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Terrestrial Tree Biomass and Carbon Stock for Forests of Thimphu District, Western Bhutan Himalaya

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Abstract

Biomass and carbon stock for forests in Thimphu district in western Bhutan were assessed using non-destructive methods where woody stem ≥ 10 cm diameter at breast height (DBH) and tree height were used as inputs. Volumetric equations with variables DBH and tree height found to be the best for biomass calculation and hence used in the present study. Carbon stock was calculated by multiplying constant factor 0.5 to biomass. Results showed carbon stock varied in different tree species. *Pinus wallichiana* contributed maximum biomass and carbon stock with 171.6 Mgha^{-1} and 85.85 MgCha^{-1} respectively. The least in *Eucalyptus robusta* and *Salix babylonica* with 0.004 Mgha^{-1} and 0.002 MgCha^{-1} each. Forests which had more anthropogenic disturbances recorded with low biomass and carbon density. Biomass assessment would assist to understand sustainable forest management and its role in carbon cycle. Forests of Thimphu district has potential to increase biomass accumulation and carbon stock if anthropogenic disturbances such as illegal harvest are reduced in addition to forest ecosystem managements.

Keywords: Biomass, carbon stock, diameter at breast height (DBH), volumetric equation, wood specific gravity.

Introduction

Bhutan has a total forest area estimated to 2.68 million ha of the total land area which constitutes 69.71%, though it has decreased from 71% in 2016 (Forest Monitoring and Information Division [FMID], 2023a). It captures atmospheric carbon dioxide (CO_2) and store carbon (C) in biomass and soil (Department of Forest and Park Services [DoFPS], 2015). Forests are enormously important element in climate change due to their capability to sequester and store C (Gibbs *et al.,* 2007) and maintain global C sink as they contain 77% of all terrestrial above ground C (Brown and Lugo, 1982). CO_2 is the major greenhouse gas (GHG) and about 60% of the observed global warming is attributed to increase in its concentration in the atmosphere (Sahu *et al.,* 2015). Estimates made for Forest Resources Assessment (FRA) in 2011 showed that world's forests store 289 gigatonnes (Gt) of C in their biomass alone (Gibbs *et al.,* 2007). Forest has the potential to store 20 to 50 times more C than barren lands (Houghton and Hackler, 2001).

Assessment of biomass accumulation play significant role in studying C stock (Rabha, 2014) and it's also useful in assessing forest structure and condition (Navar, 2009). Biomass in this paper is referred as

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the organic material both above and below ground, both living and dead (Crosby *et al.,* 2010) and C stock as total carbon stored in biomass at the time of study. The amount of C stock can be inferred from the biomass accumulation since approximately 50% of forest dry biomass is C (Cairns *et al.,* 2003; FMID, 2023b; IPCC (2006). Biomass is not only a major source of energy for nearly 50% of world's population but also a major renewable energy source and important source of food, fodder and fuel (Salunkhe *et al.,* 2016). Biomass can be measured either in terms of fresh weight or dry weight. Biomass estimation to infer CO_2 capture and C storage in plant biomass and soil attracted global attention especially after inception of Kyoto Protocol (Rabha, 2014).

In Bhutan, biomass and C storage concept grew progressively after pledged to remain C neutral during Conference of Party (COP) 21 in Paris. Total carbon stock of Bhutan is 609.01 million tonnes which translates to a carbon density of 268.94 tonnes ha-^{1} including carbon in non-forest areas (FMID, 2023b). In the context of global climate change, addressing issues related to the rising levels of CO_2 and other greenhouse gas concentrations has become a growing concern. In the overall landscape of climate change, forests play a unique role, acting as either C sinks or sources depending on their health (Sahu *et al.,* 2015).

Biomass estimation is crucial for sustainable forest management and to understand the role of forest as source or sink of C. Biomass and C stock assessment concepts through non-destructive approach are quite new in Bhutan regardless of important element of forest valuation. Studies pertaining to C stock were hardly conducted using non-destructive methods due to lack of reliable volumetric equation and wood specific gravity. Thus, the study was oriented to estimate biomass and carbon stock through non-destructive approach where tree height, DBH, species specific gravity and volumetric equations were used.

Materials and Methods

Study site

The study was conducted in four forest ranges of Thimphu District (Figure 1), namely Gidakom forest range (GFR), Thimphu forest range (TFR), Chamgang forest range (CFR) and Khasadrapchu forest range (KFR). District lies in western part of the country and shares an international boundary with China. It has 81,571.41 ha (45.18%) of its area under forest cover of the total geographical area with tree count 415 (No. ha^{-1}) (FMID, 2023a). The District has the total forest growing stock of 353.33 volume (m^{3} ha^{-1}) (FMID, 2023a). It is located at an elevation of 2,330 meters above the sea level (masl). It is situated between latitude 27.5959° N and longitude 89.5875° E. The average annual rainfall of the District is 1599 mm and annual temperature is 11.6 °C. Of the total geographical area, about 13% is under permanent snow cover and glaciers, where tree growth is not possible due to climatic and physical limitations.

Protected areas included in the District are Jigme Dorji National Park (JDNP) in the North and Biological corridor of JDNP and Jigme Singye Wangchuck National Park (JSWNP) in East. In central and southern region a drastic land use land cover (LULC) change has taken place and people's mindset over modern development is in verge of creating void for the need of forest conservation and management in the area. It is also affected with heavy/fast land conversion to developmental activities due to increasing population as 120,428 (16.1%) people of the total country's population (742,249) live in Thimphu district (Gross National Happiness Commission [GNHC], 2014).

