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Synergy between Carbon and Biodiversity in Restored Forests: A case from leasehold forestry of Nepal

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ABSTRACT

Studies on forest carbon stock have increased in Nepal, especially in community forests, as a result of worldwide recognition of the role of sustainable forest management in climate change mitigation. Leasehold forests, which contribute greatly to reviving degraded forests and livelihoods of pro-poor communities, however, have been sidelined from such studies. This study assessed the biomass carbon stock of leasehold forests and its relationship with tree diversity in the Nawalpur district in Nepal. The concentric sample plots with subplots were laid, measuring trees (8.92m radius), saplings (5.64m radius), and regeneration (1m radius), in eleven leasehold forests. Plant diversity was calculated using the Shannon–Wiener diversity index (H') to assess forest conditions. The average carbon stock was found to be 11.40 t/ha, where the stock varied by nature of intervention. The average carbon stock in non-tree-based restoration sites was estimated to be 3.81 t/ha, which was significantly lower than in tree-based restoration sites (14.49 t/ha). A total of 37 species of trees were recorded from 45 sample plots distributed across eleven LFUGs. Spearman's rank-order correlation coefficient between forest carbon stock and diversity index was 0.613, which shows a strong positive correlation and was significant at a 99% confidence interval. There was a synergy between biomass carbon stock and tree diversity because communities were protecting the existing tree species and planting multipurpose trees to meet their need for forest products. The study concludes that leasehold forestry contributes positively to the enhancement of carbon stock and tree diversity.

Introduction

Deforestation and forest degradation are two of the major factors for carbon emission as they account for about 18% of total anthropogenic carbon emissions (Paudyal et al., 2018).

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Forests play an important role in mitigating climate impacts by sequestering carbon. Forest biomass, deadwood, litter, and soil (litter decomposition and rhizome deposition) are the major carbon pools of forests (Maraseni et al., 2011; Ruiz-Peinado et al., 2017). Protection of forests, minimizing forest disturbance, reforestation (Nave et al., 2018; Pandey et al., 2014a), and enhancing forest growth are the major strategies to increase carbon stock in the forest ecosystem.

Thus, conservation and sustainable forest management can effectively contribute to mitigating the impact of climate change through enhancement of carbon sequestration potential of the forest ecosystems and reduction in carbon emissions (Price et al., 2011; Sharma et al., 2011). Forest restoration activities might significantly enhance the carbon sequestration capacity of the forest; however, overemphasis on enhancing carbon sequestration capacity of forest might undermine other ecosystem goods and services provided by the forest, including plant diversity (Pandey et al., 2014; Poudel et al., 2014).

The Government Nepal promotes different participatory forest management systems, including leasehold forestry, for restoring forests in the country.

Leasehold forestry is promoted with the twin objectives of reducing poverty and restoring forests. Studies have shown that this programme has contributed greatly to improving the household income of the poor communities as well as restoring forests (Ohler 2003; Baral et al., 2012; Poudyal et al., 2018; Kafley and Pokharel 2017; Yadav et al., 2018). Improved forest conditions can contribute greatly to carbon sequestration and might provide a platform for carbon trade (Dhungana, 2008), which will supplement the income of the users. Very few works have assessed the carbon storage potential of leasehold forests to give us an idea of the contribution of leasehold forests to carbon sequestration. Most of the studies have been carried out in community forests (CFs) (Shrestha et al., 2010; Aryal et al., 2018, Aryal et al., 2013; Pandey et al., 2014b; Maraseni et al., 2014; Aryal et al., 2018; Joshi et al., 2020). Though both community forestry and leasehold forestry fall under the community-based forest management system, carbon stock in these forest management regimes might vary as a result of different management prescriptions (Gurung et al., 2015). With a paucity of literature exploring the carbon stock in leasehold forests, findings of this paper provide baseline information on the contribution of leasehold forests to carbon sequestration. The issue of climate change has been at the forefront of scientific studies and global discussions, and assessment of carbon stock in different management regimes is of utmost importance for developing countries like Nepal to benefit from carbon-related initiatives. Furthermore, there is a need for analysing the trade-offs and synergies among a range of environmental goods and services provided by forests as these goods and services do not always go hand in hand.

