Estimation of Biomass and Carbon Stock of Bamboo Species through Development of Allometric Equations

ICIMOD

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On behalf of:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
of the Federal Republic of Germany

NORWEGIAN MINISTRY OF FOREIGN AFFAIRS

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Indian Council of Forestry Research and Education
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P.O. New Forest, Dehradun – 248006 (INDIA)

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Authors:

Dr. R.S. Rawat, Scientist Incharge, Biodiversity and Climate Change Division

Dr. Gurveen Arora, Research Associate, Biodiversity and Climate Change Division

Mr. V.R.S. Rawat, REDD+ Expert Consultant, Biodiversity and Climate Change Division

Mr. H.R. Borah, ACTO, Forest Research Centre on Bamboo and Rattan

Mr. M.Z. Singson, Head, Forest Research Centre on Bamboo and Rattan

Dr. Girish Chandra, Scientist, Forestry Statistics Division

Mr. Raman Nautiyal, Scientist, Forestry Statistics Division

Dr. Jaiyati Rawat, Consultant, Biodiversity and Climate Change Division

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International Centre for Integrated Mountain and Development (ICIMOD), Kathmandu, Nepal

Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ), Germany

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Forest Research Centre for Bamboo and Rattan (FRCBR), Aizawl, Mizoram

Department of Environment, Forest and Climate Change, Mizoram

Guidance and Support

Dr. Suresh Gairola, Director General, ICFRE

Mr. S.D. Sharma, Dy. Director General (Research), ICFRE

Dr. Bhaskar Singh Karky, Resource Economist, ICIMOD

Mr. Kai Windhorst, Chief Technical Advisor, GIZ

Mr. K. Kire, APCCF, Department of Environment, Forest and Climate Change Mizoram

Mr. Nabin Bhattarai, Research Associate, ICIMOD

Field staff of FRCBR, Aizawl

Layout & Design

Mr. Umang Thapa, BCC Division, ICFRE

Abbreviations Used

C	Carbon
CDM	Clean Development Mechanism
Cm	Centimetres
CO_2	Carbon dioxide
CO_2eq.	Carbon dioxide equivalent
COP	Conference of Parties
DBH	Diameter at breast height
Df	Degree of freedom
GPS	Global Positioning System
ha	Hectare
INBAR	International Network for Bamboo and Rattan
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
km	Kilometer
M	Meter
Mg	Megagram (1 Mg = 1 tonne)
msl	mean sea level
Mt	Million Tonnes
NTFP	Non Timber Forest Products
R^2	Coefficient of determination
REDD+	Reducing emissions from deforestation and forest degradation in developing countries, and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries
RMSE	Root mean square error
sq km	square kilometer
T	Tonnes
TDW	Total Dry Weight
UNFCCC	United Nations Framework Convention on Climate Change

Executive Summary

Bamboo is a major commodity which helps in bringing both tangible and intangible benefits such as biodiversity conservation, soil and water conservation, carbon sink, food and handicraft etc. especially in North-East India. It forms an important component in the traditional agroforestry system. It differs from timber species because of its anatomical features and its growth pattern. This necessitates modelling its growth by destructive sampling and developing predictive models for biomass on the basis diameter at breast height (DBH) and height.

This research report has comprehended an inclusive approach by developing allometric equations for five bamboo species (*Bambusa tulda, Dendrocalamus hamiltonii, Dendrocalamus longispathus, Melocanna baccifera, Schizostachyum dullooa*) to measure biomass and carbon stock from culm. The developed equations will be helpful for estimation of biomass in the similar physiographic and climatic region for all the five bamboo species.

Thirty three sample plots were laid out to develop allometric equation for the prediction of biomass estimation by using destructive method under REDD+ Himlaya project area in Mamit district of Mizoram. The sample plots each with an area of 0.1ha were laid out for the collection of data and parameters like DBH and height. Culms were categorised into three diameter classes (<3 cm, 3-5 cm, >5 cm). Samples were taken for the laboratory analysis (dry weight method) to obtain the biomass in each diameter class. These variables served the basis for development of allometric equations and estimation of biomass and carbon stock of bamboo species.

