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Carbon Sequestration Rates Using the Allometric Equations of the Fast Growing *Paulownia tomentosa* (Thunb.) in Central Nepal

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Abstract

Background: *Paulownia tomentosa* (Thunb.), a fast-growing tree native to East Asia, has recently been introduced to plantations and agroforestry systems in Nepal for its carbon sequestration and land restoration potential. This study assessed the biomass, carbon stock and carbon sequestration rate of different-aged *P. tomentosa* trees and their parts and developed species-specific allometric equations for future use.

Methods: Using destructive sampling of nineteen 15–20-year-old trees and their seven different traits (Pole, Branch, Leaf, Twig, Tap root, Lateral root and Fine root) in Nepal's mid-hills region, we developed allometric models based on diameter at breast height (DBH).
Model selections were based on Akaike Information Criterion, RSE, adjusted R^2 and Leave-One-Out Cross Validation (LOOCV).

Results: The models calculated a mean baseline carbon stock of 149.81 tC ha^{-1} in 2014, which increased to 202.01 tC ha^{-1} by 2022, yielding a sequestration rate of 5.87 tC ha^{-1} yr^{-1}. Based on the results of AIC, RSE, Adjusted R^2 and LOOCV, the most optimal model is $\ln(M) = \beta_0 + \beta_1 \ln(D)$. DBH was a reliable predictor for biomass, while adding tree height did not improve model performance.

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Conclusion: These equations provide stakeholders with a tool to accurately estimate plantation productivity, supporting the adoption of *P. tomentosa* for environmental restoration and smallholder livelihoods in Nepal's central Himalayan region and similar climatic zones.
Keywords: Fast-growing species; forest carbon stock; smallholders; small-scale plantation; re-vegetation

Introduction

Communities of the mid-hills and mountainous regions of Nepal consumed 5.23 M m^3 of fuelwood in 2011, and this demand is projected to be 5.63 M m^3 in 2020 and up to 6.07 M m^3 by 2030 (Addo-Danso, Prescott, & Smith, 2016). The domestic end-consumer timber demand is also increasing, revealing that the demand is expected to rise from current estimates of 3.37 M m^3 per annum to around 4.8 M m^3 per annum by 2030 (Bargali, Singh, & Singh, 1992; Basuki, Van Laake, Skidmore, & Hussin, 2009). The fuelwood demand is met by 40 % by the country's community-managed forests and 24 % by its private forests (Amatya & Shrestha, 2002). Community-managed and leasehold forests in the mid-hills supply 1.317 M m^3 fuelwood and timber per annum (Beckjord & McIntosh, 1983). This shows a huge gap in the projected demand and supply of fuelwood and timber in the mid-hill regions of Nepal. This undersupply led to account the illegal fuelwood extraction resulting in deforestation and forest degradation in Nepal (Paudel, 2018). Through a combination of sustainable forest management and reforestation initiatives and selection of suitable tree species for plantation and afforestation, the deforestation can be offset and gap can be narrowed. This could be substantially make up if new plantations with fass growing species are established on large areas of the available non-forested land (Beckjord & McIntosh, 1983).

Paulownia tomentosa (Thunb.) is a fast-growing tree species that is highly prized for its timber properties worldwide. Its light yet strong wood is used for making furniture and a variety of musical instruments (Birdsey, 1992). It has a high rot resistance, dimensional stability and ignition point (Brown, 1997), making it a popular internal construction timber in global markets (Brown, Gillespie, & Lugo, 1989). It is also a good source of fuelwood and fodder for livestock, and can produce high biomass and timber volumes over short rotations (i.e. 12 years) (Carpenter & Smith, 1979; Geyer, 2000). It can also be coppiced without affecting the species' long-term growth potential (Carpenter & Smith, 1979). Like other fast-growing tree species commonly grown in smallholder and community forests – such as Eucalyptus, Popular, *Dalbergia sissoo* (Chettri & Sharma, 2007, 2009) – *P. tomentosa* has also a great potential for providing goods (fuelwood , timber) and services (carbon sequestration) (Li & Oda, 2007).

Because of these useful characteristics, there is a growing interest among smallholder farmers, community forest managers and other private landowners in many parts of the developing world to invest in plantations of *P. tomentosa*. However, the species was introduced recently in Nepal. As a result, there is limited community experience with cultivating this species and

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limited information on its potential productivity and growth patterns in the local environment. This has created uncertainties in terms of information regarding growth data, rotational period, and market prices of *P. tomentosa* thus preventing its more widespread adoption by the smallholders and community forest managers. When estimating the aboveground and belowground biomass of a forest stand, locally-developed and species-specific equations that consider all diameter classes of a stand's trees are preferred because trees of different species may differ greatly in tree architecture and wood density (Ketterings, Coe, van Noordwijk, & Palm, 2001). Hence, there is a need to develop locally-applicable, reliable and rapid-use but simple models for calculating the growth and associated biomass and carbon sequestration potential of *P. tomentosa* that communicate the species biological and ecological information to the smallholders and community forest managers those are interested to extend its plantations.

Materials and Methods

Study Site

The ICIMOD Knowledge Park is located at Godavari in the Pulchowki watershed approximately 15 km southeast of Kathmandu (Figure 1). The park has a total area of approximately 30 hectares. It is surrounded by the Godavari Kunda Community Forest to the northeast and the Diyale Community Forest to the southwest. The site has an altitude range of 1,540–1,800 meters above sea level (m a.s.l.) and a slope gradient ranging from almost zero degrees to more than 60 degrees in parts of the upper forest zone. Vegetation in the study area comprises a mixture of deciduous and evergreen broadleaved species. The soil texture varies from clay loam to sandy and silty clay loams that are rich in forest humus. Soil types include a sandy alluvial soil in the lower areas and a shallow dry soil on the ridge-tops. The climate is subtropical to warm temperate, with a mean annual temperature of 17.2º C. The annual temperature ranges from -0.5º C to 33.8º C with an annual mean relative humidity of 76 %. The region's average annual rainfall is 2,062 mm, with around 80 % of this total falling during the monsoon season (June-September) (ICIMOD, 2001). The park has been actively managed for the last 30 years to restore its originally highly degraded condition, which was characteristic of the surrounding hillsides. Its natural features include forests, shrub-land, wetlands and waterways. The park is a repository for plant germ plasm resources, and is used to select, test and demonstrate the viability of different sustainable land-use technologies and practices such as conservation farming using sloping agricultural land technology. In addition, the park is used to provide hands-on training to improve the skills and technical knowledge of farmers, development workers and collaborating institutions. Overall, the park's purpose is to disseminate appropriate small-scale farming and natural resource management technologies, knowledge, information and experiences that can be replicated on degraded lands in mountain ecosystems throughout Nepal.