Considering this, we assessed the forest carbon stock at three pools, viz. aboveground tree biomass, belowground tree biomass, and above ground sapling biomass, and the variation of carbon stock with respect to restoration activities. Furthermore, we analysed trade-offs and synergies between tree species diversity and carbon stock to assess how restoration activities support environmental services enhancement.

For estimating the total carbon stock in different restoration plots, all sample plots were stratified into three classes based on three restoration activities, i.e. tree plantation (6 plots), Amriso (grass) cultivation (13 plots), and protection of existing primary forest, ie *Shorea robusta* and *Schima-Castanopsis* forest (26 plots). The average carbon stock is then estimated for these three categories and compared between practices. Finally, we assessed whether the carbon stock and tree diversity in leasehold forests are complementary or not by analysing their trade-offs and synergies.

Study Area

This study was carried out in eleven LFUGs in Nawalpur district, Gandaki province, Nepal, as the district has a long history of leasehold forest management. Leasehold forests that were handed over at least five years ago were selected. Furthermore, we selected leasehold forests in clusters as the size of individual LFUGs is quite small (about 4 ha). Adjoining smaller tracts of individual leasehold forests were clustered together to form single leasehold forest clusters. We consulted with Divisional Forest Office (DFO) of the Nawalpur district for identifying the LFUGs that met the above criteria. Eleven LFUGs were distributed in three clusters, viz. Jharnakhola cluster (Barhaben, Bojhadi, and Jharnakhola LFUG), Pangre cluster (Jhirubhanjyang, Marjheldnanda, Kajithumka, and Daitegaira LFUG) and Deurali cluster (Chilaunednada, Dumsilum, Lupchegaira, and Tinkhande LFUG) (Figure 1). Details of each LFUG are presented in Table 1.

Table 1: Details of LFUGs selected for the study

S. N.	LFUG	Forest area (ha)	Sampled area (1% SI)	No. of plots
1	Barhaben	5.4	0.054	2
2	Bojhadi	2.9	0.029	2
3	Chilaunedanda	7.3	0.073	3
4	Daitegaira	18	0.18	7
5	Dumsilum	7	0.07	3
6	Jharnakhola	4.5	0.045	2
7	Jhirubhanjyang	16	0.16	6
8	Kajithumka	18	0.18	7
9	Lupchegaira	7	0.07	3
10	Marjheldanda	17	0.17	7
11	Tinkhande	7.2	0.072	3
12	Total	110.3	1.103	45