Regression analysis was used to analyse the relationship between culm biomass with DBH and height using STATISTICA release 7.0 software. Allometric equations were obtained to develop the relationship for estimating culm biomass. Goodness of fit (R^2 and RMSE) was considered for reliability of the equations developed. Coefficient of determination (R^2) ranged from 0.68-0.85 and root mean square error (RMSE) ranged from 0.33-1.87 for different bamboo species. Allometric equations developed for five species of bamboo are $Y=-2.62+0.91*DBH+0.25*ht$ (for *Bambusa tulda*), $Y=2.43+1.17*DBH-0.70*ht$ (for *Dendrocalamus hamiltonii*), $Y=-3.53+0.71*DBH+0.33*ht$ (for *Dendrocalamus longispathus*), $Y=-1.09+0.60*DBH+0.07*ht$ (for *Melocanna baccifera*) and $Y=-0.32+1/1.85*DBH+1/6.46*ht$ (for *Schizostachyum dullooa*). Allometric equations developed for the bamboo species recommends a higher precision of biomass estimation in Mamit district of Mizoram. The total biomass ranged from 2.65-23.06 Mg/ha in different diameter class of the culm. Moreover, the maximum culm biomass was found in *Dendrocalamus longispathus* (48.34 Mg/ha) and minimum was observed in *Schizostachyum dullooa* (13.27 Mg/ha). Similarly, the carbon stock of the culms ranged from 6.22-22.71 t/ha. The total emission reduction of carbon dioxide of the culm ranged from 22.89 to 83.40 tCO_2eq. The results of this study showed a strong relationship between biomass with DBH and height which were showed as crucial predictor variables.

1 Introduction

1.1 Background

Bamboo is a group of woody grasses that belong taxonomically to the subfamily of *Bambusoideae* of the family *Poaceae* (Li and Kobayashi, 2004). Bamboo is one of the key products of economically important non-timber forest products (CFI, 2006) and it is popularly known as 'poor man's timber' and 'green gold' denoting its popularity among poor people as a good substitute for expensive wood from trees (Lobovikov *et al*., 2012). Bamboo is a versatile plant in its adaptability and utility which gives an opportunity to enhance livelihood, food security and other environmental problems apart from emission reduction of greenhouse gases. Additionally, it creates opportunities for rural communities to mainstream themselves in climate change mitigation and adaptation programmes (Dietz and Kuyah, 2011). Bamboos are known for their high productivity (Kaushal *et al*., 2016) and this has increased interest in scientific communities to study the role of bamboo in carbon sequestration, ecosystem carbon budget and ecosystem services (INBAR, 2006, 2010). Bamboos can be considered equivalent to trees for CDM afforestation and reforestation projects due to its huge carbon sequestration potential (Lobovikov *et al*., 2012). Bamboo is important for rehabilitation of degraded land, as a timber substitute, for erosion control and watershed protection (INBAR, 2006). On account of extensive shallow rhizome-root system and accumulation of leaf mulch, bamboo serves as an efficient agent in preventing soil erosion and conserving moisture, reinforcement of embankments and drainage channels, etc. With its fast growth rate and high annual re-growth after harvesting, bamboo forests have a high carbon stock potential (INBAR, 2010), especially when the harvested culms are used as durable products (Nath *et al*., 2009). Bamboo species has a pivotal role as a carbon sink and thus contributing to climate change mitigation (Singnar *et al*., 2017). However, critical ecosystem services provided by bamboos still remain unrecognized in terms of carbon farming and subsequently carbon trading.

There are approximately 1500 species under 87 genera of bamboo worldwide (Li and Kobayashi, 2004). About 125 indigenous and 11 exotic species of bamboo belonging to 23 genera are reported from India. More than 50 per cent bamboo species occur in the north eastern part of the country (FSI, 2017). The annual production of bamboo in India is about 14.6 million tonnes and annual yield varies from 1 to 3 tonnes per ha. Pulp and paper industries use about 35 per cent of the bamboo production followed by housing and rural sectors. The bamboo and rattan industry of India is worth of US$ 4.35 billion (ICFRE, 2017).

Bamboo growing stock is a major indicator of the extent of bamboo resources. Growing stock is normally measured in culms (for monopodial species), clumps (for sympodial species) and weight (for both types of species). About 332 million tonnes of bamboo growing stock are reported from the Asian countries (Lobovikov *et al*., 2007) and 189 million tonnes of bamboo growing stock were reported from India out of which green sound bamboos contribute 70 per cent and dry sound bamboos contribute remaining 30 per cent (FSI, 2017). North Eastern states covers about 54.97 per cent of the total growing stock of the bamboo in India. In Mizoram, 57 per cent percent of the geographical area is covered under bamboo cover and between the altitudinal ranges of 400 m - 1500 m above mean sea level. Bamboo has been an integral part of cultural, social and economic traditions of the people of Mizoram state. About 34 species of bamboo (22 species are indigenous and 12 species are introduced) have been reported by Bisht and Naithani (2010) from the state of Mizoram. Bamboo species, *Melocanna baccifera* contributes 95 per cent of the growing stock of bamboo in Mizoram. Other bamboo species found in Mizoram are given in Table 1. According to FSI (2017), about 3267 sq km are bamboo bearing area within the forest area of Mizoram. It has been proved that bamboo in terms of natural resource is playing a major contribution towards the socio-economic development of the state.

