age, and composition of the species. The large carbon percentage of *Schima wallichii* and large input of such species as *Ficus benjamina*, *Pyrus pashia* and *Stranvaesia nussia* suggest a structurally intricate mature forest in Swayambhu Sacred Grove (SSG). Investigations in the Central Himalayas indicate that the carbon stock in biomass is highly controlled by stand structure and species diversity, and bigger trees and mature stands are the most important sources of carbon (Kaushal & Baishya, 2021). The widespread dispersion of carbon across numerous species in SSG indicates a long-term stable forest regime with minimal disturbance a strategy consistent with the observation of structurally heterogeneous forests providing more carbon storage by reason of the increase in resource-use productiveness and the stratified canopies (Poudel et al., 2025).

In comparison, *Pinus roxburghii* (51.96%), and *Alnus nepalensis* (20.32) are highly skewed in their distribution of carbon in Dakshinkali Sacred Grove (DSG). The result of this domination of fewer species is a composite forest with fewer species that is more homogenous, with most of the biomass carbon reaching out to a small number of fast-growing or disturbance-tolerant species. This trend agrees with findings that in structurally simpler forests a minor fraction of the species can explain over half of the carbon stocks (Kaushal & Baishya, 2021). The small involvement of other species in accumulating carbon at DSG is perhaps due to the historical disturbance, selective regeneration or ecological limitations which some species prefer over others in the ecosystem. Notably, these low species diversity and concentrated biomass could be detrimental to ecological stability in the long term since less species contribute to forests, making them more susceptible to pests, diseases and climatic stress (Obonyo & Tsingalia, 2023).

The significant variation of total carbon in the tree stocks 113.76 ± 1.687 t/ha SSG and 79.87 ± 1.113 t/ha DSG highlights the extent to which structural and compositional variables are manifested in the carbon storage capacity. This is further proven by the fact that the mean carbon stock per unit of sampling in SSG (3.792 t/ha) is almost twice that of DSG (1.997 t/ha). These high values at SSG agree with the finding that mature stands with large trees, compositions and preserved conditions hold more carbon (Chave et al., 2005). In addition to this, the results of the research in Nepal support the claim that carbon density is heavily influenced by forest structure, species composition and site conditions (Pandey et al., 2020). The outcomes of this work lead one to the consideration of sacred groves as important resources not only about cultural value but also regarding their valuable role as carbon reservoirs under the current carbon-accounting schemes.

Lastly, these findings are in line with the biomass quantification: SSG registered much higher above-ground biomass, below-ground biomass, and total biomass than DSG. An increase in above-ground biomass implies large tree size and maturity whereas an increase in below-ground biomass implies developed root systems which are characteristic of stable and longstanding stands (Shrestha et al., 2019). In comparison, the accompanied lower biomass values at DSG could signify younger stands, reduced structural complexity or past disturbance. These findings support the literature that articulates that both stand maturity and structural heterogeneity are major carbon stocks predictors (Poudel et al., 2025). In totality, the comparison of the two groves meets the objective of the study to compare the potential of the carbon sequestration, and the integration of the traditional protected groves and modern carbon accounting could show the variation in the sequestration capacity and serve as a guide in identification of specific conservation techniques.

Conclusion

This research study has brought out a distinct ecological and structural difference between Swayambhu Sacred Grove (SSG) and Dakshinkali Sacred Grove (DSG), which causes significant differences between the tree biomass and carbon storage capacities of the two sacred groves. SSG showed much more above-ground, below-ground and total biomass, indicating that there were larger and older and structurally complex tree stands. This diversity of the forest also enhanced even distribution of carbon among various broadleaf species, which strengthens the argument that SSG is a mature and ecologically stable patch of forest. Conversely, it was found that DSG had two main species, *Pinus roxburghii* and *Alnus nepalensis*, with most of its carbon stocks which are highly concentrated into only two species, implying a more homogenous stand structure that might be the result of a historical disturbance or selective regeneration. The research also presents some new quantitative data wherein SSG accumulates significantly greater carbon than DSG with total carbon stocks amounting to 113.76 1.687 t/ha in SSG and 79.87 1.113 t/ha in DSG. This difference was further illustrated by the mean carbon stock of trees per plot whereby, SSG trees contained almost twice the amount of carbon compared to DSG. The statistically significant difference ($p = 0.021$) proves that the species composition, forest maturity, and structural complexity are significant factors of carbon sequestration in sacred groves of Kathmandu District.

These findings provide valuable novel information on the difference between culturally secure forests concerning ecological functions and potential in carbon storage. SSG is proven to be a superior natural carbon storage compared to others as it is richer in species, more mature and well distributed biomass. On the contrary, carbon accumulation capabilities of DSG are constrained by the monopoly of a select few species. This comparative evidence highlights the fact that not every sacred grove is equally effective in sequestering carbon and that any management interventions designed to increase the species diversity and complexity may greatly increase the carbon storage of DSG. In general, the research identifies the acute importance of sacred groves as the type of localized climate-mitigating properties and the necessity of site-specific conservation policies. The research offers first-hand quantitative data on these two groves, which makes the scientific foundation of the integration of sacred groves in urban forest management and carbon-accounting systems more robust in Kathmandu Valley.

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