Note: SI is the sampling intensity

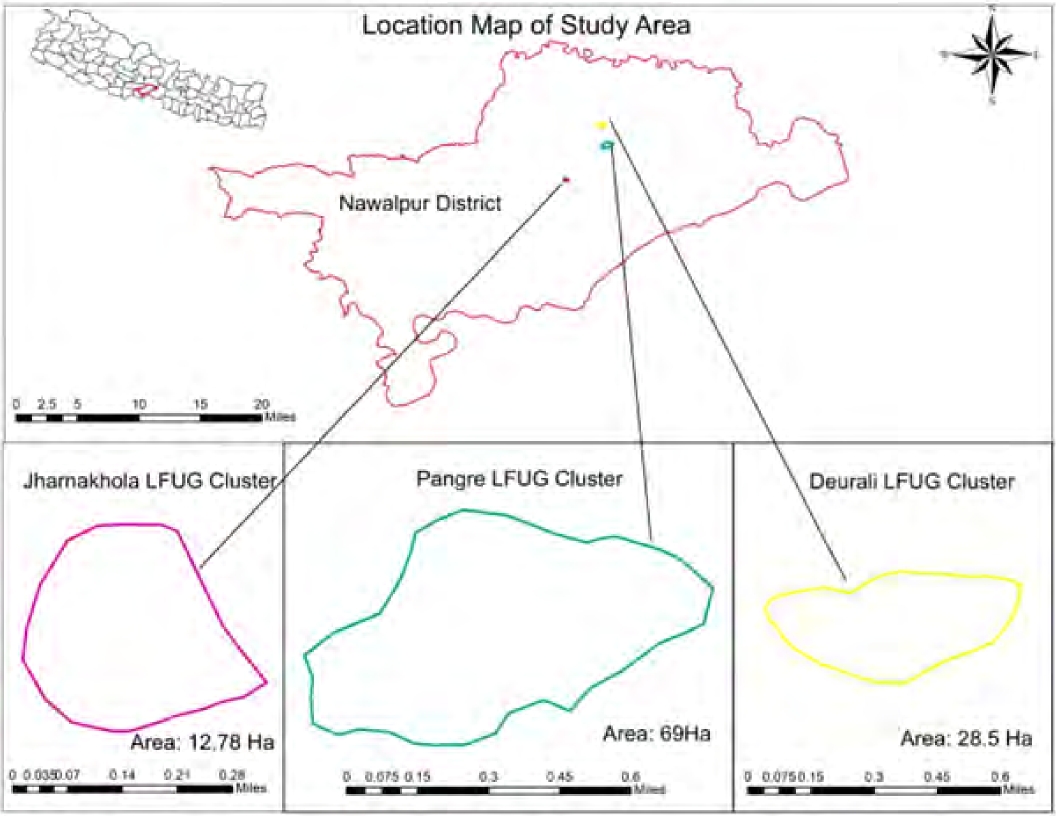

Figure 1: Map of the study area

Among these LFUGs, Jharnakhola, Barhaben, and Bojhadi are located in a tropical zone with an altitude range of 346masl to 381masl. Jharnakhola LFUG is characterized by the presence of degraded Shorea robusta forest. In the case of Barhaben and Bojhadi forests, fodder species (especially *Ficus sps*) and grasses are prevalent. All other LFUGs are located in the subtropical zone with the dominance of degraded *Schima-Castanopsis forest* and Amriso *(Thysanoleana maxima)*, cultivated for improving the livelihood of users and restoring degraded forests. The LFUGs range in elevation from 1,055 masl to 1,250 masl. Collection of forest products, e.g. grasses, fodder, leaf litter, and fuelwood, is prevalent in all eleven LFUGs. These LFUGs are actively involved in forest restoration activities in the form of protection of existing primary forests and plantations of tree species and commercial grass with assistance of DFO and non-governmental organizations.

Data collection

A carbon inventory was carried out in April 2021 following the guidelines on measuring the carbon stock in community forests (ANSAB/FECOFUN/ICIMOD, 2010). In each LFUG, sample plots were laid out systematically, taking 1% sampling intensity (Lama et al., 2013), comprising a total of 45 sample plots (Table 1). Concentric circular sample plots with three radii were established for measuring trees, saplings, and seedling characteristics (Table 2). Environmental variables, including slope, aspect, elevation, and types of vegetation, were also recorded in each plot.

Table 2: Data collection in each concentric sample plot

S. N.	Variables	Plot radius (m)	Data collection
1	Trees (DBH ≥ 5cm)	8.92	Species name, DBH, Height
2	Saplings (1-5cm DBH)	5.64	Species name, DBH
3	Regeneration (<1cm DBH)	1	Species name, and its number

Methods

Aboveground tree biomass (AGTB) and aboveground sapling biomass (AGSB) were calculated by using the allometric equation developed by Chave et al. (2005) and Tamrakar (2000) respectively (Table 3). In each sample plot, the total AGTB obtained by summing the AGTB of each tree was divided by the area of the sample plot to obtain the biomass stock per unit area, which was then converted into biomass stock per ha. Belowground tree biomass (BGTB) was calculated by using a root to shoot ratio of 1:5 (Mac Dicken, 1997). Biomass stock was calculated for AGSB and BGTB as in the case of AGTB. All biomass stocks were then multiplied by an IPCC default fraction of 0.47 to convert the biomass stock into carbon stocks (IPCC, 2006). Finally, the total carbon stock of the plot was calculated by adding three carbon pools (AGTB, BGTB, and AGSB).