Major forest types of Thimphu are coniferous forests, mixed coniferous forests, broad-leaved ad cool broad-leaved forests. Dominant tree species recorded from sampled plots in central and southern District are *Pinus wallichiana, Juglans regia, Quercus griffithii* and *Quercus semecarpifolia*. Common species found in Northern area are *Rhododendron arboretum, Taxus baccata* and *Pinus wallichiana.* All five carbon pools associated with tree species such as above ground biomass (AGB), below ground biomass (BGB), dead wood, litter and soil organic matter (SOM) were included to get the total biomass accumulation and infer C stock (Suberi *et al.,* 2018).

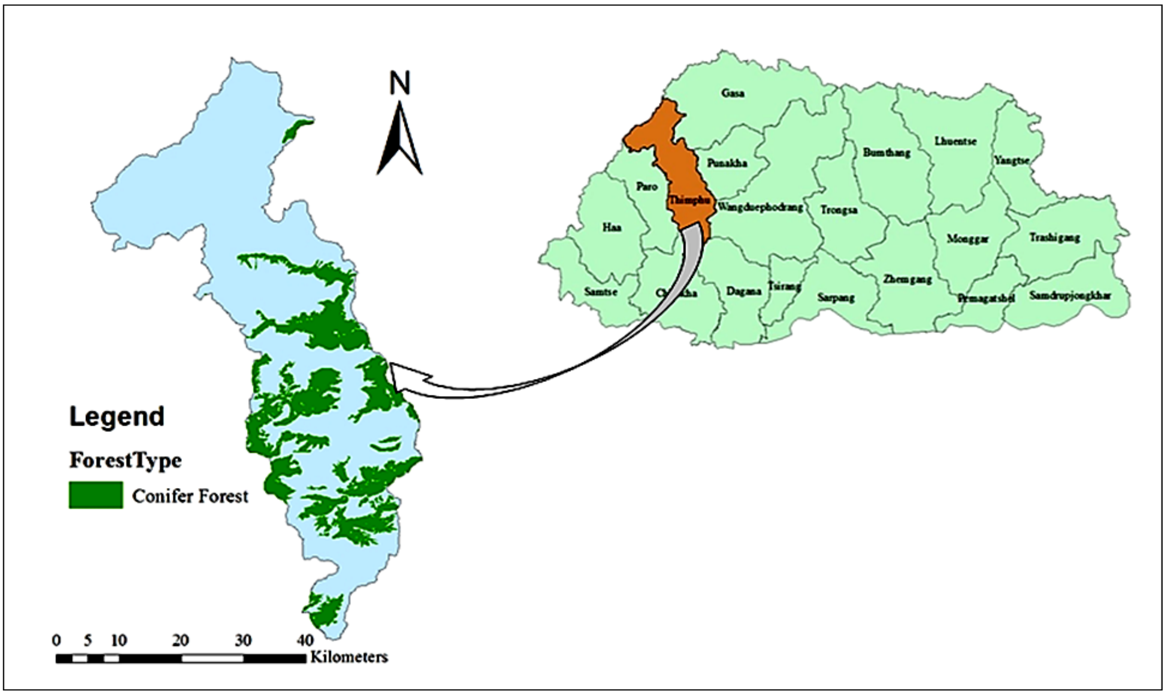

Figure 1. Study area showing conifer forest

Study design and data collection

Total sampling plots required was calculated using formula N1 = C1/TA (where N1=maximum number of sampling plots required, C1=size of the cluster (ha), TA=size of sampling plot (ha)). The 14% sampling intensity was used resulting to 56 sampling plots. Following good practices guidance (GPG) of Intergovernmental Panel on Climate Change, IPCC (2006) and Forest Survey of India (FSI) 2015, nested quadrates size of 31.62 m x 31.62 m were drawn. Tree trunk having ≥ 10 cm diameter at breast height (DBH: 1.37 m above ground) were considered as trees (Borah *et al.,* 2013; FMID, 2023a; FMID, 2023b; Rabha 2014; Salunkhe *et al.,* 2016; Shahid and Joshi 2015).

A total of 1187 plant taxa belonging to six families and 12 species were recorded from sampled inventory plots. DBH was recorded using diameter tapes on standing trees and Forestry 550/Hypsometer was used for measuring tree height. The diameters were classified into 10 classes of ≥10-20 cm, 20-30 cm, 30-40 cm, 40-50 cm, 50-60 cm, 60-70 cm, 70-80 cm. 80-90 cm, 90-100 cm and ≥100 cm following FMID (2023a) and FMID (2023b). *Quercus griffithii, Pinus wallichiana* and *Quercus lanata* were common species in most of the sampling plots.

Non-destructive biomass estimation

To estimate biomass accumulation using non-destructive approach, DBH i.e. 1.37 m above ground were measured using diameter tape (FMID, 2023a; FMID, 2023b). The DBH (cm) obtained was converted to DBH (m) as it is the requirement of species specific volume equations. Species specific volume equations developed by FSI (1996) and (2015) were used to calculate volume (V: m^3). For species without specific volumetric equations, general volumetric equations were applied based on FSI (1996). Majority of wood density (WD) values of different species were selected from FSI (2015). For species with unknown wood density, the general constant factor was used. Volume (V) of trees (m^3 $tree^{-1}$) with ≥10 cm diameter obtained was converted into individual bole biomass (BB) by multiplying with species specific WD (Equation 1) (Ahmad *et al.,* 2014; Mandal and Joshi, 2015). The BB of all individual trees were summed to obtain biomass in hectare basis.

