

## forest policy

# Assessments of Biodiversity, Carbon, and Their Relationships in Nepalese Forest Commons: Implications for Global Climate Initiatives

Harisharan Luintel, Robert M. Scheller, and Randall A. Bluffstone

Assessments of forest carbon, biodiversity, and their relationships have become important, particularly to devise effective approaches to forest policy and management, particularly in the context of emerging carbon-forestry. We measured forest data and estimated biodiversity and carbon from 620 plots across Nepal and found an average of  $3.67 \pm 0.09$  effective numbers of plant tree species (eH') per plot (250m<sup>2</sup>) and  $98.30 \pm 4.19$  Mg ha<sup>-1</sup> Above Ground Tree and Sapling Carbon (AGBC). Our results indicated highly variable biodiversity and carbon across plots, indicating the potential for additional biodiversity and carbon storage. For instance, the plots in the upper quartile of eH' had 5 times greater mean eH' ( $6.89 \pm 0.30$ ) compared to the plots in the lowest quartile ( $1.21 \pm 0.08$ ). Similarly, the plots in the top quartile of the AGBC had 18 times higher mean AGBC ( $244.19 \pm 16.45$  Mg ha<sup>-1</sup>) compared to the plots in the lowest quartile ( $11.09 \pm 1.25$  Mg ha<sup>-1</sup>). We found >80% carbon occurs in 10 dominant species. Our results reflect the complex and varied relationships of carbon and biodiversity across different forest categories. We found weak positive correlations between biodiversity and carbon storage ( $P < 0.27$ ) and small significant coefficients of biodiversity indices with AGBC, indicating the absence of tradeoff or weak possibility for synergy between carbon-forestry and biodiversity conservation. Our results reinforce the need of biodiversity safeguards in carbon-forestry.

**Keywords:** biodiversity, carbon, forest, Nepal, REDD+, species

Climate change and biodiversity loss are two potentially interlinked, contemporary environmental crises of global magnitude, each posing serious risks to human well-being and ecosystem function (Metz et al. 2007, Millennium Ecosystem Assessment 2005). To address such issues, the global community has put in place agreements such as the United Nations Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity (CBD). These initiatives recognize the contributions of forests to carbon storage and biodiversity conservation and highlight the importance of forest management and forest health monitoring at the national scale. Particularly, the management of tropical forests has been prioritized, as they are both major terrestrial carbon sinks and biodiversity hotspots (Pan et al. 2011, Parmentier et al. 2007, Phillips et al. 1998). Recently, concerns have been raised that carbon-focused forestry, for example

Reducing Emissions from Deforestation and Forest Degradation (REDD+) under UNFCCC, could compromise biodiversity conservation by increasing deforestation of diverse forests and converting natural forests into less diverse plantations (Canadell and Raupach 2008, Miles and Dickson 2010, Secretariat of the Convention on Biological Diversity [SCBD] 2011). However, less attention has been given to jointly considering both carbon storage and biodiversity conservation; rather, biodiversity enhancement has often been considered an “ancillary benefit” from achieving carbon storage goals (Diaz et al. 2009).

The literature suggests variable positive relationships between biodiversity and ecological services. For instance, Folke et al. (1996) and Tilman et al. (2012) documented the significance of [functional] biodiversity to ecological services (e.g., above-ground biomass) at a large scale through time. By providing more functional

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variations in biotic communities, biodiversity buffers against environmental variability, because declining capacity, or loss, of any one species is offset by the growth of more resilient species that withstand diverse environmental conditions, helping stabilize the ecosystem (Folke et al. 1996, Fridley 2001, Schlapfer et al. 1999, Schwartz et al. 2000). Biodiversity promotes complementarity in utilizing different resources, such as through niche partitioning and facilitation, that allow different species to increase overall ecosystem production, while dominant species may competitively exclude other species (Loreau and Hector 2001, Paquette and Messier 2011, Warren et al. 2009). Biodiversity and ecological services have varying degrees of correlations across scale (e.g., negative at the population level and steadily stronger as one moves up in the scale such as community and ecosystem levels) (Balvanera et al. 2006). Such relationships vary across time and space due to spatial heterogeneity and disturbance regimes (Cardinale et al. 2000). Such buffering of biodiversity could be uncertain or fail, particularly in the context of rapidly changing environment (including land use change, human use of species, and climate change), as the extinction of biodiversity is projected to be ten times more than the current rate (MEA 2005).

Forest biodiversity may alter carbon storage by influencing the magnitude, turnover rate, and longevity of carbon storage in soil and vegetation (Diaz et al. 2009). Caspersen and Pacala (2001) demonstrated positive correlations between species diversity and carbon storage. However, there is inadequate empirical knowledge about the relationship between biodiversity and carbon storage, particularly in tropical forests; either synergies or trade-off may predominate (Diaz et al. 2009, Midgley et al. 2010, Szwagrzyk and Gazda 2007, Thompson et al. 2011). This knowledge gap hinders the ability of forestry stakeholders interested in creating synergies between the CBD and REDD+ initiatives.

We assess biodiversity and carbon storage and explore their relationships at the national level in Nepal and across elevations, slopes, and canopy covers, and tested the hypothesis that plot-level biodiversity and carbon are positively correlated. These research findings have the potential to inform forestry stakeholders, who prepare REDD+ policies and programs, about the possibility of effective, integrated ways of dealing with the dual environmental challenges of biodiversity conservation and carbon storage. Knowledge about biodiversity, carbon, and their relationships in different forest types at national and regional scales forms the basis to simultaneously promote biodiversity conservation and carbon storage (Gardner et al. 2012, Midgley et al. 2010, Miles and Dickson 2010, Sharma et al. 2010, Strassburg et al. 2010). Such knowledge also informs understanding about the effects of various forest management activities on ecosystem function (Woodall et al. 2011).