Table 3: Allometric equations to calculate AGTB and AGSB carbon stock

Variables to measure carbon stock	Allometric equations
Aboveground Tree Biomass (AGTB)	0.0509*wood specific gravity*(dbh)2* total height (Chave et al., 2005)
Aboveground Sapling Biomass (AGSB)	Log (AGSB) = a + b log (D) (Tamrakar, 2000) D = over bark diameter at breast height
BGTB	AGTB/5
Total Biomass Stock	AGTB+BGTB+AGSB
Total Carbon Stock (TCS)	Total Biomass Stock*0.47

Analysis of Forest Condition

Plant diversity, tree density, regeneration density, sapling density, and volume of growing stock were calculated for assessing forest condition. Plant diversity was estimated using Shannon–Wiener diversity index (H’). Density of trees, regeneration and saplings were calculated following Yadav et al. (1987).

$$\text{Tree density (number per ha)} = \frac{Total\ number\ of\ trees\ in\ all\ plots}{Total\ number\ of\ plots * size\ of\ the\ plot\ (m2)} * 10{,}000$$

Density of regeneration and saplings was calculated accordingly.

Volume of growing stock was calculated by using DBH, height and form factor (0.5), where, Volume (V) = $\frac{\pi d2}{4} * height * form\ factor$

Only trees were considered for calculating Shannon–Wiener Diversity Index (H) in each plot following Aryal et al. (2018).

$$H = -\sum p_i \ln p_i$$

Where, p_i is the proportion of i^{th} species

For estimating the total carbon stock in different restoration plots, all sample plots were stratified into three classes based on restoration activities, i.e. tree plantation (6 plots), Amriso (grass) cultivation (13 plots), and protection of existing primary forest, i.e. *Shorea robusta* and *Schima-Castanopsis* forest (26 plots). Sample plots were also classified into two restoration categories, i.e. tree-based restoration activities and non-tree based restoration activities on the basis of incorporation of trees in restoration activities. Tree plantation plots and protection of existing primary forest plots were under tree-based restoration category whereas Amriso cultivation plots were under non-tree-based restoration category. Average carbon stock was then estimated for these categories and compared between practices.

Trade-offs and synergies between total carbon stock and tree species diversity, i.e. Shannon–Wiener Diversity Index (hereafter diversity), were assessed following Rana et al. (2017) to identify plots that had high or low values for both total carbon stock and diversity (positive and negative synergy respectively) or had high value for total carbon stock and low value for diversity or vice versa (trade-off) (Figure 2). First, we computed the correlation coefficient between the total carbon stock and diversity using Spearman's correlation coefficient to determine the strength of association between total carbon stock and diversity across all plots. Five categories, viz. zero (0), weak (0.01–0.3), moderate (0.31–0.60), strong (0.61–0.90), and perfect (0.91–1.00), were used to assess the strength of association between these two variables (Dancey and Reidy, 2007). Then, we analysed trade-offs and synergies between these two variables following Luck et al. (2009). For this purpose, we first standardized the numerical values of carbon stock and diversity for each plot using Z-score so that the values of each attribute (carbon stock and diversity) had a mean of zero and a standard deviation of one. After that, we calculated the median value for each of the two variables (carbon stock and diversity) to determine the threshold value. Then, we used this threshold value to determine if the value of these two variables was high or low (i.e. above or below the median value respectively) for each plot. Finally, we plotted the values in pair-wise comparisons to identify plots with trade-off and synergy (Figure 2). The total numbers of plots showing trade-off positive synergy and negative synergy were examined. Furthermore, a number of plots showing trade-offs and synergy between total carbon stock and diversity under different restoration activities were examined.

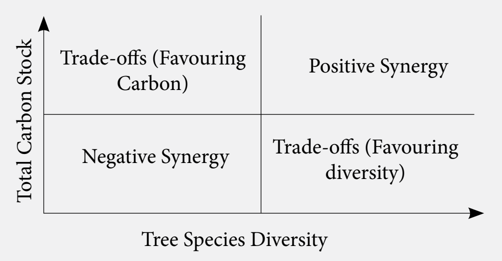

Figure 2: Framework for assessing the trade-offs or synergies between total carbon stock and tree species diversity. Solid black lines represent the median values. The top left quadrant represents forests with high carbon values (above the median value for carbon) but low values for diversity (below the median value for plant species diversity).