(BB = V x WD) (Equation 1)

To obtain aboveground biomass (AGB), WD obtained in hectare basis was multiplied with biomass extension factor (BEF) as prescribed by GPG of IPCC (2006), and Mandal and Joshi (2015).

(AGB = W x BEF) (Equation 2)

Belowground biomass (BGB) was calculated by multiplying the value of AGB with constant factor 0.26 (Joshi *et al.,* 2020; Sahu *et al.,* 2015; Shahid and Joshi 2015; Srinivas and Sundarapandian 2019; Subashree and Sundarapandian, 2017

(BGB=AGBx 0.26) (Equation 3)

Dead organic matter (DOM) obtained by adding AGB and BGB and then by multiplying the sum with constant factor 0.11 of IPCC (2006) and Mandal and Joshi (2015).

DOM=(AGB+BGB)x 0.11 (Equation 4)

Total biomass (TB) was obtained by adding AGB, BGB and DOM.

TB=AGB + BGB + DOM (Equation 5)

Carbon stock

The C stock for individual tree species was calculated by multiplying total biomass of specific species with constant factor as prescribed by GPG of IPCC (2006). Total C stock estimation was computed by multiplying total biomass of all species of the sampled forest inventory with constant factor 0.5 (Borah *et al.,* 2013; Chaudahury and Upadhaya, 2016; IPCC, 2006; Mandal and Joshi, 2015; Rabha, 2014; Shahid and Joshi, 2015; Sun *et al.,* 2016; Terakunpisut *et al.,* 2007; Tshering, 2019; Tshering and Rinzin, 2022).

C= TB x 0.5 (Equation 6)

Results and Discussion

Biomass and carbon stock in four forest ranges of Thimphu

Total bole biomass (BB) accumulated was 86.115 Mg ha^{-1} with average 21.529±5.293 Mg ha^{-1}. Thimphu forest range (TFR) had the highest BB accumulation 28.019 Mg ha^{-1} and lowest from Gidakom forest range (GFR) 14.450 Mg ha^{-1} (Figure 2). Total above ground biomass (AGB) was 136.923 Mg ha^{-1} with an average 34.231±8.416 Mg ha^{-1}. Dominant trees which contributed maximum BB and AGB were *Pinus wallichiana* followed by *Cedrus deodara, Juglans regia,* and *Rhododendron arboretum.* Total belowground biomass (BGB) and dead organic matter (DOM) recorded from the sampled forest inventory was 35.600 Mg ha^{-1} and 18.978 Mg ha^{-1} respectively. TFR had the highest DOM 6.175 Mg ha^{-1} and lowest from GFR 3.184 Mg ha^{-1} (Figure 2). Average BGB and DOM accumulation was 8.899±2.188 Mg ha^{-1} and 4.744 Mg ha^{-1} respectively (Table 1).

Mandal and Joshi (2015) had done site wise biomass and C stock analysis and reported highest biomass 426.75 Mg ha^{-1} in Rajpur Forest Range from Doon valley which is situated in western Himalaya. A similar comparison was carried out in Thimphu District which is situated in eastern Himalaya. TFR was reported with highest biomass accumulation of 62.306 Mg ha^{-1} and C stock 31.153 Mg C ha^{-1} when converted from biomass with prescribed conversion factor provided by GPG of IPCC (2006) and Rabha (2014). In agreement with Mandal and Joshi (2015), low biomass and C sequestration potential of GFR and CFR was due to more anthropogenic disturbances which resulted into large canopy gaps and big patches in forest. This has reduced the per hectare density of tree species and affected the DBH and tree height and therefore received a comparatively less biomass and C stock.

Biomass contribution from four territorial forests ranged between 32.133 - 62.308 Mg ha^{-1} with an average 47.875 ± 11.77 Mg ha^{-1} (Table 1). Biomass represented the largest organic carbon pool in forest ecosystem. The change in forest biomass was considered as key characteristic of forest ecosystem and its variability can be explained by certain parameters like climate, topography, wood density, volumetric equation and distribution of tree species.

Total carbon (C) stock of the sampled inventory was 95.740 Mg C ha^{-1} with average of 23.938 ± 5.886 Mg C ha^{-1}. C stock of four territorial forests ranged between 16.066 - 31.154 Mg C ha^{-1}. Total C stock in different forest biomass of the study area were as follows: Bole biomass (43.058 Mg C ha^{-1}), AGB (68.462 Mg C ha^{-1}), BGB (17.800 Mg C ha^{-1}) and DOM (9.489 Mg C ha^{-1}) (Table 2). TFR had sequestrated the maximum C 31.154 Mg C ha^{-1} with average 11.291 ± 7.509 Mg C ha^{-1} (Table 1).