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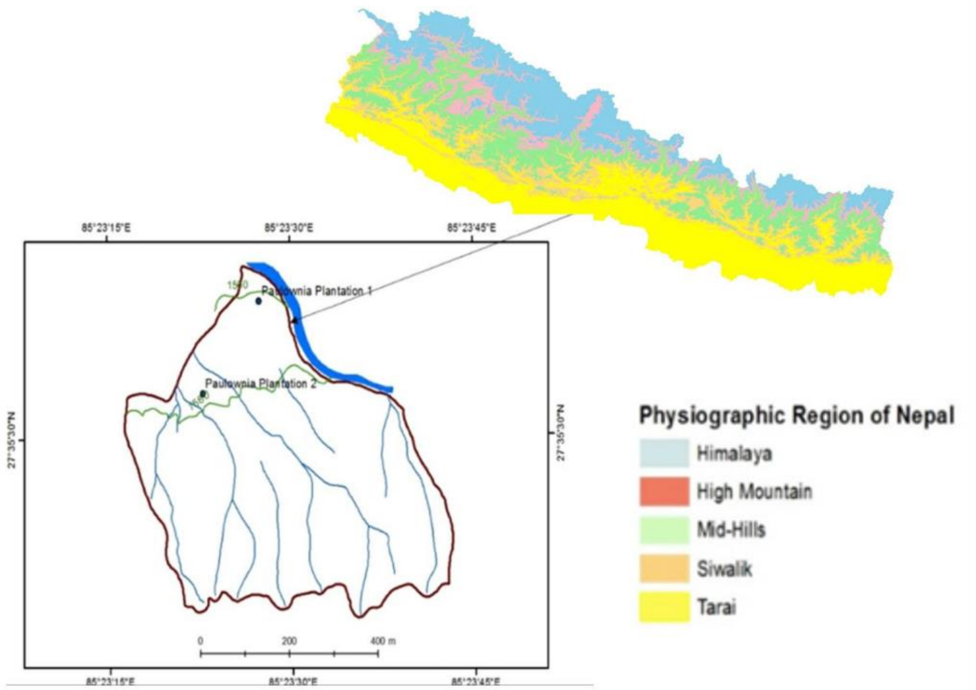

Figure 1. Study Site in Living Mountain Lab, Godavari, Lalitpur Nepal

Sample Population

Two small trial plantations of *P. tomentosa* located within the ICIMOD Knowledge Park were selected for this study. Each plantation was 0.1 ha and the original tree spacing was 4 m x 6 m. The coordinates of the two plantations are latitude 27º 25' 40" N, longitude 85º 23' 18.7" and latitude 27º 35'34.2" N, longitude 85º 23' 14.2", respectively (Figure 1). The history of these plantations dates back to the mid-1990s. Root suckers for the establishment of plantation 1 were imported from Sichuan Province in China and planted in 1994. Plantation 2 was established in 1999 with root suckers from the plants in plantation 1. The total number of trees were 56 in plantation 1 and 34 in plantation at the time of sampling. At the time of sampling in October 2014, plantation 1 was 20-years old and plantation 2 was 15-years old. Figure 1 shows an example of the *P. tomentosa* growing within plantation 1.

Tree Measurements

The co-centric-circular sampling plot of 17.84 m radius was established within each plantation. A total of 90 trees were located within the two sample plots. All of these trees were marked and measured. Measurements of the plantation stocking, the DBH distribution, stand basal area, and tree stem volume were taken. These variables served as the basis for selecting the destructive sample trees for the development of the allometric equations. To develop the equations, we categorised all of the measured trees into six DBH ranges (Table 1). Based on these six DBH ranges, 19 trees were randomly selected for destructive sampling and were manually harvested.

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Table 1: Sample size and DBH range of trees harvested to determine the allometric equations

DBH Class (cm)	No. of trees		Mean DBH		No. of destructive sample trees
	Plot 1	Plot 2	Plot 1	Plot 2	
<10	NA*	5	NA	8.70	3
10.1-20	2	15	19.15	13.25	4
20.1-30	19	2	25.26	26.33	4
30.1-40	12	10	34.49	33.80	3
40.1-50	10	1	45.62	40	3
>50	11	3	54.88	64.40	1
Total	54	36			18

*NA= Not available

Recognised methods of standard forestry harvesting practices as described by Kantola and Virtanen (1986) were followed to mitigate the human hazards and forest damage associated with tree felling operations. The harvested trees were dissected into seven different tree components i.e. i) stem, ii) branches, iii) twigs, iv) leaves, v) stump root, vi) lateral roots, and vii) fine roots. Stem, branches, twigs and leaves were categorised as the aboveground tree components. Stump roots, lateral roots and fine roots were categorised as the belowground tree components. The fresh weight of the seven tree components were weighed using methods described by Rawat (1983), Rana et al.,(1989), Chave et al., (2005) and Singh et al. (2011). Root excavation was undertaken using the soil pit method. This method used water to wash soil from the roots so as to minimize root loss.

Three discs were taken from each of the 19 tree stems, one disc from each of the bottom, middle and top parts of the stem. A similar process was applied to each tree to obtain three samples of branches and stump roots. One sample only was taken for each tree's twigs, lateral roots and fine roots. The entire foliage of the harvested trees was also taken as a single sample. Therefore, for each of the 19 harvested trees, a total of 13 samples of the seven tree components were taken. This resulted in a total of 247 samples being freshly weighed, put into poly bags, labelled, and tied tightly to prevent evaporation. These samples were then sent to the laboratory for oven-dry weight determination (Table 2).

The fresh weight of the samples sent to the laboratory consisted of 74.68 kg of stem, 63.40 kg of branches, 7.5 kg of twigs, 1.90 kg of leaves, 62.40 kg of stump roots, 0.10 kg of lateral roots and 0.50 kg of fine roots. The oven-dry weight of the component samples was obtained using an oven drier at a temperature of 105ºC for 72 hours until the samples reached a constant

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weight. Likewise, basic wood densities for the stem-wood discs were obtained at a moisture content of 0 %.