Nepal is a particularly appropriate country to investigate the relationship between forest carbon and biodiversity. For instance, Nepal has been actively participating in CDB and the REDD+ preparation processes. It also possesses a high gradient of biodiversity, with over 3% of the world's known flora and 1% of all fauna despite only 0.1% of the total land area (Ministry of Forest and Soil Conservation [MoFSC] 2014). Such a gradient and level of biodiversity is attributed to its location at the crossroads of the Indo-Malayan and Palearctic biogeographic regions and the wide range of geographic diversities (e.g., 16% high elevation Himalaya, 68% middle hills, and 17% lowland plains referred to as Terai) and climatic variations (e.g., tropical to Alpine) (MoFSC 2014) in the country. Moreover, forest management and utilization practices

also influence the level of biodiversity (e.g., Acharya 2004, Pandey 2007). Similarly, Nepal also possesses a high gradient of carbon storage, higher in old growth, well-protected natural forests in the Terai and lower in degraded forest and/or recently regenerating secondary forests in mid-hills (e.g., Gurung et al. 2015, Pandey et al. 2014). Moreover, the dependence of approximately 28 million people on 5.8 million hectares of forest for ecosystem services, such as forest products and watershed services, poses challenges to biodiversity conservation and carbon storage and thereby adds dynamism in the biodiversity and carbon relationships.

We assess different dimensions of biodiversity (e.g., richness, abundance, and evenness) and carbon storage, and explore their relationships in the Nepalese forest commons. Forest commons—forest resources that are held in common, not owned privately, and accessible to all members of a society—constitute the major part of Nepalese forestry and primarily constitute community forests (CFs) managed and used by local communities and non-CFs (NCFs) that are loosely managed by government or communities but used by local communities. To implement the study, we collected data from 130 forest commons throughout the nation (i.e., 42 out of 75 districts) from February to May 2013. Realizing that global or regional estimates of carbon storage and biodiversity are less useful to achieve our research goals, particularly to inform national policymakers and local forest managers, we use inventory-based carbon and biodiversity measurements. In addition to the national level, we also analyzed the data across altitude, slope, and canopy cover, as these levels of analyses provide regionally/locally useful information for forest managers.

## Methods

### Data Sources and Sampling Methods

We collected data from 130 forest commons in collaboration with ForestAction Nepal, a non-profit located in Katmandu. These forest commons include 65 CFs that are owned and actively managed by local communities and 65 NCFs that are owned and loosely managed by the government, but traditionally used by local communities; these categories make up the major types of forest

### Management and Policy Implications

In the context of mounting concerns about sustainable environmental health, our assessments of Nepalese forest biodiversity, carbon, and their relationships offer insights for researchers, policymakers, and practitioners at global, national, and local levels. It is evident that Nepalese forest commons offer the potential for increased carbon storage and biodiversity conservation and therefore contribute to the emerging global policy initiatives such as Reducing Emissions from Deforestation and Forest Degradation, sustainable management of forests, conservation of forests, and enhancement of forest carbon (REDD+), and Convention on Biological Diversity (CBD). As carbon and biodiversity fluctuate across altitudes, slopes, and canopy covers, they are critical factors to be considered for planning and implementing forestry projects at the local level. As more than 80% carbon is accumulated in less than a dozen species, and weak positive correlation exists between biodiversity and carbon, safeguards are critical for biodiversity conservation under carbon-forestry. To make such safeguards effective, dedicated policy and institutional arrangements, careful site-specific planning of silvicultural activities, proper implementation, and periodic monitoring of forestry projects are required.

management structures in Nepal (Figure 1). Our interest in this paper is not to compare the results across CFs and NCFs, but to instead identify relationships between biodiversity and carbon with less emphasis on management. The selected CFs were part of a national representative random sample from MoFSC (2013). As we did not have information about NCFs beforehand, we were not able to select the NCFs randomly. Therefore, we selected NCFs in consultation with district forest office staff members. Such forests were not next to CFs, to avoid being used simultaneously by the same communities. No forest commons are currently being explicitly managed for Above Ground Tree and Sampling Carbon (AGBC) and/or plant diversity, but are instead managed primarily for provisioning services, such as fuelwood production/supply and watershed services.

To determine the required number of statistically valid sample plots to be analyzed in our 65 CFs and 65 NCFs, we selected a total of 45 “pre-sample” plots. Such plots constitute three concentric circular plots with different radii for collecting environmental data and measuring trees (>5cm diameter at breast height [DBH]), saplings (1–5cm DBH), and counting seedlings, which are suitable for moderate to dense vegetation and are widely used (MacDicken 1997, 54, MoFSC 2010, 24). The trees and environmental data were measured in 8.92 m. radius plots, and data related to saplings and seedlings were measured in 5.64 m. and 1 m. radii plots, respectively. Data related to plant diversity, such as name of species and their frequency of occurrence, were also collected from those plots. We placed those plots in nine CFs across physiographic regions to capture the most heterogeneity possible in plot basal area, a proxy for forest biomass. Then we deployed a field team to measure the diameter at breast height (DBH) of trees and saplings and estimated basal area per plot. Using the data we collected from the pilot survey and standard formula of Saxena and Singh (1987)

(equation 1) and considering variance of basal area at 10% error and 95% confidence level, we estimated that 650 sample plots were required for nationally representative samples.

$$N = C_v^2 t^2 / E^2 \tag{1}$$

where, N = Required number of sample plots;  
 $C_v$  = Coefficient of variation,  $s/\mu$  ( $s$ = standard deviation and  $\mu$ = sample mean);  
 E = Standard error,  $s/\sqrt{n}$  ( $n$ = sample number);  
 t = Value of t-distribution for (n-1) degrees of freedom and 95% confidence

We placed 3 to 7 sample plots randomly in each forest based on the quintile of the forest size (vertical projected area) distribution. We placed more samples in bigger forests than smaller to capture higher diversity of larger forests. As forest size in the hills (i.e., 1000–3000 m. elevation) is markedly smaller than in the Terai (i.e., flat, productive Gangetic plain in the southern part of Nepal bordering to India, which is <1000 m. in elevation), we considered different quintile ranges for the hills and Terai (Table 1). The map and size of CFs was available in forest operational plans, while such information was absent for NCFs. Therefore, the field team carried out forest boundary surveys of NCFs using Geographic Positioning Systems (GPS), prepared forest maps, and estimated forest areas. The estimated required numbers of sample plots in the CFs, i.e., 325 were randomly allocated in the 65 CFs chosen. Same criteria were followed to allocate the sample plots in the chosen NCFs, but due to field implementation difficulties the field team was able to collect data from a total of 295 sample plots. The field teams divided the forest maps into smaller grid cells, and randomly selected the required number of plots in each forest. Then the X and Y coordinates of the center point of selected cells were identified, which were fed