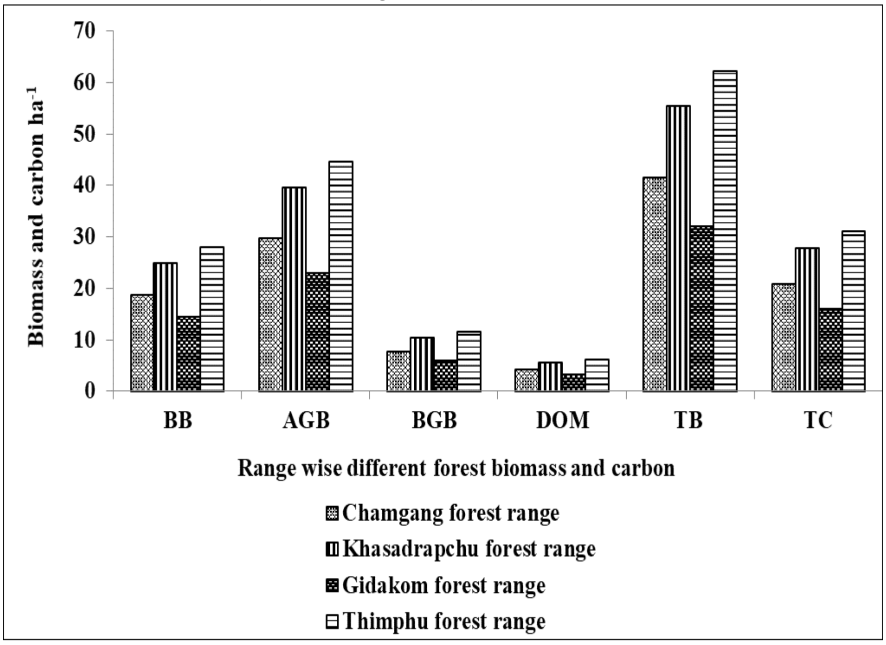

Figure 2. Different forest biomass and carbon sequestration in four forest range

The total biomass 191.501 Mg ha^{-1} of present study is comparable to total biomass of Asarori forest range, and Selaqui and Jhajra forest fange of Doon valley with 196.47 Mg ha^{-1} and 185.86 Mg ha^{-1} respectively (Mandal and Joshi, 2015). Total biomass of the present study is much less than estimated average biomass 258.98 Mg ha^{-1} of coniferous forest of Dir Kohistan (Ahmad *et al.,* 2014), total biomass 51.61 ± 0.60 Mg ha^{-1} of oak scrub forest of Sheringal valley Dir Kohistan by Khan *et al.* (2015) and the tropical forest of Nagathol forest (261.64 $Mgha^{-1}$) (Borah et al. 2013) is much less than the present study. However, present study score (191.501 $Mgha^{-1}$) was found higher than that of Monbel forest (166.94 $Mgha^{-1}$), Rose Kandy (144.01 $Mgha^{-1}$), Bhuban hill (116.8 $Mgha^{-1}$) and Dolu forest (99.10 $Mgha^{-1}$) (Borah et al. 2013). the present score falls within the biomass range of temperate forests of Kashmir Himar laya (Dar & Sundarapandian 2015) and tropical dry forest of East Godavari region, Andhra Pradesh (58.04 to 368.39 $Mgha^{-1}$) (Srinivas & Sundarapandian 2019).

Total C stocks reported by Terakunpisut *et al.* (2007) of Tropical rain forest (Ton Mai Yak station), dry evergreen forest (KP 27 station) and mixed deciduous forest (Pong Phu Ron station) with 137.73 ± 48.07, 70.29 ± 7.38 and 48.14 ± 16.72 Mg C ha^{-1} respectively are much higher than total C stock 95.740 ± 5.886 Mg C ha^{-1} of present sampled inventory. Average C stock 119.73 ± 6.4 Mg C ha^{-1} and 25.80 ± 0.47 Mg C ha^{-1} of an undisturbed regenerating sal forest of Goalpara district, Assam of northeast India (Rabha, 2014) and oak scrub forest of Sheringal valley Dir Kohistan (Khan *et al.,* 2015) are also higher than present C stock average of 23.938 ± 5.886 Mg C ha^{-1}. However, C stock in aboveground tree biomass of 11-74 Mg C ha^{-1} in crop trees of managed conifer forests in northern Ontario of Canada (Hunt *et al.,* 2010) is less than present study. Further, total C stock of 77.34 Mg C ha^{-1} and 57.36 Mg C ha^{-1} of sal forest of Golatappar forest range and Asarori forest range of Doon valley (Mandal and Joshi, 2015) are also less than present total C stock 95.740 ± 5.886 Mg C ha^{-1}. The variation in biomass and C stocks in forest ecosystems could be due to geographical regions and their locality factors (Joshi et al. 2020), forest

Table 1. Range wise biomass accumulation and carbon stock

	Above ground		Below ground		Dead Organic Mat-		Total	
Range ID	**Biomass**	**Carbon**	**Biomass**	**Carbon**	**Biomass**	**Carbon**	**Biomass**	**Carbon**
1a	29.713	14.856	7.725	3.863	4.118	2.059	41.556	20.778
1b	39.685	19.843	10.318	5.159	5.5	2.75	55.503	27.752
1c	22.975	11.487	5.973	2.987	3.184	1.592	32.133	16.066
1d	44.55	22.275	11.583	5.792	6.175	3.087	62.308	31.154
Mean	**34.231**	**17.115**	**8.899**	**4.45**	**4.744**	**2.372**	**47.875**	**23.938**
SD	**± 8.416**	**± 4.208**	**± 2.188**	**± 1.094**	**± 1.167**	**± 0.583**	**± 11.77**	**± 5.886**

types, species composition, vegetation management pattern, and stand age (Chaudhury & Upadhaya 2016; Singh & Verma 2018) and certain environmental factors like climate, topography, distribution of tree species and its abundance in sampled plots (Chaudhury & Upadhaya 2016; Prasadrao and Rao, 2015).

The overall total biomass (201 tonnes ha^{-1}) reported for the whole Thimphu District by FMID (2023b) was higher than the present total biomass score (191.501 Mg ha^{-1}). This was to the fact that FMID (2023b) included four main components (trees, saplings, shrubs and herbs) as well as soil carbon, but the present study only included biomass of trees.