Table 2: Dry weight biomass (Kg) of the tree components

DBH (cm)	Stem	Branch	Twigs	Leaves	Stump root	Fine root	Lateral root	Total (kg)
4.5	1.9	0.53	0.085	0.32	1.12	0.015	0.133	4.1
7.8	9.6	2.05	0.342	0.59	2.832	0.046	0.321	15.8
9.5	10.5	7.84	0.424	0.74	3.07	0.049	0.385	23.0
10	13.3	10.23	0.632	0.79	4.28	0.132	0.583	30.0
12	43.8	15.21	0.863	0.83	5.63	0.194	0.732	67.3
15.5	58.4	17.76	1.532	0.97	5.76	0.253	0.931	85.6
17	72.6	20.23	1.733	1.07	8.94	0.452	2.46	107.5
20	93.3	23.94	2.032	1.55	13.82	0.534	3.96	139.2
21	104.2	26.29	2.795	3.85	10.44	0.564	4.82	153.0
24	116.7	30.57	2.847	5.85	11.47	0.675	6.21	174.3
25.9	135.2	34.37	1.04	6.32	16.82	1.83	8.29	203.9
29	150.2	39.56	3.21	8.46	20.46	2.06	9.37	233.4
31	252.7	49.95	5.63	10.83	25.28	2.53	9.93	356.9
35.5	236.7	64.17	5.94	11.46	26.81	2.97	10.82	358.9
37.4	268.2	69.39	6.02	13.07	27.53	3.04	11.06	398.3
41.6	304.5	83.23	7.945	14.89	29.8	3.16	11.73	455.3
44.4	356.1	122.80	7.84	15.23	30.39	3.66	14.82	550.8
47.2	395.4	126.43	8.78	16.29	31.25	3.97	15.43	597.6
53	445.3	132.57	9.45	17.93	35.21	4.07	15.93	660.5

Data Analysis

The biomass for each tree component for each of the sampled trees was calculated using equation 1.

$$\text{Biomass of individual tree components (tonne/ha)} = \frac{W_{field}}{A} \times \frac{W_{sub-sample\ \text{dry wt}}}{W_{sub-sample\ \text{wet wt}}} \times 10,000 \ldots\ldots\ldots\ldots(1)$$

Where,

W_{field} = total fresh weight of each component from all sample trees [tonnes],

A = total area of plots in which biomass data for each component were collected (m^2)

$W_{sub\text{-}sample,drywt}$ =

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		weight of the oven-dry sub-sample of individual tree component [tonnes]; and
Wsub-sample ,wet wt	=	Weight of the fresh sub-sample of individual tree component [tonnes].

Researchers have used variety of regression models for establishing and estimating tree its components biomass. In this study, several models were tested using tree biomass and other tree components as a function of DBH and tree height. Since the biomass data shows heteroscedasticity because the variance increases as the diameter increases across the observations. Therefore, power functions with natural logarithm transformation were used in this study. The power function assumes the form $M = aD^b$ where and b are the scaling coefficient, D is the diameter at the breast height and M is the total weight of above ground biomass of a tree. The logarithm transformation stabilizes the variance over the entire range of biomass values corresponding different DBH values. A constant variance is prerequisite of the linear regression model (James, Witten, Hastie, & Tibshirani, 2013). We fitted the following models to the sampled tree data.

$$\ln(M) = \beta_0 + \beta_1 \ln(D) \ldots\ldots (1)$$

$$\ln(M) = \beta_0 + \beta_1 \ln(D) + \beta_2 \ln(H) \ldots\ldots (2)$$

$$\ln(M) = \beta_0 + \beta_1 \ln(D^2 \times H) \ldots\ldots (3)$$

Where M is the above ground dry biomass or any of the components of the tree; D the diameter at breast height (cm); H the total height of a tree (m); β_0, β_1 and β_2 are the regression coefficients. In these models β_0 is the scaling components whereas β_1 and β_2 represent scaling exponent. Even though logarithm transformation converts power function into linear function and stabilizes the variance, the transformation creates a systematic bias on the original scale. The prediction using the log transformed model underestimate the biomass because of the bias. The error is corrected by using a correction factor (CF), which is given as in Equation (4). To remove the bias the final result is multiplied by a correction factor calculated using Equation (4).

$$CF = \exp(RSE^2 / 2) \ldots\ldots (4)$$

Where RSE the residual standard error. The larger the RSE, larger the correction factor implies that the model more underestimate the biomass (Djomo et al., 2010).

First, we developed equations using only diameter as an independent variable. Then we included height and analyse its effect on the predictive quality of the models. For selecting the best models slope coefficient of the regression, Akaike Information Criteria (AIC), confidence intervals of the predictions, Adjusted R^2 and Residual standard error of estimate (RSE). The formula for AIC used as a criterion for model selection is:

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$$AIC = -2\ln(L) + 2p \quad (5)$$

Where L is the likelihood of the fitted model and p is the total number of parameters in the model. A model is considered best fit which exhibits the least AIC value (Basuki et al., 2009).

Other than approaches discussed before, we also used cross validation method to select the best model for predicting biomass. To this end, we calculated cross validation error for each model under consideration and selected the model which exhibits the least test error. The cross-validation approach has an advantage than the AIC, Adjusted R^2 and RSE because it produces a direct estimate of test error and makes less assumptions about the true regression model. We used Leave-One-Out Cross Validation (LOOCV) approach for selecting the best model. Many other studies on allometric biomass equations have used LOOCV approach for selecting the best model (Jachowski et al., 2013; Muukkonen, 2007). In this approach set of observations are split into two subsets one with single observation and other with the rest of the observations. The single observation is used for the validation and the remaining observations are used for training set. The validation is repeated n-1 times if n is the number of observations. The LOOCV estimate for the test MSE is the average of these n test error estimates:

$$CV_{(n)} = \frac{1}{n}\sum_{i=1}^{n} MSE_i \quad (6)$$

Before establishing the model equations, scatter plots were used before log transformation to see whether the relationship between dependent and independent variables was linear. Furthermore, linear regression model was fitted and residual value versus biomass was plotted. The residual plots are the useful graphical tool for knowing nonlinearity of a relationship(James et al., 2013). The plot showed nonlinear tendency and showed non-constant variance in the residual or heteroscedasticity indicated by the widespread (funnel shape) of residuals at the higher end than at the lower end of biomass (James et al., 2013).

Forest biomass estimations are typically the result of applying a common equation considered applicable to large geographic areas (De-Miguel, Pukkala, Assaf, & Shater, 2014). However, biomass estimates can vary widely depending on a range of biophysical factors including tree species, the age and spacing of a stand, and the topography and climatic conditions of a site. Field-based measurements are the most reliable non-destructive source of biomass and carbon data (Djomo, Ibrahima, Saborowski, & Gravenhorst, 2010), however, the national forestry inventories containing such site-specific data are often not publicly available and so questions are often raised about the reliability and suitability of these biomass and carbon stock estimates (Djomo et al., 2010; Dudley & Fownes, 1992). The most accurate method for estimating aboveground and belowground tree biomass is to weigh the entire tree's biomass in the field, but this is an extremely time consuming and destructive method. Destructive sampling is therefore generally limited to small areas and small sample sizes. Reliable estimates of forest biomass are also made using allometric equations, and there are many examples of the

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development and application of such equations in the literature (García-Morote et al., 2014; Houghton, 2003).

Allometry generally relates easily measured independent variables like a tree's diameter at breast height (DBH) to other tree components, and it can provide relatively accurate species-specific biomass and carbon estimates (Joshi, Tewari, & Singh, 2013). However, recent research has noted that errors in estimates of biomass stocks can be the result of the absence of species-specific allometric equations for trees of large diameter classes, in general, and small diameter classes, in particular (Crow, 1978).