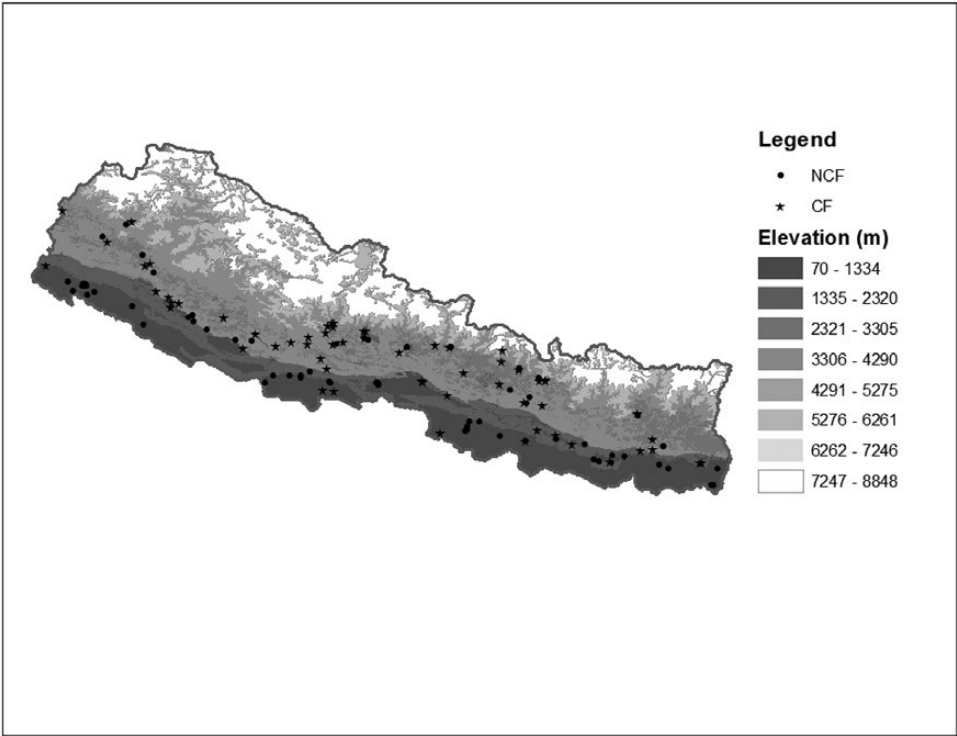


Figure 1. Distribution of forest commons (both CFs and NCFs) samples across the country.

**Table 1. Distribution of sample plots in community forests.**

Quintile distribution	Forest size (ha)		Sample plots per forests	No. of forests	No. of plots
	Hill	Terai			
1 <sup>st</sup> quintile	<18	<113	3	13	39
2 <sup>nd</sup> quintile	18–64	113–154	4	13	52
3 <sup>rd</sup> quintile	64–91	154–335	5	13	65
4 <sup>th</sup> quintile	91–183	335–526	6	13	78
5 <sup>th</sup> quintile	≥183	≥526	7	13	91

into a GPS unit. Finally, by using the GPS, the field team located the plots in the forests.

### Description of Data Variables

We collected a range of data related to individual trees, saplings, and seedlings, as well as more general environmental factors. All trees, saplings, and seedlings were identified by their local and/or scientific names, and their frequencies (numbers) were counted in each plot. In addition, circumference at 1.37 m height (in cm) of saplings and trees was measured using linear tapes. For trees, height (in m) was measured by using clinometers. While the plot-wise information regarding the name and count of species is indispensable to identifying biodiversity indices, the circumferences and heights are essential to estimate carbon storage. Trees were used to estimate biodiversity, while saplings and trees were used to estimate AGBC.

From each sample plot, data on elevation (m), slope (degree), and canopy cover (%; the percentage of total ground area of the plot covered by the vertical projection of tree crowns) were also collected, as these variables affect AGBC and biodiversity (Ensslin 2015, Gandolfi et al. 2007, Maren et al. 2015, Rahbek 1995). It is equally important to control elevation, slope, and canopy cover while exploring relationship between AGBC and biodiversity. In addition, information about forest area (hectare), fuelwood collection, forest fire, and management regime (CF or NCF) was also gathered to use these variables in our data analysis, as these provide context and at times mediate effects of disturbances and therefore affect forest composition and productivity.

### Assessment of Forest Carbon and Biodiversity

To estimate AGBC, different methods (e.g., biome average, remote sensing, and forest inventory) are available with their benefits, limitations, and levels of uncertainty. For instance, biome average and remote sensing are highly uncertain due to their fairly generalized nature, lack of properly sampled data, and saturation of spectral indices at relatively low AGBC (Gibbs et al. 2007). On the other hand, forest inventory methods are relatively inexpensive (due to their low-tech nature) and can estimate AGBC with known level of accuracy and precision (Gibbs et al. 2007, Intergovernmental Panel on Climate Change [IPCC] 2006). We used forest inventory-based methods in this study due to our limited access to resources.

Despite the fact that there are various pools of carbon, we examine only AGBC, as it is a major and dynamic forest carbon pool. Recent studies using estimates of AGBC have indicated a growing potential for tropical forests to serve as carbon sinks (Baker et al. 2004, Lewis et al. 2009, Pan et al. 2011, Phillips et al. 1998). The AGBC storage in shrub and litter pools jointly in Nepalese Terai forest is less than 1% (Gurung et al. 2015). Though carbon

in the soil is much more significant, we were not able to measure it due to logistical and resource limitations.