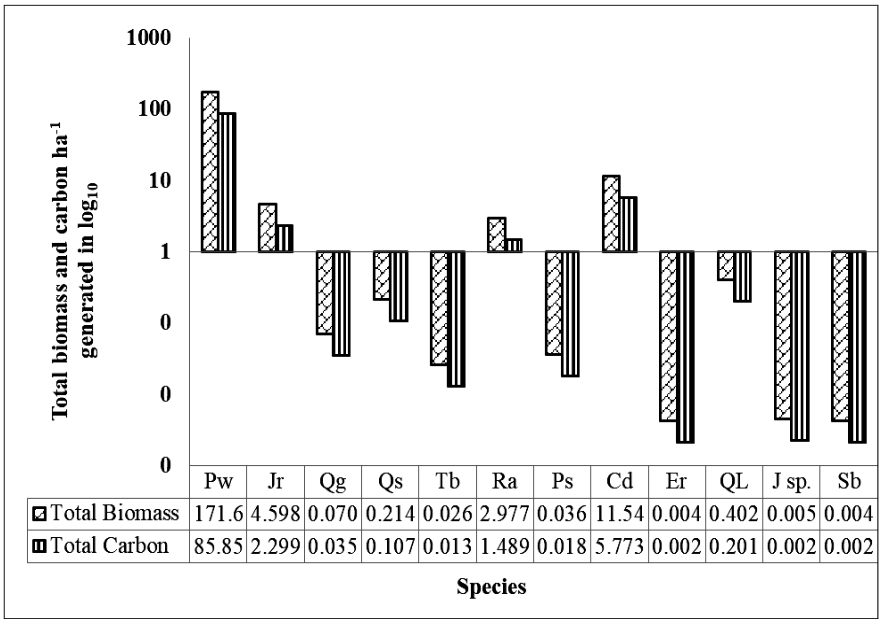

Figure 3. Species wise comparison of biomass accumulation and carbon stock

Abbreviations: Pw- *Pinus wallichiana,* **Jr**- *Juglans regia,* **Qg**- *Quercus griffithii,* **Qs**- *Quercus semecarpifolia,* **Tb**- *Taxus baccata,* **Ra**- *Rhododendron arboretum,* **Ps**- *Picea spinulosa,* **Cd**- *Cedrus deodara,* **Er**- *Eucalyptus robusta,* **QL**- *Quercus lanata,* **J sp**- *Juniper* sp. and **Sb**- *Salix babylonica.*

Tree species wise biomass and carbon stock

The *Pinus wallichiana* was dominant species with biomass 35.550 Mg ha^{-1}, 50.579 Mg ha^{-1}, 31.780 Mg ha^{-1} and 53.789 Mg ha^{-}1 with C stock of 17.775 Mg C ha^{-1}, 25.579 Mg C ha^{-}1, 15.890 Mg C ha^{-}1 and

26.895 Mg C ha^{-1} from CFR, KFR, GFR and TFR respectively. In total, *Pinus wallichiana* had biomass accumulation of 171.6 Mg ha^{-1} sequestering total C stock 85.85 Mg C ha^{-1}. Co-dominant species *Cedrus deodara* from TFR had total biomass 4.919 Mg ha^{-1} with C stock 2.459 Mg C ha^{-1}. The lowest was reported in *Salix babylonica,* and *Eucalyptus robusta* with biomass 0.004 Mg ha^{-1} and C stock potential 0.002 Mg C ha^{-1} each (Figure 3). High biomass and C stock potential in *Pinus wallichiana* was due to its abundance occurrence (705 individuals of the total 1187 trees) in sampled inventory. The present study is also in agreement that Pines (*Pinus*) are the most widely distributed conifers in montane forests (Waring, 2002). This variability in biomass accumulation and carbon stock can be also explained by several factors like wood density, specific tree volumetric equation and species richness.