Allometric equations are recognised as a crucial non-destructive and time- and cost-saving approach to estimating aboveground and belowground forest biomass (Picard, Saint-André, & Henry, 2012). Allometric models vary widely, but the simplest and most commonly used is a linear model with a single independent variable such as DBH (Ketterings et al., 2001). In Nepal, only a small number of species-specific allometric equations are currently available for estimating tree biomass. These include equations for Eucalyptus camaldulensis, D. sissoo, Acacia auriculiformis and Cassia siamea , Pinus roxburghii, and Shorea robusta (Hawkins, 1987). In the absence of other species-specific allometric equations, estimates of forest biomass and carbon stocks, in the Nepalese context, are still dependent on the generalised values provided by the Intergovernmental Panel on Climate Change's Tier 1 approach (IPCC, 2006) and other existing volume-based biomass estimation models (Sharma, 1990).

This study reports on the development of allometric equations for assessing the aboveground and belowground biomass and carbon stocks of P. tomentosa grown in the Nepalese mid-hills region. Growth data was sourced from two small plantations within the International Centre for Integrated Mountain Development's (ICIMOD) Knowledge Park at Godavari near Kathmandu. The models were developed through destructive sampling of the plantations and will be useful as a cost-effective method for estimating the biomass and carbon stocks of P. tomentosa plantations in mid-hills of central Nepal with a higher level of accuracy. Overall, the findings are important for providing the Nepalese government, smallholders and community forest managers, as well as rural development non-government organizations operating in the country with the type of precise forest growth and productivity information they are seeking to support their reforestation decision-making.

Results

Test for outlier

Outlier can occur for incorrect recording of data during the data collection and processing process. The outlier has big impact on regression model (Khan, Razali, Daud, Nor, & Fotuhi-Firuzabad, 2015). Therefore, to find the outliers in the data set, we used studentized residuals which is calculated by dividing each residual by it estimated standard error (James et al., 2013).

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Observation which studentized residual is greater than absolute 3 are considered as possible outliers (James et al., 2013). Figure 2 depicts a plot of studentized residual against the fitted values. The observation indicated that none of a studentized residual observations have value of less negative 3, hence the set of data is free from an outlier.

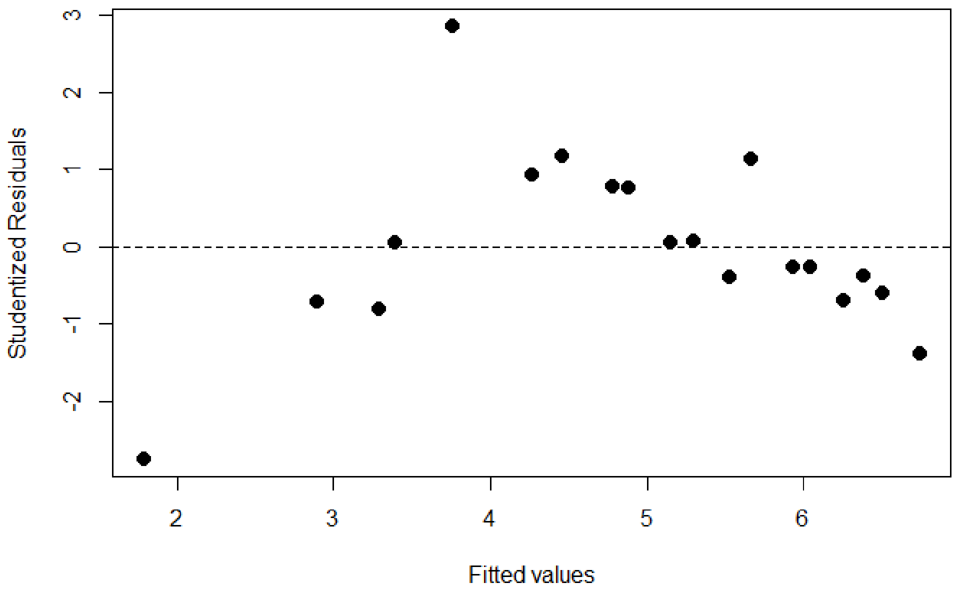

Figure 2. Plot of Studentized Residuals versus fitted values.

Evaluation of linearity

The linear regression model assumes that there is straight line relationship between the dependent and independent variables. If the true relationship deviates from linear then conclusions drawn from the relationship mislead. Therefore, to test the linearity between predictor (DBH) and response variable (biomass) residual plots are used for identifying linearity (James et al., 2013; Picard et al., 2012). Figure 3(a) shows a residual plot from linear regression of DBH and total biomass and red line is a smooth fit to the residuals. The residual exhibits U-shape and indicates nonlinearity in the data. Figure 3 (b) exhibits residual plots after logarithmic transformation. The figure displays little pattern in the residuals, suggesting that logarithmic transformation improves the fit to the data.

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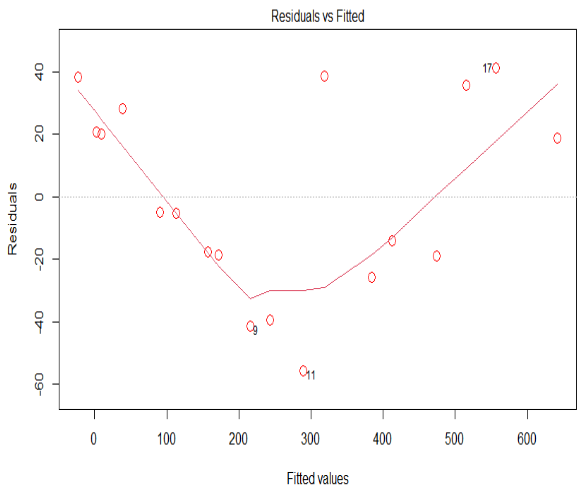

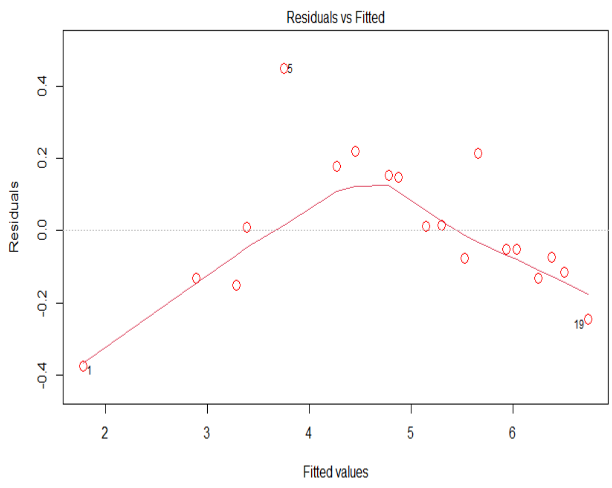

(a) (b)

Figure 3. Plot of resi[d]uals versus fitted values of the total biomass of trees before and after logarithm transformation. (a) depicts before and (b) depicts logarithm transformation. The red line is smooth fit to the residuals and shows a trend.