To estimate AGB from the forest inventory data, different site-specific and/or species-specific allometric models were prepared based on the power-law relationship of AGB with tree diameter and height. The accuracy of such models has been questioned, as mechanical and physiological limits to an increase in tree height at large diameters lead to over-estimation of biomass (Chave et al. 2005, Niklas 1995). However, incorporation of wood-specific gravity in the model provides AGB estimates with better accuracy and precision (Brown et al. 1989, Chave et al. 2005, Djomo et al. 2010). Such wood gravity varies across regions (Nogueira et al. 2007).

As our sample forests are diverse in terms of tree and sapling species, a region-specific mixed species tree biomass regression model is required, as the form of tree and allometric relationships is expected to be different for different regions due to changes in genetic, biotic, and environmental factors (Vielledent et al. 2012). However, region-specific models are not available for Nepalese forests and therefore we use Chave et al.'s (2005) models, which (i) were prepared using a large global dataset of trees across different climatic conditions, (ii) have been widely used and gave accurate tree biomass estimates for Madagascar (Vielledent et al. 2012), and are recommended by the Nepalese government for forests in Nepal (MoFSC 2010). As Chave et al. (2005) suggested, we used equation (2) in dry forests, where <1500mm average annual rainfall occur, and equation (3) in moist forests, where 1500–4000mm average annual rainfall occur, to estimate Above Ground Biomass (AGB); these equations over estimate 0.5–6.5% AGBC (Chave et al. 2005).

$$\text{AGB (kg)} = 0.112 * (\rho * D^2 H)^{0.916} \quad (2)$$

$$\text{AGB (kg)} = 0.0509 * \rho * D^2 H \quad (3)$$

where

$\rho$  = Specific gravity of wood ( $\text{g m}^{-3}$ );

$D$  = DBH (cm) (calculated by dividing circumference by  $\pi$  i.e. 3.14);

$H$  = Tree height (m).

We used the following Nepal-specific biomass model developed by Tamrakar (2000) to estimate the green biomass of individual saplings:

$$\text{Log (AGSB)} = a + b \log (D).$$

where

$\log$  = natural log [dimensionless];

AGSB = above-ground sapling biomass [kg];

$D$  = over bark diameter at breast height in cm (measured at 1.3 m above ground); and

$a$  and  $b$  = constants.

We used species-based wood-specific gravity recommended by Jackson (1994) to calculate biomass. Where such information was unavailable, we used general values derived from the average specific gravity of associated species (same genus and family) within a forest type (Baker et al. 2004, Ngugi et al. 2011). We then converted the green biomass into dry biomass by multiplying by species-wise fractions or the average of associated species identified in the literature. We used the fractions 0.627, 0.613, 0.58, 0.57, 0.545, 0.517, 0.5, and 0.45 for *Quercus* species, *Lyonia ovalifolia*,



*Pinus roxburghii*, *Alnus nepalensis*, *Schima wallichii*, *Shorea robusta*, *Terminalia tomentosa*, and *Pinus wallichiana*, respectively (Bhatt and Tomar 2002, Jain and Singh 1999, Kataki and Konwer 2002, Shrestha et al. 2006, Wihersaari 2005). For unidentified species, or for which wood density information was not available, we use the overall mean wood density obtained from the database of species analyzed in this study (Baker et al. 2004).<sup>1</sup>

Despite the fact that carbon content in wood varies substantially, we used the fraction 0.5. This fraction, though an oversimplification, is widely promulgated as a generic value for wood to estimate carbon (Lamlom and Savidge 2003) and was also used by other researchers for Asian moist forests (e.g., Ajtay et al. 1979, Brown and Lugo 1982). This value falls within the range of values different scholars have suggested. For instance, IPCC (2006) suggested different fractions (0.46–0.55) for different types of forests to convert dry biomass into carbon. Similarly, Thomas and Martin (2012) suggest that carbon content in wood ranges 41.9–51.6% in tropical species, 45.7–60.7% in subtropical/Mediterranean species, and 43.4–55.6% in temperate/boreal species. Such variation is caused due primarily to the tissue types available in the heartwood, sapwood, and small branches (Jones and O'Hara 2012, Martin et al. 2015).

We checked the names of all tree and shrub species for orthography and synonymy and calculated plot-wise (250 m<sup>2</sup>) biodiversity indices to reflect different salient features: species richness (*S*) to account for the number of tree species present, Shannon Wiener index (*H'*) to account for *S* and abundance of tree species, effective number of tree species (*e<sup>H'</sup>*) to account for *S* and *H'* in an unbiased and easily interpretable form, and Shannon equitability index (*E<sub>sw</sub>*) to account for the evenness of tree species.

We simply counted the number of tree species present in a plot and found the *S*. Using equation (4), we calculate *H'*, which positively correlates with the number and evenness of tree species and takes a value of zero when there is only one species and a maximum value when all species are present in equal abundance (Mohan et al. 2007).

$$H' = -\sum_{i=1}^S p_i \ln p_i \quad (4)$$

where *S* = species richness;

*i* = individual species;

*p<sub>i</sub>* = individuals of one species (*n*) divided by the total number of individuals of all species in a plot (*N*);

$\Sigma$  = sum of the calculations.

We transformed *H'* to *e<sup>H'</sup>*, which is the number of species present if all species were equal in abundance. This transformation is an unbiased estimate of a diversity index (Beck and Schwanghart 2010) and reduces inaccuracies when comparing diversity across plots (Jost 2006). We use *e<sup>H'</sup>* as the primary biodiversity index in our analysis.

We calculated *E<sub>sw</sub>*, which normalizes *H'* to a value between 0 and 1 (1 = evenness) for each plot by using equation (5).

$$E_{sw} = eH' / \ln S \quad (5)$$

We assess forest and tree characteristics, including AGBC and biodiversity indices, for the national average and across elevations, slopes, and canopies, as they are important aspects to account for forest health and management decisions, and identify the species that constitute the highest amount of AGBC in many Nepalese

forest commons. We utilize a regression model to see the impact of tree attributes, forest management regime, disturbances, and environmental variables on tree diversity.