Results

Forest Stand Conditions

A total of 37 species of trees (n = 318), saplings (n =187), and seedlings (n = 60) were recorded from 45 sample plots distributed across eleven

LFUGs. Tree stem density, i.e. the number of stems (DBH ≥ 5cm) per hectare (ha), was found to be 333, which shows the forest condition to be very poor in terms of tree density. Sapling density was found to be 400 per ha whereas the regeneration density, i.e. the number of regenerations per ha, was found to be 3325. Average growing stock of stem (DBH ≥ 5cm) was found to be 73.6 m^3 per ha. S*chima wallichi, Ficus hispida, Calicarpa arborea,* and *Shorea robusta* were the dominant tree species, with relative density of 25.47, 12.58, 9.12, and 6.92 respectively. Tree species with the highest biomass were *(Schima wallichi, Shorea robusta, Engelharida spicata,* and *Callicarpa arborea),* with the value of 8273.86, 4510.62, 2159.81, and 1651.28 kg respectively. Mean height of the trees was found to be 6.13 m, with an average dbh of 13.60 cm.

Forest Carbon Stock

Average carbon stock (t/ha) in AGTB, BGTB, and AGSB was found to be 9.22, 1.85, and 0.35 respectively (Table 4). The average of the total carbon stock of these three carbon pools was found to be 11.40 t/ha. The total carbon stock in the three pools in the eleven LFUGs was found to be 1,257.42 tons, of which AGTB, BGTB, and AGSB accounted for 1,016.97, 204.05, and 38.61 tons of carbon. AGTB contributed the highest (80.88%) to the total carbon stock and AGSB contributed the lowest (3.07%). Out of 45 plots, one plot had total carbon stock (t/ha) of zero, 20 plots had carbon stock between 0 and 5, 11 plots had carbon stock between 5 and 10, and the remaining 13 plots had more than 10 to/ha of total carbon stock.

Table 4: Average Carbon Stock (t/ha) at different pools

Carbon Pools	Min	Max	Average	Std. error
Above Ground Tree Carbon stock	0	41.4	9.22	1.57
Below Ground Tree Carbon Stock	0	8.3	1.85	0.31
Sapling Carbon stock	0	3.29	0.347	0.076
Total Carbon Stock	0	49.89	11.4	1.885

Forest carbon stock at different restoration sites

Three restoration activities (tree plantation, Amriso cultivation, and protection of primary forest) were identified for estimating carbon stock at different restoration sites. Out of the total sample plots, 13 plots were subjected to non-tree-based restoration activities and the remaining 32 were subjected to tree-based restoration activities. Average carbon stock in the non-tree-based restoration sites was estimated to be 3.81 t/ha, which was significantly lower than in tree-based restoration sites (14.49 t/ha), with a p value of 0.009 at 99% confidence interval. Among the three restoration sites, the highest forest carbon stock was found in the primary forest plot (16.05 t/ha), followed by tree plantation plots (7.69 t/ha), and the Amriso cultivation site had the lowest carbon stock (3.81 t/ha) (Figure 3).

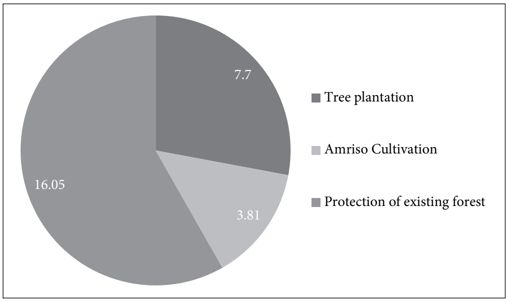

Figure 3: Average of total carbon stock (t/ha) in different restoration plots

Trade-off and Synergy between forest carbon stock and diversity index

We found a total of 32 tree species in the 45 sample plots. Average Diversity Index (Shannon–Wiener Diversity Index) was found to be 0.289 (range 0–0.76) with standard error of 0.036. Average diversity index in tree plantation site, Amriso cultivation site and protection of existing forest restoration site were found to be 0.51, 0.16, and 0.30 respectively. Spearman's rank order correlation coefficient between forest carbon stock and diversity index was found to be 0.613, which shows a strong positive correlation, and it was significant at 99% confidence interval. This means plots with high tree diversity had higher carbon stock. Correlation coefficient between these variables in tree plantation site, Amriso cultivation site and protection of existing forest restoration site were found to be 0.77 (p value 0.072), 0.838 (p value 0.0003; sig. at 0.01 level), and 0.525 (p value 0.006; sig. at 0.01 level) respectively. Thus, tree diversity and carbon stock were strongly correlated in the tree plantation site and Amriso cultivation site while the relationship was moderate in the case of protection of existing forest restoration site.