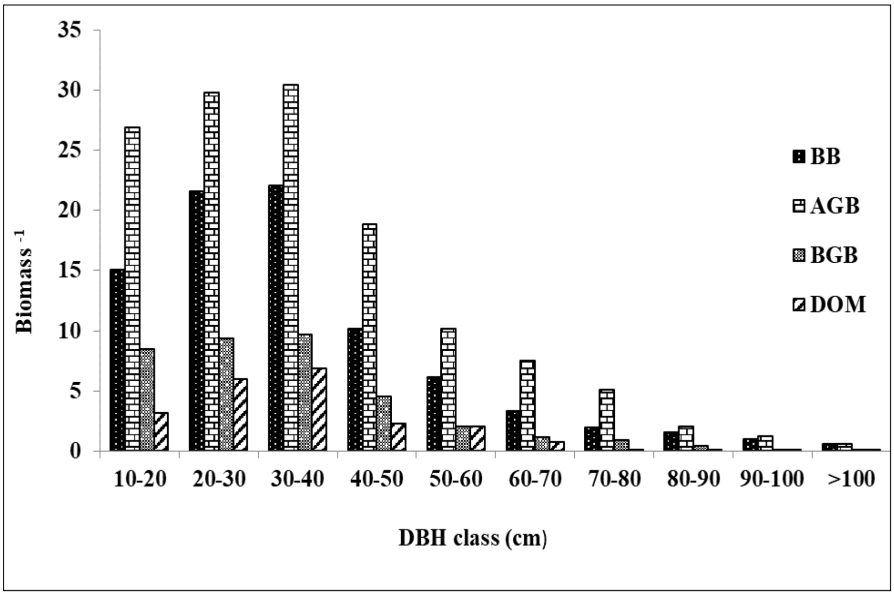

Figure 4. Comparison of different forest biomass in different DBH classes

Biomass and carbon stock by diameter classes

Dominant DBH class was 30–40 cm followed by 20–30 cm which accounted with highest AGB accumulation i.e. 30.446 Mg ha^{-1} and 29.798 Mg ha^{-1} respectively. DBH class 30–40 cm also had the highest BB, BGB and DOM accumulation with 22.054, 9.676 and 6.893 Mg ha^{-1} respectively (Figure 4). High tree density at lower DBH classes showed right skewed trend indicating young forest stands like that of the right- skewed trend at protected forest of the International Centre for Integrated Mountain Development (ICIMOD) Knowledge Park (Karki et al., 2016). The DBH class >100 cm had BB 0.574 Mg ha^{-1}, AGB 0.607 Mg ha^{-1}, BGB 0.052 Mg ha^{-1} and DOM 0.001Mg ha^{-1}. The comparison of DBH class distribution and biomass accumulation showed biomass reduction in larger DBH of 60–70, 70–80, 80–90, 90–100 and > 100 cm. Similar findings on biomass reduction in larger DBH classes was reported by Rabha *et al.*

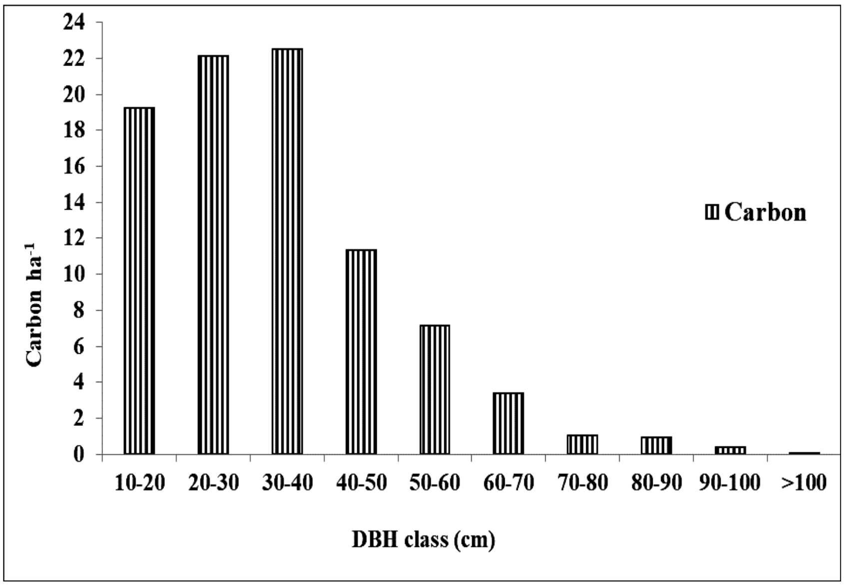

Figure 5. Comparison of total carbon sequestration in different DBH classes

(2014). Biomass reduction at DBH class > 60-80 and > 80-100 cm were also found by Terakunpisut *et al.,* 2007). Causes of biomass reduction in larger DBH tree sizes in the present study was mainly due to low tree density at DBH size > 60 - >100 cm.

Contrary fact is that biomass accumulation should be found high in bigger trees of DBH size at ≥ 80-100 cm and > 100 cm as its usually found with highest stem volume, high basal area, and large diameter and vice-versa for small trees (Fredeen *et al.,* 2005; He *et al.,* 2013; Rabha, 2014). Highest biomass accumulation in present study at lower DBH tree size was due to the fact that study area had almost similar pattern of tree size class with dominant at ≥ 10-40 cm.

The C stock of trees which would be about 50 % of the total biomass was calculated with the method used by IPCC (2006), Mandal and Joshi (2015) and Rabha (2014). The highest C stock was found at DBH tree size 30-40 cm with 22.507 Mg C ha^{-1} and lowest at > 100 cm with 0.005 Mg C ha^{-1} of the total 88.096 Mg C ha^{-1}. Similar finding of high C stock at DBH tree size > 4.5-20 up to > 40-60 cm was reported by Terakunpisut *et al.* (2007) in tropical rain forest and dry evergreen forest, and > 20-40 cm up to > 40-60 cm in mixed deciduous forest. In present study, larger tree size of DBH from > 60-70 cm up to > 100 cm were reported with low C stock due to low tree density, species relative frequency and abundance at larger DBH tree size. Similarly, Rabha (2014) also reported high C stock at DBH 20-30 cm compared to 30-40 cm. This indicates that C sequestration potential at lower DBH tree size (young trees) is more compared to old tree stand.

DBH class distribution that had the highest potential in C stock ranged from small to medium tree size 10–20 cm, 20–30 cm and 30–40 cm. DBH class 30–40 cm was reported the highest with 23.507 Mg C ha^{-1} and lowest in >

Table 2. Different forest biomass and carbon stock potential

Different biomass and carbon	CFR	KFR	GFR	TFR	Total biomass	Total carbon
BB	18.687	24.959	14.450	28.019	86.115	43.058
AGB	29.713	39.685	22.975	44.550	136.923	68.462
BGB	7.725	10.318	5.973	11.583	35.600	17.800
DOM	4.118	5.500	3.184	6.175	18.978	9.489
Total biomass	41.556	55.503	32.133	62.308	191.501	-
Total carbon	20.778	27.752	16.066	31.144	95.740	-

Abbreviations: BB-Bole biomass, **AGB**-Above ground biomass, **BGB**-Below ground biomass, **DOM**-Dead organic matter, **CFR**-Chamgang forest range, **KFR**-Khasadrapchu forest range, **GFR**-Gidakom forest range and **TFR**-Thimphu forest range.