## Relationships Between Carbon and Biodiversity

We calculate Spearman's correlations between different biodiversity indices (i.e., *S*, *H'*, *e<sup>H'</sup>*, and *E<sub>sw</sub>*) and between biodiversity indices and AGBC for overall forests and forests of different elevations, slopes, and canopies (e.g., for this we divided forests into lower (<1000m) and higher (≥1000m) elevations, lower (<15°) and higher (≥15°) slopes, and open (<50%) and closed (≥50%) canopies). We then develop linear regression models with AGBC (Mg ha<sup>-1</sup>) as the dependent variable and different biodiversity indices as independent variables, controlling for management/ownership status of forest, fuelwood collection, fire, average tree DBH, average tree height, tree density, forest area, elevation, slope, and canopy cover (equation 6).

$$Y = \beta_0 + \beta_1 (X_1) + \dots + \beta_n (X_n) + \varepsilon \sim N(0, \sigma^2) \quad (6)$$

where

*Y* = the dependent variable, AGBC

*X<sub>1</sub>* ..... *X<sub>n</sub>* = the predictor (biodiversity indices) and/or controlled variables (i.e., CF status, presence of fuelwood collection, occurrence of forest fire, average tree DBH, average tree height, tree density (number of trees per hectare), forest area, elevation, slope, and canopy cover)

$\beta_0$  = the intercept, the value of the function when *X<sub>1</sub>*.... *X<sub>n</sub>* = 0

$\beta_1$ ... $\beta_n$  = the slope of the fitted line representing the rate of change in AGBC for each unit change of *X<sub>1</sub>*....*X<sub>n</sub>*

$\varepsilon$  = error term accounting for variation not attributed to the relationship between dependent variables and predictor and/or controlled variables, which is a normally distributed random variable with a mean of 0 and variance  $\sigma^2$

Finally, we check diagnostics for each model by looking at residual plots. A relatively flat line of residual versus fitted values indicated linearity of residuals. Most of the residuals appeared normal except at the upper end. We calculated Cook's distance, which confirmed that no observations exhibited strong influence on the model and therefore no outliers were detected. A relatively flat line of standardized residuals versus fitted values showed a constant variance, indicating homoscedasticity. Finally, we found < 4 variance inflation factors for each model (except in the closed canopy, where it was 4.77), indicating little to no multicollinearity.

## Results

### Current Status of Biodiversity and Carbon

We present forest and tree attributes in Table 2. A total of 264 (57.4%) plots are in the Terai region, and the remainder are in the hills. Altogether, we recorded 324 species. The mean plot *S*, *H'*, *e<sup>H'</sup>*, and *E<sub>sw</sub>* were  $4.54 \pm 0.11$ ,  $3.67 \pm 0.09$ ,  $0.99 \pm 0.02$ , and  $0.32 \pm 0.01$ , respectively. Given the small plot sizes, *S*, *H'*, and *e<sup>H'</sup>* seemed to be moderately diverse, while *E<sub>sw</sub>* was relatively low. AGBC across elevations, slopes, and canopy covers also show that the 95% confidence intervals of mean *e<sup>H'</sup>* across elevations and slopes broadly overlap. Sizes of standard errors (SE) increase with elevations or slopes, except in the 1500–2000 m elevation class and in the 20–30-degree slope class, indicating increased variance at

higher elevations and slopes. Similarly, the 95% confidence intervals of  $e^H$  overlap across canopy cover classes except 0 to <25% class. The 155 plots within the upper quartile of  $e^H$  had 5 times greater mean  $e^H$  ( $6.89 \pm 0.30$ ) compared to the 155 plots in the lowest quartile ( $1.21 \pm 0.08$ ), indicating a high degree of variation in biodiversity across plots.

We estimate an average of  $98.34 \pm 4.19$  Mg ha<sup>-1</sup> AGBC. The 155 plots in the top quartile of the AGBC distribution had 18 times higher mean carbon ( $244.19 \pm 16.45$  Mg ha<sup>-1</sup>) compared to the 155 plots in the lowest quartile ( $11.09 \pm 1.25$  Mg ha<sup>-1</sup>), indicating high AGBC variation across plots.

The plots falling in the top quartile of the AGBC distribution had a higher mean  $e^H$  ( $4.15 \pm 0.37$ ) compared to plots in the lowest quartile of the AGBC distribution ( $2.81 \pm 0.33$ ), indicating a difference in  $e^H$  between plots with higher and lower AGBC. Among 155, only 45 plots in the upper quartile of the  $e^H$  distribution fell in the upper quartile of AGBC estimates, indicating that not all plots having higher levels of AGBC have higher biodiversity.

We find that 84% of AGBC is available in 10 (3%) dominant species, indicating a highly skewed AGBC distribution by species. Each species in Table 3 contributed >1% of total AGBC. *Shorea robusta*, *Terminalia tomentosa*, and *Pinus roxburghii* jointly contribute the most: >74%, >80%, and >51% in overall and lower and higher elevations, respectively. While *Shorea robusta* and *Terminalia tomentosa* are major contributors to AGBC in <1000 m. elevations, *Pinus roxburghii*, *Shorea robusta*, and *Schima wallichii* contribute the most in > 1000 m elevations.

## Relationships Between Biodiversity and Carbon

We present the correlation coefficients between S, H',  $e^H$ , and  $E_{sw}$  in Table 4. Most of these biodiversity indices are strongly positively correlated with each other. However, the strength of correlation varies as indicated by correlation coefficients ranging 0.63–0.96. We observe a general trend that  $E_{sw}$  is moderately correlated with S and  $e^H$ .

S, H', and  $e^H$  were weakly positively correlated with AGBC (always <0.27) or insignificant (Table 5) and strength of correlations

varies across elevations, slopes, canopies, and biodiversity indices. For instance, while correlations between AGBC and S, H', or  $e^H$  are statistically significant at lower elevations, correlations are insignificant at higher elevations. Correlations at lower elevations are higher than in open and closed canopies, high and low slopes, and overall forests. For the remaining combinations, the correlation is low and the sample is not big enough to detect significance.

The species richness model for the overall forest indicates that the CF status (0.75), fuelwood collection (0.84), average DBH (0.05), tree density (0.002), canopy cover (0.02), and forest area (0.002) have positive, statistically significant regression coefficient estimates (Table 6). However, forest fire, average tree height, elevation, and slope do not have significant regression coefficients to explain species richness.