Developing allometric equations

Regression relationship was established between biomass of the different parts of the tree with DBH A single allometric equation incorporating all seven tree components for *P. tomentosa* was derived using $\ln(M) = \beta_0 + \beta_1 \ln(D)$. The values of the coefficients are presented in Table 3. For this model adjusted R^2 ranged from 0.895 to 0.979 and the lowest was found for twigs biomass. Below ground and total biomass have the highest value of R^2 (0.976) whereas twig has the lowest value (0.895) of adjusted R^2. The values of the coefficient of determination (R^2) indicated that fitted model explained between 89.5 % and 97.6 % of the observed biomass variance of the components of trees as well as AGB, BGB and TB. Thus, a strong correlation existed between tree DBH and biomass for the seven tree components, AGB, BGB and TB indicating that DBH could be used as an accurate predictor for biomass estimation. On the other hand, performance of the model for twigs, leaves and branch biomass was less reliable with relatively lower value of adjusted R^2 and higher values of RSE and AIC. We also noted that adjusted R^2 values were different for tree components. Also, graphical examination of the biomass data of different parts of the trees showed the existence of strong relationship between tree attribute (DBH) and biomass of the tree parts on the logarithmic scale (Figure 4).

Model 1 only uses only DBH as a predictor, however tree biomass is affected by its height as well. Therefore, height and DBH and height in combination with DBH were incorporated as additional independent variables. Two more regression models as shown by equation 2 and 3 were also tested. Various statistics for evaluating goodness of fit such as AIC, adjusted R^2, and MSE are computed and a quality of a statistical fit was compared. Table ..,. presents the values

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of parameters of goodness of fit. By adding a height of the tree as the second predictor in the model (Equation 2) and the model becomes a multiple linear regression. Since DBH is highly correlates with TB, AGB and BGB of the trees, the incorporation of height did not contribute significantly to biomass estimation. The coefficient associated with height predictor is statistically not significant at $P<0.05$.

We also tested a double entry biomass model (Equation 3), in which we fit a simple regression to predict ln (M) from ln $(D^2 \times H)$. An addition of H to the model only slightly improved value of adjusted R^2 associated with BGB. On the other hand, adjusted values of R^2 associated with AGB and TB remains higher in the model which contains only DBH. Along with adjusted R^2, values of AIC and RSE were also calculated and compared for three biomass models. Table 3 and 4 depicts the values of AIC and RSE. AIC values for AGB and TB for the model 1 (2.54, -3.73) were lower than that for model 3 (5.301, 0.542). On the other hand, value of AIC was lower for BGB for model 3 than model 1. Performances of model 1 and 3 in terms of adjusted R^2 were consistent with performance in terms of AIC values.

The values of Residual Standard Error (RSE) varied among the components of trees as well between models. For model 1 the RSE values for the tree components varied between 0.163 and 0.539. Thus, model 1 used in this study produced the most reliable estimates for different components including AGB, BGB and TB. Most of the RSE values obtained from this model were close to zero, indicating that model 1 provided accurate estimation of biomass. In terms of RSE value, model 2 also exhibited lower values of RSE for AGB, BGB, and TB but addition of tree height as a predictor did not contribute significantly to prediction of biomass. Therefore, model 2 was not applicable for the biomass prediction. The values of this statistics obtained for BGB from biomass model 3 were smaller than model 1. Like AIC and adjusted R^2 values, goodness of fit in terms of RSE values showed consistent performance across the model except model 2.

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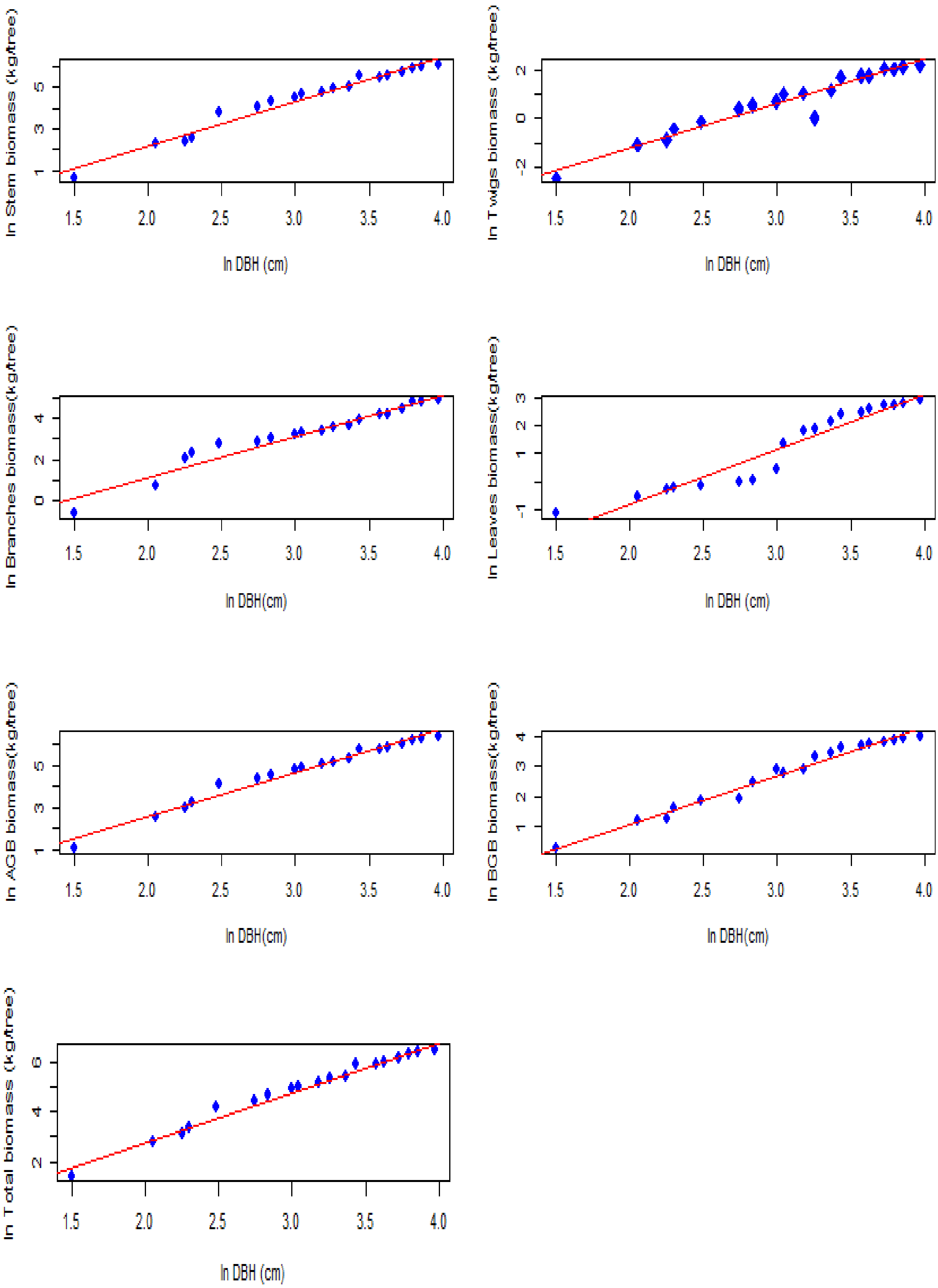

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Figure 4. Relationship between biomass of the tree parts and diameter at breast height (DBH) on a logarithmic scale.