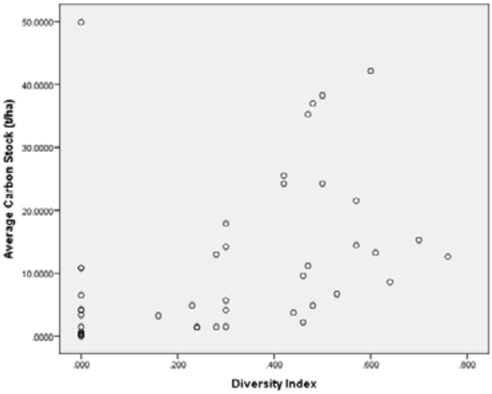

Figure 4: Scatter plot between plot level average carbon stock (t/ha) and diversity index

Regarding trade-offs and synergies between the forest carbon stock and diversity, most plots (35) showed synergy and a few (10) showing trade-offs (Figure 5).

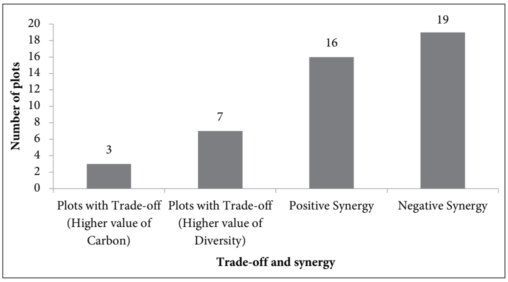

Figure 5: Trade-off and synergy between carbon stock and tree species diversity

In the Amriso cultivation site, most of the plots (10) showed negative synergy, indicating both lower diversity and lower carbon stock. In the case of the primary forest site, most plots showed positive synergy, which indicated that such forests support high diversity and high carbon stock (Table 5).

Table 5: Trade-offs and synergy in different plot types

Site category	Total Plots	Plots with High Diversity	Plots with High Carbon stock	Plots with Positive Synergy	Plots with Negative Synergy
Trees plantation	6	0	1	4	1
Amriso cultivation	13	1	1	1	10
Primary Forest	26	6	1	11	8

Discussions

We found very low carbon stock (11.4t/ha) in three carbon pools in the study leasehold forests. Regular lopping of trees for livestock rearing and incidence of high frequency of small-sized trees due to initial stage of forest restoration might be the reason for this low value as the level of disturbance in the forest affects the biomass and carbon content of the forest (Brown et al., 1997; Wang et al., 2001; Keith et al., 2009). Carbon stock in the three pools estimated in our study is higher than in other leasehold forests studied by Lama and Mandal (2013) in Dolakha district and Shrestha et al. (2013). LFUGs in our study area have been actively involved in forest restoration activities through the planting of tree species, protection of existing forests, and cultivation of commercial species, which might have resulted in higher carbon stock than in other degraded leasehold forests.

We found lower carbon stock in the Amriso cultivation and tree plantation sites. Removal of inferior tree species to make room for the cultivation of Amriso might have resulted in low carbon stock as those plots were composed mostly of scattered trees and some were devoid of trees. Fewer trees consequently lead to lower tree species diversity and lower carbon stock. We ran multivariate regression by taking the carbon stock as the dependent variable and the diversity index and the number of trees as the independent variables. We found that an increase in the number of trees by one unit resulted in increase in carbon stock by 62%, which was significant at 5% confidence interval. The tree plantation sites had slightly better carbon stock compared to the Amriso cultivation site as the promotion of trees in the former site resulted in higher carbon stock. Carbon storage in Nepal's forests is higher in old growth and well-protected natural forests and lower in degraded or recently regenerated secondary forests (Ranabhat et al., 2008; Pandey et al., 2014b; Gurung et al., 2015), which is consistent with our findings as we found higher carbon stock in primary forest plots compared to the regenerating forest plots. Moreover, regular lopping of fodder trees and preponderance of younger commercial tree species might have resulted in lower carbon stock in the tree plantation sites compared to the primary forests.