The AGBC (Mg ha<sup>-1</sup>) models indicate that S has a positive, statistically significant regression coefficient estimate in the overall forest (3.99), lower elevations (6.22), lower slopes (5.29), and closed canopies (8.25), and H' has positive, significant coefficients in overall forests (14.29), lower elevations (21.71), and closed canopies (38.05) (Table 7, and Appendix 1–I, II, and III). The  $e^H$  also has positive, statistically significant coefficients in overall forest (4.49), lower elevations (6.42), lower slopes (5.54), and closed canopies (9.98) and insignificant coefficient for other forest categories (Table 7, and Appendix 1–I, II, and III).  $E_{sw}$  has statistically insignificant coefficients in the overall and all other forest categories. No biodiversity indices are significant in explaining AGBC in high slopes and open canopies.

## Discussion

### Assessment of Carbon and Biodiversity

Our national-level estimates of AGBC (i.e.,  $98.34 \pm 4.19$  Mg ha<sup>-1</sup>) are comparable with the results of other recent field-based studies in the region. For instance, Baral et al. (2009), Gurung et al. (2015), and Pandey et al. (2014) report 34.30 to 97.86 ton ha<sup>-1</sup>,  $105.58 \pm 17.05$  ton ha<sup>-1</sup>, and 92.55 ton ha<sup>-1</sup> carbon in Nepalese forests. Average AGBC was slightly higher than the IPCC default biome average (90 Mg ha<sup>-1</sup>) and studies of similar Indian forests (e.g. Chaturvedi et al. 2011, Haripriya, 2000), but is markedly less

**Table 2. Summary statistics of forest, disturbance, tree, AGBC, and species diversity for the overall forest. Continuous and ordinal variables are presented as means  $\pm$  standard errors (95% confidence interval) of the mean; dichotomous variables are presented as percentages ( $N = 620$ ).**

Variables (units)	Overall forest	Minimum	Maximum
Forests in the hills (%)	42.50	–	–
Forests in the Terai (%)	57.50	–	–
Presence of fuelwood collection (%)	69.35	–	–
Occurrence of forest fire (%)	28.87	–	–
Elevation (m)	$748.20 \pm 25.20$	75.00	2775.00
Slope (degree)	$15.40 \pm 0.53$	0.00	60.00
Area of forest stand (ha)	$127.70 \pm 27.92$	1.10	1088.00
Average tree height (m)	$11.60 \pm 0.22$	0.00	29.33
Average tree DBH (cm)	$21.11 \pm 0.47$	0.00	73.30
Canopy cover (%)	$49.70 \pm 0.93$	0.00	100.00
Tree density (no. ha <sup>-1</sup> )	$570.11 \pm 18.14$	0.00	3160.00
Sapling density (no. ha <sup>-1</sup> )	$491.73 \pm 22.04$	0.00	6100.00
Regeneration density (no. ha <sup>-1</sup> )	$323164.00 \pm 13692.00$	0.00	210190.10
Total biomass (Mg ha <sup>-1</sup> )	$196.67 \pm 8.37$	0.00	1464.42
AGBC (Mg ha <sup>-1</sup> )	$98.34 \pm 4.19$	0.00	732.21
S	$4.54 \pm 0.11$	0.00	16.00
H'	$0.99 \pm 0.02$	0.00	2.95
$e^H$	$3.67 \pm 0.09$	0.00	13.9
$E_{sw}$	$0.32 \pm 0.01$	0.00	1.00

Note: Some plots were devoid of plants (trees, shrubs and regeneration).

**Table 3. Percent contribution of AGBC by species at national level and across elevations.**

Species	National	<1000 m elevation	≥1000 m elevation
<i>Sal (Shorea robusta)</i>	57.01	69.25	16.48
<i>Saj (Terminalia tomentosa)</i>	9.12	11.08	2.65
<i>Jamun (Syzygium cumini)</i>	1.10	1.36	0.24
<i>Sissoo (Dalbergia sissoo)</i>	0.88	1.09	0.19
<i>Bot dhangeri (Lagestroemia parviflora)</i>	1.36	1.50	0.90
<i>Pinus roxburghii</i>	8.39	1.19	32.21
<i>Chilaune (Schima wallichii)</i>	3.66	1.55	10.67
<i>Katus (Castanopsis indica)</i>	0.89	0.19	3.22
<i>Gurans (Rhododendrom arboretum)</i>	0.50	0.00	2.14
<i>Utis (Alnus nepalensis)</i>	0.99	0.01	4.22
Total	83.90	87.22	72.92

than the secondary data-based estimates of Asian moist forests (e.g., 264 Mg ha<sup>-1</sup>) (Houghton 2005).

Differential AGBC estimates across elevations, slopes, and canopy covers reflect variation in site quality, climatic factors, topographic conditions, and past disturbances. As elevation and slope increases, soil erosion increases, retarding tree growth. Average temperature drops for longer periods at higher elevations, resulting in shorter growing seasons and incidence of past disturbances, such as forest fires and loss of forest cover lowering the base AGBC (Eckholm 1975). Increased AGBC as canopy cover increases reflects the presence of more or big trees in which both vertical and horizontal spaces of forest are occupied.

Variations in plot-level AGBC suggest that there could be potential to increase carbon storage in Nepal's forest. This conclusion is supported by Thapa-Magar and Shrestha (2015), who demonstrate that forest carbon stocks in mid-hill *Shorea robusta* forests increase proportionally with management duration at the rate of 2.6 Mg ha<sup>-1</sup>yr<sup>-1</sup>, and by Pandey et al. (2014), who report that forest carbon stock increased by 25% from 2010 to 2012 in 104 CFs subject to enhanced management. Well-managed forests provide better site, space, and nutrients for remaining trees and saplings, leading to enhanced growth (Lung and Espira 2015, Taylor et al. 2008).