Table 3. Correlation relationship between DBH and biomass, and DBH and carbon stock

	DBH class	BB	AGB	BGB	DOM
DBH class	x	x	x	x	x
BB	-.879**	x	x	x	x
AGB	-.941**	.983**	x	x	x
BGB	-.908**	.987**	.990**	x	x
DOM	-.809**	.982**	.940**	.944**	x
Carbon	-.920**	x	x	x	x

100 cm (0.330 Mg C ha^{-1}) (Figure 5) of total 95.751 Mg C ha^{-1}. Larger tree size of DBH classes from > 60 – 70 cm up to > 100 cm were reported with low C stock due to low tree density at larger DBH tree size. It was also found that C stock decreased considerably with biomass reduction. In this study, *Pinus wallichiana* was dominant tree having maximum C stock as most of its DBH falls within 15–50 cm and also high density compared to other species.

Correlation analysis generated strong negative association between DBH above 60 – 100 cm and different biomass accumulation with r = -.879** (BB), r = -.941** (AGB), r = -.908** (BGB) and the r = -.809** (DOM) at p value < 0.01 as different biomass started decreasing drastically with DBH above 60 – 100 cm. Similar trend was observed for total estimates for carbon stock with r = -.920** at p value < 0.01. However, the different biomass (BB, AGB, BGB, DOM) and carbon stock increases with increase in DBH class, till it reaches a peak of BB = 22.054 Mg ha^{-1}, AGB = 30.446 Mg ha^{-1}, BGB = 9.676 Mg ha^{-1}, DOM = 6.893 Mg ha^{-1} and C = 23.507 Mg C ha^{-1} in 30-40 DBH Class, and then decreases. The BB, AGB, BGB and DOM were strongly associated with positive relations to changes in each other's biomass at p value < 0.01

Conclusion and Recommendation

Biomass accumulation and carbon stock in different DBH classes showed a right-skewed trend indicating young forests for high biomass accumulation and carbon stock potential if it's conserved sustainably by reducing anthropogenic disturbances such as illegal harvest. However, Bhutan has limited data on non -destructive biomass estimation and carbon stock potential. This resulted due to limited number of species specific volume equation and wood density particularly on conifer forests. Additionally, study area has undergone land use land cover change causing reduction in forest cover. This resulted from disturbances such as timber harvest, anthropogenic forest fire, grazing, garbage and clearing of forests for increasing demand of housing structures.

The similar methods of non-destructive biomass estimation and carbon stock conversion may be applied in other forest types with similar vegetation composition distribution and climatic condition. This findings may serve as baseline data. The reliability on the methodology and similar findings of repetitive studies will enable benefit transfer to forests conservation. It is therefore, necessary to obtain more accurate and precise biomass estimation and carbon stock potential to understand the role of forests in carbon cycle.

References

Ahmad, A., Mirza, S.N. and Nizami, S.M. (2014). Assessment of Biomass and Carbon Stocks in Coniferous Forest of Dir Kohistan, KPK. *Pak. J. Agri. Sci,* 51(2):335-340.

Brown, S. and Lugo, A.E. (1982). The Storage and Production of Organic Matter in Tropical Forests and Their Role in the Global Carbon cycle. *Biotropica,* 14(3):161-187.

Borah, N., Nath, A.J. and Das, A.K. (2013). Aboveground biomass and carbon stocks of tree species in tropical forests of Cachar District, Assam, Northeast India. *Int. J. Econ. Environ. Stud.,* 39(2):97-106.

Cairns, M.A., Olmsted, I., Granados, J. and Argaez, J. (2003). Composition and aboveground tree biomass of a dry semi-evergreen forest on Mexico's Yucatan Peninsula. *Forest Ecology and Management,* 186:125-132.

Chaudhury, G. and Upadhaya, K. (2016). Biomass and carbon stock in sub-tropical broad-leaved forest ecosystem of Meghalaya, Northeast India. *Int. J. Econ. Environ. Stud.,* 42(2):125-133.

Crosby, C., Ford, A., Free, C., Hofmann, C., Horvitz, E., May, E. and Vara, R. (2010). *Carbon Sequestration and its Relationship to Forest Management and Biomass Harvesting in Vermont.* Vermont: Middlebury College.

Dar, J. A. and Sundarapandian, S. (2015). Variation of biomass and carbon pools with forest type in temperate forests of Kashmir Himalaya, India. *Environ. Monit. Assess.* 5(3):81-96.

Department of Forest and Park Services. (2015). *600th community forest handed over.* Thimphu: Ministry of Agriculture and Forest (MoAF).

Forest Monitoring and Information Division. (2023a). *National Forest Inventory Volume I: State of Forest Report.* Thimphu, Bhutan.

Forest Monitoring and Information Division. (2023b). *National Forest Inventory Volume II: State of Forest Carbon Report.* Thimphu, Bhutan.

Forest Survey of India (FSI). (2015). *India State of Forest Report.* Dehradun, Uttarakhand, India: Forest Survey of India.

Forest Survey of India (FSI). (1996). *Volume Equations for Forests of India, Nepal and Bhutan.* Dehradun, India: Forest Survey of India, Ministry of Environment and Forest.

Fredeen, A.L., Bois, C.H., Janzen, D.T. and Sanborn, P.T. (2005). Comparison of coniferous forest carbon stocks between old-growth and young second-growth forests on two soil types in central British Columbia, Canada. *Canadian Journal of Forest Research,* 35(6): 1411-1421.