Biomass model

TABLE 3. Model description for the estimation of total biomass of tree and its different components ($\ln(M) = \beta_0 + \beta_1 \ln(D)$ for N=19)

Tree part	Value of coefficient		Standard error of coefficient	Adjusted R^2	RSE	AIC	Confidence Intervals (5%)	
	Symbol	Value					Lower	Upper
Stem	β_0	-1.744	0.326***	0.958	0.249	8.89	-2.781	-1.529
	β_1	2.008	0.068***				1.956	2.357
Branch	β_0	-2.151	0.352***	0.938	0.268	7.67	-2.898	-1.404
	β_1	1.784	0.110***				1.550	2.018
Leaves	β_0	-5.255	0.456***	0.927	0.348	16.95	-6.221	-4.288
	β_1	2.114	0.143***				1.811	2.417
Twigs	β_0	-5.273	0.492***	0.895	0.418	14.28	-6.312	-4.234
	β_1	1.949	0.156***				1.618	2.280
Lateral root	β_0	-6.848	0.527***	0.929	0.490	30.76	-7.960	-5.735
	β_1	2.598	0.168***				2.242	2.954
Stump root	β_0	-1.952	0.164***	0.976	0.153	-13.45	-2.299	-1.604
	β_1	1.438	0.052***				1.326	1.549
Fine root	β_0	-6.665	0.580***	0.874	0.539	34.37	-7.888	-5.441
	β_1	2.083	0.185***				1.692	2.475

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AGB	β_0	-1.600	0.250***	0.973	0.233	2.54	-2.130	-1.071
	β_1	2.083	0.080***				1.914	2.253
BGB	β_0	-2.186	0.175***	0.979	0.163	-11.12	-2.556	-1.817
	β_1	1.623	0.056***				1.505	1.741
TB	β_0	-1.233	0.212***	0.979	0.198	-3.73	-1.682	-0.784
	β_1	2.008	0.068***				1.864	2.151

Note: The statistical analyses ar4e significant at 95% confidence intervals. ***P<0.001, ^{ns}P>0.05
AGB=Above Ground Biomass, BGB= Below Ground Biomass, and TB=Total Biomass.

TABLE 4. Model description for the estimation of total biomass, AGB, BGB of trees (for N=19)

Equation	Tree part	Value of coefficient		Standard error of coefficient	Adjusted R^2	RSE	AIC	Confidence Intervals (5%)	
		Symbol	Value					Lower	Upper
2	AGB	β_0	-1.657	0.276***	0.972	0.230	4.196	-2.243	-1.070
		β_1	1.941	0.273***				1.361	2.522
		β_2	0.182	0.335^{ns}				-0.529	0.893
	BGB	β_0	-2.316	0.174***	0.982	0.150	-13.22	-2.686	-1.945
		β_1	1.299	0.173***				0.932	1.666
		β_2	0.416	0.212^{ns}				-0.033	0.866
	TB	β_0	-1.293	0.233***	0.979	0.201	-2.279	-1.787	-0.798
		β_1	1.8580	0.230***				1.368	2.347
		β_2	0.1932	0.283^{ns}				-0.406	0.793
3	AGB	ln β_0	-1.794	0.278***	0.969	0.251	5.301	-2.381	-1.207
		β_1	0.745	0.030***				0.680	0.811
	BGB	ln β_0	-2.356	0.165***	0.982	0.149	-14.50	-2.705	-2.007

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	β_1	0.583	0.018***				0.544	0.621
TB	ln β_0	-1.421	0.238***	0.976	0.21 5	0.542	-1.924	-0.918
	β_1	0.718	0.026***				0.662	0.774

Note: The statistical analyses were significant at 95% confidence intervals. ***P<0.001, ^{ns}P>0.05

AGB=Above Ground Biomass, BGB= Below Ground Biomass, and TB=Total Biomass.

Cross validation of the models

We also used Leave-One-Out Cross-Validation (LOOCV) tool in order to obtain additional information about the fitted models and to select the best performing model. Figure 5 depicts the MSE of LOOCV estimates for the two models. The model 1 which uses only DBH as a predictor exhibits lower test MSEs for stem, TB, AGB models. On the other, model 3 which uses DBH and tree height as a predictor displays lower value of test MSE. The value of MSE of LOOCV for model 1 range from 0.028 to 0.094, lowest is for BGB and highest was for stem biomass. For model 3 the lowest value of MSE was for BGB and the highest MSE value was for stem biomass.

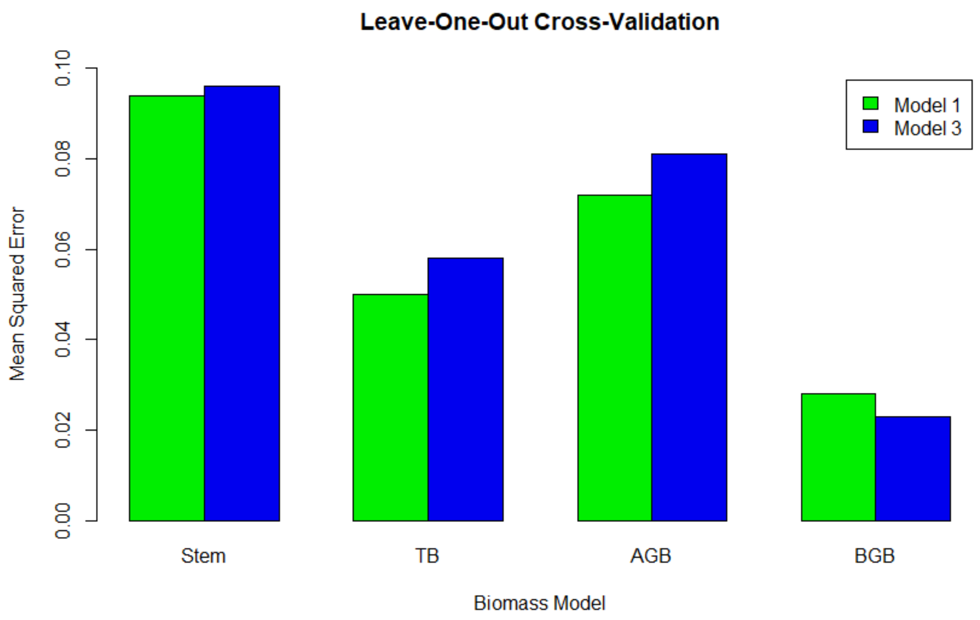

Figure 5. Comparison of values of MSE obtained by using Leave-One-Out Cross-Validation to Model 1 and 3.