Plot-level variations in biodiversity across the country indicate a wide range of variables (e.g., forest management regime, fuelwood collection, tree DBH, tree density, canopy cover, and forest area), simultaneously affecting the distribution of biodiversity. Higher variances in e<sup>H'</sup> in higher elevations and higher slopes may be due to greater uncertainties and more variation in local factors (e.g., microclimate or edaphic conditions). Increased mean e<sup>H'</sup> with increases in canopy cover reflects the existence of multi-layer canopies and better utilization of vertical and horizontal spaces in forests. The higher variance in e<sup>H'</sup> in open canopy cover forests may be due to higher levels of anthropogenic disturbances reducing biodiversity

**Table 4. Correlations among different biodiversity indices (n = 620). All p-values <0.001.**

Biodiversity indices	S	H'	e <sup>H'</sup>	E <sub>sw</sub>
S	1			
H'	0.83	1		
e <sup>H'</sup>	0.96	0.78	1	
E <sub>sw</sub>	0.60	0.87	0.63	1

and the availability of gaps in the forest floor, which provide space for more species to regenerate (Sapkota et al. 2009).

A highly skewed AGBC, with most carbon in a few species, reduces the influence of biodiversity on AGBC. In the case of carbon forestry, silvicultural activities could keep only high carbon-yielding species, putting other ecologically important species at risk. Such a forest management approach may result in a less resilient ecosystem and reduced livelihood opportunities for forest-managing communities.

### Relationships between Carbon and Biodiversity

The biodiversity indices have variable relationships with AGBC. For instance, the S and e<sup>H'</sup> show positive, but weak, relationships with AGBC in overall forests and forests in lower elevations, lower and higher slopes, and closed canopies based on regression coefficients. This finding resembles earlier studies showing weak positive correlations between biodiversity and carbon (e.g., Nadrowski et al. 2010, Potvin et al. 2011, Thompson et al. 2009). It also indicates the possibility of dominant interspecific complementarity rather than interspecific competitive exclusions in such forests.

S and e<sup>H'</sup> show no relationship with AGBC in high elevation and open canopy forests, which is consistent with earlier studies (e.g., Egoh et al. 2009, Wendland et al. 2010). This finding also indicates no change in carbon as number and abundance of species increases. E<sub>sw</sub> showed an insignificant correlation with AGBC in national level overall as well as all categories of forests.

These variations in the relationships between different indices of biodiversity and carbon in different forests across elevations, slopes, and canopies reflect a complex set of interactions between co-varying abiotic and biotic environmental factors that affect biodiversity, AGBC, and their relationships with each other. For instance, soil quality, drainage, and topography strongly influence the relationships between biodiversity and carbon (Healy et al. 2008).

### Relevance of Findings for Global Environmental Initiatives and Future Research

The large variance in inter-plot AGBC reveals the availability of space to increase carbon storage, indicating the potential for Nepal's

**Table 5. Correlations of AGBC with different biodiversity indices. P-values of coefficients are given in parentheses. Bolded correlation coefficients are significant at a 0.05 level of significance. The sign “-” denotes an inverse relationship.**

Forest Type	S	H'	e <sup>H'</sup>	E <sub>sw</sub>
Overall forest (n = 620)	<b>0.19</b> (<0.001)	<b>0.11</b> (0.006)	<b>0.19</b> (<0.001)	-0.00 (0.941)
Lower elevation (<1000m) (n = 413)	<b>0.26</b> (<0.001)	<b>0.14</b> (0.005)	<b>0.25</b> (<0.001)	0.00 (0.945)
Higher elevation (≥1000m) (n = 207)	0.05 (0.435)	0.07 (0.351)	0.06 (0.370)	-0.02 (0.767)
Lower slope (<15 degree) (n = 277)	<b>0.20</b> (<0.001)	<b>0.12</b> (0.043)	<b>0.20</b> (0.001)	-0.01 (0.826)
Higher slope (≥15 degree) (n = 343)	<b>0.21</b> (<0.001)	<b>0.14</b> (0.008)	<b>0.21</b> (0.000)	0.03 (0.575)
Closed canopy (≥50%) (n = 344)	<b>0.17</b> (0.002)	0.10 (0.053)	<b>0.19</b> (<0.001)	0.02 (0.742)
Open canopy (<50%) (n = 276)	<b>0.18</b> (0.003)	0.06 (0.285)	<b>0.16</b> (0.008)	-0.04 (0.476)

**Table 6. Biodiversity (species richness) models for overall national-level forest. Along with the coefficient of each variable, standard errors are given in the parentheses and the level of significance are presented as \*\*\* = .001; \*\* = .01, \* = .05, and . = .1.**

Model attributes	Overall
CF	0.75** (0.26)
Fuelwood collection	0.84*** (0.23)
Forest fire	-0.08 (0.26)
Average DBH	0.05*** (0.02)
Average height	-0.05 (0.03)
Tree density	0.002*** (0.0003)
Canopy cover	0.02*** (0.01)
Elevation	0.0003 (0.0002)
Slope	0.003 (0.01)
Forest area	0.002*** (0.001)
Residual std. error	2.685
Degree of freedom	610
Adjusted R <sup>2</sup>	0.7478
F-statistic	184.8
Model P value	.000
Cook's D	≤0.02
VIF	4.030013

forest commons to contribute to emerging global environmental initiatives, such as REDD+, through planning and implementing appropriate management interventions. This potential can best be harnessed using accurate field-based methods of carbon measurement, which we find estimate slightly higher levels of carbon than the IPCC default value. The skewness of carbon toward a few species indicates a critical need for effective REDD+ biodiversity safeguards. Such safeguards may synergize biodiversity conservation and carbon storage, particularly in the context of the positive relationships between AGBC and biodiversity (i.e., S, H', and e<sup>H</sup>).

In light of the studies by Gibson et al. (2011) and SCBD (2009), which show that the conservation of primary and mature forests maintains higher levels of AGBC and biodiversity simultaneously,

our findings suggest that biodiversity conservation may support carbon storage goals, particularly in overall forest, lower elevations, lower and higher altitudes, and closed canopies. However, E<sub>sw</sub> may not affect carbon storage goals. Of course, policies that explicitly promote carbon storage could upend this weakly positive and/or insignificant relationship of carbon and biodiversity as communities focus on the few carbon-intensive species.