Gibbs, H.K., Brown, S., Niles, J.O. and Foley, J.A. (2007). *Monitoring and estimating tropical forest carbon stocks: making REDD a reality.* IOP Publishing Ltd.

Gross National Happiness Commission. (2014). *Ecological Footprint of Bhutan and its Regions.* Thimphu: Royal Government of Bhutan in collaboration with Otago Polytechnic.

He, Q., Chen, E., An, R. and Li, Y. (2013). Above-Ground Biomass and Biomass Components Estimation Using LiDAR Data in a Coniferous Forest. *Forests*, 984-1002.

Houghton, R.A. and Hackler, J.L. (2001). *Carbon Flux to the Atmosphere from Land-Use Changes: 1850 to 1990.* Environmental Sciences Division .

Hunt, S.L., Gordon, A.M. and Morris, D.M. (2010). Carbon Stocks in Managed Conifer Forests in Northern Ontario, Canada. *Silva Fennica,* 44(4): 563–582.

Intergovernmental Panel on Climate Change. (2006). *Guidelines for National Greenhouse Gas Inventories.* Hayama, Japan.

Joshi, R., Singh, H., Chhetri, R. and Yadav, K. (2020). Assessment of carbon sequestration potential in degraded and non-degraded community forests in the Terai region of Nepal. *Journal of Forest and Environmental Science*, 36(2):113-121.

Karki, S., Joshi, N.R., Udas, E., Adhikari, M.D., Sherpa, S., Kotru, R. and Ning, W. (2016). *Assessment of Forest Carbon Stock and Carbon sequestration Rates at the ICIMOD Knowledge park in Godavari.* Kathmandu, Nepal: International Centre for Integrated Mountain Development .

Khan, A., Ahmad, A., Rahman, Z., Din, S.U., Qureshi, R. and Muhammad, J. (2015). The Assessment of Carbon Stocks in the Oak Scrub Forest of Sheringal Valley Dir Kohistan. *Open Journal of Forestry*, 510-517.

Mandal, G. and Joshi, S.P. (2015). Biomass accumulation and carbon sequestration potential of dry deciduous forests. *International Journal of Ecology & Development,* 30(1):65-82.

Navar, J. (2009). Allometric equations for tree species and carbon stocks for forests of northwestern Mexico. *Forest Ecology and Management,* 257: 427–434.

Prasadrao, B.R. and Rao, V.S. (2015). Carbon sequestration potential of tropical deciduous forests of Nallamalais, India. *Asian Journal of Plant Science and Research,* 5(3):24-33.

Rabha, D. (2014). Aboveground Biomass and Carbon Stocks of an Undisturbed Regenerating sal (Shorea robusta Gaertn. f.) Forest of Goalpara District, Assam, Northeast India. *International Journal of Environment,* 3(4):147-155.

Sahu, S.C., Sharma, J. and Ravindranath, N.H. (2015). Carbon stocks and fluxes for forests in Odisha (India). *Tropical Ecology,* 56(1):77-85.

Salunkhe, O., Khare, P.K., Sahu, T.R. and Singh, S. (2016). Estimation of tree biomass reserves in tropical deciduous forests of Central India by non-destructive approach. *Tropical Ecology,* 57(2):153-161.

Singh, S. and Verma, A. K. (2018). Biomass and carbon stocks in different forest types of western Himalaya. *Tropical Ecology*, 59(4):647-658.

Shahid, M. and Joshi, S.P. (2015). Biomass and carbon stock assessment in moist deciduous forests of Doon Valley, Western Himalaya, India. *Taiwania*, 60(2):71-76. https://doi.org/10.6165/tai.2015.60.71.

Srinivas, K. and Sundarapandian, S. (2019). Biomass and carbon stocks of trees in the tropical dry forest of east Godavari region, Andhra Pradesh, India. *Geology, Ecology, and Landscapes*, 3(2):114-122.

Subashree, K. and Sundarapandian, S. (2017). Biomass and carbon stock assessment in two savannahs of Western Ghats, India. *Taiwania*, 62(3):272-282.

Suberi, B., Tiwari, K.R., Gurung, D.B., Bajracharya, R.M. and Sitaula, B.K. (2018). Effect of Harvesting and Non-Harvested Forest Management on Carbon Stocks. *International Journal of Environment and Climate Change,* 8(3):152-164.

Sun, X., Wang, G., Huang, M., Chang, R. and Ran, F. (2016). Forest biomass carbon stocks and variation in Tibet's carbon-dense forests from 2001 to 2050. *Scientific Reports*, 6(1).

Terakunpisut, J., Gajaseni, N. and Ruankawe, N. (2007). Carbon sequestration potential in aboveground biomass of Thong Pha Phum National Forest, Thailand. *Applied Ecology and Environmental Research,* 5 (2):93-102.

Tshering, S. (2019). Importance value index and assessment of carbon stocks in western Bhutan Himalaya (Thimphu). *Curr. J. Appl. Sci. Technol.*, 32(2):1-8.

Tshering, S. and Rinzin, P. (2022). Terrestrial Biomass and Carbon Stock in Broad-leaved Forests of Punakha District, Western Bhutan. *Nature Environment and Pollution Technology,* 21(1):175-181.

Waring, R. H. (2002). Temperate Coniferous Forests. (H. A. Mooney, J. G. Canadell and T. Munn, Eds.) *Encyclopedia of Global Environmental Change,* 2:560–565.