Contribution of tree components

The contribution to total tree biomass made by the seven components are: stems 66.57 %, branches 19.14 %, twigs 1.5 %, leaves 2.87 %, stump root 6.52 %, lateral roots 2.76 % and fine roots 0.67 % (Figure 6). Therefore, the aboveground tree components contributed 90.22 % and the belowground tree components contributed 9.94 % of the total biomass, giving a root-to-

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shoot ratio of 0.11. Using the default values for carbon suggested by (IPCC, 2006), total carbon content in the two plantations were found to be 202.01 ha^{-1} and 149.81 tons ha^{-1}, respectively. The variation in biomass and carbon stocks are due to the difference in age and stocking rates in each plantation. Plantation 1 was around 20 years old and has a stocking rate equivalent to 540 stems ha^{-1}, while plantation 2 was 15 years old and had a stocking rate equivalent to 360 stems ha^{-1}.

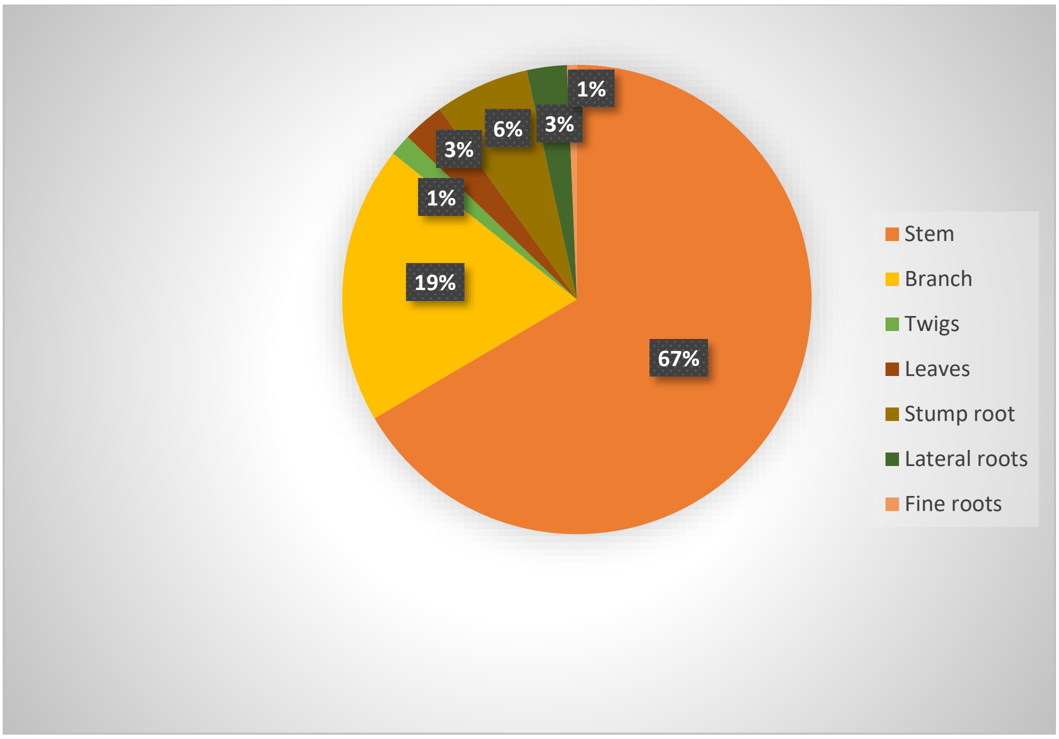

Figure 6. Total Biomass stock by tree components

Carbon sequestration rates

In the Living Mountain Lab (LML) forest, an annual increment of forest carbon by *Paulownia tomentosa* was 5.87 tC $ha^{-1}yr^{-1}$ (Table 8). Our results are comparable and these results fall within the range of carbon sequestered rates 2.4 to 5.6 tC $ha^{-1}yr^{-1}$ calculated by Rana et al. (1989) for the forests lying in Central Himalayan region. Carbon sequestration by *Paulownia tomentosa* measured in LML also comply with the enhanced carbon stocks experimented under REDD+ piloting sites in three watersheds of Nepal (Kayarkhola Watershed in Chitwan, Ludikhola watershed in Gorkha and Charnawati watershed in Dolakha). The mean annual enhanced carbon stock rate from the year 2010-2013 in these three sites are 2.61t C ha^{-1} yr^{-1} 2.46 tC ha^{-1} yr^{-1} and 3.33 tC $ha^{-1}yr^{-1}$ respectively. (ANSAB, ICIMOD and FECOFUN 2013). Similarly, study by Malhi et al. (2000) reported carbon sequestration rate of 2.69 tC $ha^{-1}yr^{-1}$ in Indian Himalayan forest. Another study in the LML showed that the mean forest biomass was 194.33 t ha^{-1} , contributed by trees, saplings, herbs, and leaf litter biomass pools. The tree biomass pool contributed about 93.5%, the sapling pool contributed only 0.64 %, the herb and

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grasses biomass pool contributed 1.90 % of the total biomass, and the leaf litter biomass pool contributed about 3.96 % (Joshi et al. 2024)

Table 5: Carbon sequestration rates by *Paulownia tomentosa* in Living Mountain Lab

Strata	Carbon stock in 2022 C2 (tC ha^{-1})	Carbon stock in 2014 C1 (tC ha^{-1})	Net change in carbon (ΔC = C2-C1)	Carbon sequestration rate ΔC = C2-C1/Yr (tC ha^{-1}yr^{-1})
Dense	246.82	189.91	56.91	6.32
Sparse	157.21	108.46	48.75	5.42
Mean	202.01	149.81	52.82	5.87

Discussion

Relevance of the allometric equation for science and policy

Three regression models were fitted to predict AGB, BGB, TB and tree components biomass were assessed for their performance and accuracy of the estimates. The regression models which used DBH alone and interaction of DBH and tree height were the most accurate. The logarithmic transformed model which used only DBH as a predictor performed better and met the criteria of accuracy and biomass prediction quality. Tree stem diameter is considered the main indicator of tree vigor and productivity (García-Morote et al., 2014). Inclusion of tree height to develop allometric equations may increase their applicability (Wang, 2006), but tree height does not necessarily explain more about the tree biomass (Yoon et al., 2013). Studies by Wang (2006) and Yoon et al. (2013) have also shown that DBH is the most common predictor of tree biomass. Similarly, De-Miguel et al. (2014) and Návar (2009) showed a strong relationship between DBH and estimations of tree biomass. Furthermore, allometric equations based on a single tree attribute such as DBH are very cost-effective for estimating biomass, which is essential for accurate determination of related factors such as carbon (Yoon et al., 2013). Thus, this study also used tree DBH as a single tree attribute to develop an allometric equation for *P. tomentosa*.