Varied relationships of different biodiversity indices with AGBC suggest that policymakers, planners, and managers may need to clarify which of their biodiversity interests (i.e., species richness, abundance, or evenness) are of prime importance. If the interest is species richness and abundance, carbon and biodiversity appear to be complementary. However, if species evenness is also a target of biodiversity conservation, then efficient trade-offs between biodiversity conservation and carbon storage may need to be a focus for forest management, which can partly be achieved by incorporating both carbon and biodiversity in spatial planning processes (Thomas et al. 2013). Strassburg et al. (2009), for example, suggest that gains in biodiversity conservation are possible without compromising effectiveness of carbon storage if forest managers explicitly take biodiversity into account.

The high variability of biodiversity and AGBC and differences in their relationships across geography and forest quality warrant further study. We therefore concur with the conclusions of Day et al. (2013) and Thompson et al. (2012), who indicated the need for studies to understand the relationship between biodiversity and carbon. Novel biodiversity indices, such as functional and evolutionary diversities, may help refine our understanding of the relationships between biodiversity and AGBC. There is also a need to analyze changes in biodiversity and carbon over time at different scales and under different management regimes to gain a better understanding of biodiversity and carbon dynamics. Studies on adaptive capacity of forests and the impacts of management

**Table 7. Ordinary Least Squares regression models with AGBC (Mg ha<sup>-1</sup>) as the dependent variable and S, H', e<sup>H</sup>, and E<sub>sw</sub> as independent variables, controlling for forest management regime (CF status), disturbance (fuelwood collection and forest fire), tree dimensions (average tree DBH and height), forest plot characteristics (tree density, canopy cover, elevation, and slope), and forest area. Models are presented for overall national-level forest. Along with the coefficients for each variable, standard errors are given in parentheses and the level of significance presented as \*\*\* = .001; \*\* = .01, \* = .05, and . = .1.**

Model attributes	Overall forest			
S	3.99*** (1.16)			
H'		14.29* (5.60)		
e <sup>H</sup>			4.49** (1.40)	
E <sub>sw</sub>				8.541 (6.18)
CF	8.88 (7.33)	9.43 (7.36)	9.14 (7.34)	10.71 (7.41)
Fuelwood collection	-5.86 (6.93)	-6.98 (7.02)	-5.59 (6.93)	4.69 (7.04)
Forest fire	17.08* (7.35)	18.03* (7.42)	17.19* (7.36)	16.33* (7.44)
Average DBH	3.07*** (0.43)	3.07*** (0.44)	3.09*** (0.43)	3.19*** (0.44)
Average Height	5.63*** (0.93)	5.72*** (0.94)	5.60*** (0.93)	5.38*** (0.94)
Tree density	0.07*** (0.01)	0.07*** (0.01)	0.07*** (0.01)	0.08*** (0.01)
Canopy cover	-0.25 (0.15)	-0.28 (0.16)	-0.24 (0.15)	-0.20 (0.15)
Elevation	-0.02** (0.01)	-0.02** (0.01)	-0.02* (0.01)	-0.02** (0.01)
Slope	0.19 (0.32)	0.15 (0.32)	0.19 (0.32)	0.16 (0.32)
Forest area	0.11*** (0.02)	0.11*** (0.02)	0.11*** (0.02)	0.12*** (0.02)
Residual std. error	75.55	75.87	75.64	76.26
Degree of freedom	608	608	608	608
Adjusted R <sup>2</sup>	0.4768	0.4723	0.4756	0.4669
F-statistic	52.29	51.37	52.03	50.29
Cook's D	≤0.10	≤0.10	≤0.10	≤0.09
VIF	2.88	2.87	2.85	2.88
Resettest (P-values)	.000	.000	.000	.000
BPtest (P-values)	.000	.000	.000	.000
Model P-values	.000	.000	.000	.000



modalities on species composition, forest structure, and growth are crucial to improve understanding of biodiversity and carbon relationships.

This study did not investigate implication of management actions in the improvement in biodiversity, carbon storage, and their relations. We also note that the AGBC and biodiversity estimates are conservative, as we only use trees and saplings  $\geq 5$  cm DBH for AGBC estimation (and ignore below-ground and soil carbon) and assess biodiversity only for tree and shrub species. Estimates of both biodiversity and AGBC, of course, include uncertainties derived from plot variation. Within-plot variation, errors associated with allometric equations, wood density, and carbon factors, and uncertainties arising from sample design and inferences to large landscapes might have affected estimates.

## Conclusions

In the context of mounting concerns about sustainable environmental health, our assessments of forest biodiversity, carbon, and their relationships offer insights for researchers, policymakers, and practitioners at global, national, and local levels. Our estimated average carbon is comparable to other local and regional field studies, but slightly greater than the IPCC biome average. As our detailed plot-level measurements suggest that the IPCC averages are underestimates for Nepal, payments would be greater under mechanisms such as REDD+ if field-based estimation methods are used.

Our research indicates that Nepalese forest commons may extend support to the REDD+ program. The large variance in inter-plot biodiversity and AGBC reveals the availability of space to increase biodiversity and carbon storage, indicating the potential for Nepal's forest commons to contribute to emerging global environmental initiatives, such as CBD and REDD+, through planning and implementing appropriate management interventions. As carbon and biodiversity fluctuate across elevations, slopes, and canopy covers, they are critical factors for planning and implementing forestry projects. In addition, our analysis suggests the absence of trade-off or a weak possibility for synergies between carbon storage and biodiversity conservation in Nepalese forest commons as long as biodiversity is measured as  $S$ ,  $H'$ , and/or  $E^H$ . The low correlations of  $S$  and  $H'$  with AGBC indicate the need for effective biodiversity safeguards in the planning and implementation of REDD+. Biodiversity safeguards are critical if species evenness is of key importance in the management of forests. Dedicated policy and institutional arrangements, careful and site-specific planning of silvicultural activities, proper implementation, and periodic monitoring of forestry projects are required to ensure synergies between carbon and all the main measures of biodiversity.

## Endnote

<sup>1</sup>Due to lack of availability of data and the fact that calculations from our own data were beyond the scope of our research, we were not able to use region-specific wood-specific gravity data.

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