Our study indicated a positive relation between the forest carbon stock and tree diversity. Previous studies on the relationship between the carbon stock and diversity have shown mixed results. Similar to our findings, Wang et al. (2013), Behera et al. (2017), and Bhusal et al. (2019) found a positive relation between carbon stock and tree diversity. Whereas, Sharma et al. (2010), Aryal et al. (2013), Kimaro and Lulandala (2013), Mandal et al. (2013), and Aryal et al. (2018) found an inverse relation of carbon stock with tree diversity. In our study area, the plots mostly had few trees, thereby having lower carbon stock and, consequently, lower species diversity, which might be the reason for the positive relation between carbon stock and tree diversity. Moreover, some plots were devoid of trees, which resulted in the absence of carbon stock and tree species diversity.

The relationship between carbon and biodiversity varies across time and space as a result of spatial heterogeneity and disturbance regimes (Cardinale et al., 2000). Several studies (Chhatre and Agrawal, 2009; Visseren-Hamakers et al., 2012; Law et al., 2015) have demonstrated trade-offs between carbon and plant diversity. However, our study showed a synergy between carbon and plant diversity. This synergy might be due to the initial phase of forest restoration, which has enhanced both tree diversity and carbon stock of forests. Another reason could be the nature of leasehold forests as these forests are still in poor condition, leading to low diversity and low carbon stock. Wherever restoration activities have been carried out, the increase in tree cover has resulted in higher carbon stocks and, consequently, higher diversity. This finding is in line with that of Pedro et al. (2015), who stated that high plant diversity may enhance ecosystem resilience, thereby generating greater biomass, leading to higher carbon sequestration. Kunwar and Adhikari (2007) also highlighted the improved forest condition of leasehold forests through planting of tree species and promotion of natural regeneration. The negative synergy shown by majority of plots in the Amriso cultivation site might be due to the removal of tree species from such plots, which has resulted in lower carbon stock and lower tree species diversity. This suggests that such interventions might not be sustainable in the long run as a result of decreased ecosystem services in terms of tree diversity and carbon sequestration. However, it should be noted that the cultivation and selling of Amriso has contributed to improving the economic condition of the users of LFUGs within a short period of time. We found a positive synergy between carbon and tree diversity in primary forests and the tree plantation sites, which highlights the role of forest restoration activities in enhancing the ecosystem services. Thus, instead of mono-cultivation, the emphasis on planting of diverse trees and promotion of existing regeneration (Lu et al., 2017) might be a promising alternative to enhance the environmental services and ensure long-term sustainability of leasehold forests as appropriate management practices can optimize ecosystem services (Canadell and Raupach, 2008: Aryal et al., 2018). Monoculture plantations could have detrimental impacts on biodiversity (Acharya 2004; Shrestha et al., 2010), and enhancing both biodiversity and carbon storage potential of the forest is possible if forest managers explicitly take biodiversity into account (Pandey et al., 2016 and 2017; Strassburg et al., 2009; Thomas et al., 2013). Conservation of primary mature forests helps in maintaining higher levels of aboveground biomass carbon and biodiversity simultaneously (Gibson et al., 2011). This is consistent with our results as we found higher carbon stock and higher tree diversity in plots with primary forests, i.e. *Shorea robusta* and *Schima-Castanopsis* forests.

Conclusion

Through improvements in management practices and restoration activities, environmental services, including carbon sequestration and biodiversity conservation, can greatly be enhanced, as evident from the higher carbon stocks in the present study. However, the carbon storage potential of leasehold forests is very low. As in other forest management modalities, the carbon storage potential of leasehold forests was found to be affected by site characteristics and management practices. Protection and promotion of tree-based forest restoration activities have higher potential for delivering greater environmental services than restoration based on a single species, although the latter may provide higher economic returns in the short term. We found a synergy between carbon stock and tree diversity because of the leasehold forests providing carbon sequestration and diversity services in a lesser amount due to their poor condition. Moreover, in the initial phase of forest restoration, the increase in tree cover has the potential for increasing both carbon storage and diversity of the forest, thereby creating synergy between these two services. Thus, we recommend adoption of forest restoration activities by promoting the revival of existing degraded forests and planting of diverse trees for optimizing environmental services of leasehold forests than through planting of mono species. In this study, we only estimated the biomass carbon stock and analysed its relationship with diversity and forest restoration activities. Further study is required to estimate carbon stocks in other carbon pools, including soil, and to assess the relationship of total carbon stock with other environmental and anthropogenic variables.

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