The results have shown that total biomass of the seven tree components of the sampled *P. tomentosa* trees are linearly related with tree DBH after logarithmic transformation. The allometric equation developed by compiling all seven tree components also revealed a strong relationship between DBH and total biomass (adjusted R^2=0.979). Of the seven tree components, the stem contributed the highest amount of biomass followed by the branches, twigs, leaves, stump root, lateral roots and fine roots.

The resulting root-shoot ratio of 0.11 will enable the accurate estimation of belowground biomass using estimates of aboveground biomass. However, this ratio indicates that this species allocates more biomass to the aboveground parts than the belowground components and may

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not be suitable for highly erosive areas such as denuded hill slopes. No such study estimating the ratio between aboveground biomass and belowground biomass of *P. tomentosa* has been done elsewhere. Comparing the ratio to previous work, a meta-analysis by Cairns et al. (1997) found a large variation in aboveground and belowground biomass ratios (0.05-0.70). The differing ratios were found to be dependent on a range of environmental characteristics such as precipitation and the latitude of a site where the species is growing as well as ecological characteristics of the species such as its age and type of tree (broadleaf or coniferous) (Cairns, Brown, Helmer, & Baumgardner, 1997). Birdsey (1992) identified root: shoot ratios for softwood forests ranging from 0.19 to 0.20, which is higher than the ratio this study estimates. One possible reason for this higher value is that the forests investigated by Birdsey were more mature than the *P. tomentosa* plantations sampled in this study.

The stronger relationship of *P. tomentosa's* DBH with stem biomass (adjusted R^2 =0.958) relative to the branches (adjusted R^2 =0.938), leaves (adjusted R^2 =0.927) and twigs (adjusted R^2 =0.895) demonstrates that it is difficult to predict the biomass of branches, leaves and twigs with the same precision as that of the stem. As observed by Návar (2009), this could be due to factors including differences in competition between trees (i.e. stand stocking) or their position within a stand which can affect their form or structure. For example, compared to trees growing within a plantation, trees growing in an open space or on the edges of a plantation tend to have a wider crown and an associated higher proportion of biomass in the branches and leaves relative to the stem. In the study area, a spacing of 4 m x 6 m was maintained and the plantations were very small, hence the sampled trees included both interior and edge specimens.

The non-linear regression equations developed for the seven tree components of *P. tomentosa* constitute an additional improvement for estimations of biomass when inventory data provide information on DBH. The single variable-based allometric equations provide information on the dry weight biomass in kg for different DBH classes (Table 2) which can be easily measured and calculated by small-scale farmers, the scientific community (including rural development organizations) and policymakers either for commercial market analyses. These stakeholders can use the equations to estimate individual tree or stand biomass and timber volumes before making harvesting and other silviculture management decisions. According to the Forest Act and Regulation of Nepal [69], tree owners require felling permission from the relevant government agencies. This felling permission is dependent upon the provision of detailed information on individual tree attributes including volume. This allometric equations will facilitate this for *P. tomentosa* plantations. Moreover, with Nepal attempting to implement its REDD+ policy, the equations will provide smallholders, other investors and the government with precise estimates of the carbon stocks in such plantations.

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Relevance of *P. tomentosa* plantations to small-scale forestry and environmental conservation

As identified by Subedi et al. (2014), there is a vast scope for developing plantations of fast-growing and commercially-important trees on the large areas of non-forested public and private lands of Nepal, especially in the country's Terai and mid-hills regions. Small-scale, private landholders have an opportunity to plant *P. tomentosa,* as a fast-growing tree species for short- and long-term subsistence and economic benefits. Compared to the commercial harvesting ages for other commonly-promoted plantation species in Nepal – e.g. 45 years for *Pinus patula* (DFRS, 2008), 35 years for *Dalbergia sissoo* (Hawkins, 1987) and 50 years for *Tectona grandis* (Thapa & Gautam, 2005) – a smallholder farmer can expect to harvest commercial logs (i.e. DBH of >25cm) from *P. tomentosa* plantations at age 12 (Carpenter & Smith, 1979). Based on the stem biomass, our study suggests that there may not be economic benefit to letting the tree grow beyond 30 cm DBH which corresponds approximately to 12 years. This information provides growers with a much more attractive plantation investment opportunity.

Well-managed plantations of *P. tomentosa* on Nepal's large areas of degraded hillsides could provide multiple benefits for growers and support the much-needed environmental restoration of these areas. Firstly, such plantations will provide fodder and fuelwood to the growers thereby saving them much money that would otherwise be required to purchase these products from elsewhere. Secondly, as *P. tomentosa* is a fast-growing tree species with recognised quality timber characteristics, it presents an attractive opportunity for growers to profit by selling timber into local markets. Equally importantly, such new plantations would help to lessen hillside communities' dependency on the region's dwindling and increasingly degraded natural forests for fodder, fuelwood and timber resources. As a result, the region's biodiversity-rich natural forests (Shrestha, Shrestha, & Shrestha, 2010), which are also large carbon sinks, can be kept intact.

Concluding Comments

This study developed allometric equations for *Paulownia tomentosa* and $\ln(M) = \beta_0 + \beta_1 \ln(D)$ is the most optimal model. In addition, model 3 ($\ln(M) = \beta_0 + \beta_1 \ln(D^2 \times H)$) is an alternative model since tree height is an important factor for estimating the biomass. Such equations have not been previously developed in Nepal and so they are important for reducing uncertainties in estimating tree biomass and carbon storage in *P. tomentosa* plantations in the country. The equations provide a simple, rapid-use and reliable method for accurately estimating the biomass and carbon stocks of *P. tomentosa* plantations. The methodology applied to develop the equations can be easily replicated for other species and in other regions. The equations developed in this study can be used for estimating biomass and carbon stocks of *P. tomentosa* grown in regions with biotic, climatic and edaphic conditions similar to the study site. However, based on observed root-shoot ratio, it may not be a very desirable species in denuded areas with steep slopes. Although this study was conducted in a specific site in mid-hills of central Nepal, the findings may have broader implications for the similar biophysical regions in Nepal and other countries.

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Conflicts of Interest: The authors declare no conflict of interest.

List of abbreviations
DBH, Diameter at Breast Height; ICIMOD, International Centre for Integrated Mountain Development; REDD+, Reducing Emissions from Deforestation and Forest Degradation.

Disclaimer:
The views and interpretation in this publication are those of the authors and are not necessarily attributable to ICIMOD.

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