Biomass estimation of bamboo species helps in quantifying the carbon dioxide which can be sequestered. Its estimation largely depends upon variety of factors (i.e., age of the stand, topography etc). In forestry, it can be generally done by direct method (destructive techniques) and indirect method (biomass equations). Out of this, the indirect method is less time consuming and cost effective. The approach for biomass estimation of bamboo species by indirect method has been preferred by several workers (Nath *et al*., 2015; Ardalan and Homuz, 2016). The reliability of the usage of the indirect method for biomass and carbon stock estimation can be improved by applying existing knowledge on tree allometry. The accuracy increases with the increase in the development of regional or local biomass equations by representing the varied factors like species-specific culm, culm growth behaviour, different culm ages in each clump, climatic parameters and soil properties etc. The basic principle of the allometry is that dependent variable relates quantifiably with independent variables like DBH, height or both and provides relatively accurate estimates (Philips *et al*., 2002). Different linear and non-linear models have been developed worldwide for estimating biomass. Both linear and nonlinear models like monomolicular, logistic and allometric etc. are considered better for predicting biomass and depicting height-diameter relationship (Verma *et al*., 2014; Gao *et al*., 2016).

However, there are no generalized biomass estimation models (Brown and Lugo, 1984, 1992), which can be used for different bamboo species. Species-specific biomass equations for some of the Indiain bamboo species have been developed by following the harvest method (Kumar *et al*., 2005; Nath *et al*., 2009 and Singnar *et al*., 2017). However, there is a dearth of studies involving biomass based allometric models for bamboo species in North Eastern part of the country. The relationships between diameter and height have been found to vary across environmental conditions, reducing importance of species type in determining accuracy of equation (Banin *et al*., 2012; Fayolle *et al*., 2013). Additionally, the potential contribution of bamboo species in biomass production and terrestrial carbon capture in different climate is limited (Nath *et al*., 2015). Moreover, due to structural habit of being uneven aged, the challenging part in biomass estimation is to quantify the differently aged culms distributed in a clump and makes it a complicated process. Hence, there is a need to harmonise the measurements of biomass and carbon density across different sites, species, climates and other conditions and develop the predictive linear and non-linear models for the five bamboo species which will provide the useful information to farmers, private sector and researchers especially for the implementation of REDD+ activities.

Table 1. Common bamboo species of Mizoram state

S. No.	Species	S. No.	Species
1	*Bambusa balcooa*	13	*D. giganteus*
2	*B. bambos*	14	*D. hamiltoni*
3	*B. dampeana*	15	*D. hookeri*
4	*B. mizorameana*	16	*D. laetiflorus*
5	*B. multiplex*	17	*D. longispathus*
6	*B. nagalandiana*	18	*D. manipureanus*
7	*B. nutans*	19	*D. sikkimensis*
8	*B. tulda*	20	*D. strictus*
9	*B. vulgaris*	21	*Melocalamus compactiflorus*
10	*B. vulgaris* var. *vittata*	22	*Melocanna baccifera*
11	*B. vulgaris* var. *waminii*	23	*Neomicrocalamus mannii*
12	*Dendrocalamus asper*	24	*Phyllostachys edulis*

25	*Phyllostachys manni*	30	*S. pergracile*
26	*Schizostachyum dullooa*	31	*S. polymorphum*
27	*S. fuchsianum*	32	*Sinarundinaria falcata*
28	*S. mannii*	33	*S. griffithiana*
29	*S. munroi*	34	*Thyrsostachys oliveri*

(Source: Bisht, 2016)

Limitations: Site and species specific allometric equations were developed in this study, therefore, it is confined to similar physiographic regions representing the particular bamboo species and its culm growth behaviour characteristics of the species. Influence of the climatic, edaphic, topographic and biotic factors will also affect the productivity of the bamboo and hence biomass and carbon sequestration potential. Due to these limitations, it is recommended that the use of the site-specific allometric equations developed in this study should be confined to similar physiographic region. Further, the power of reliability of an allometric equation and degree of dependency of dependent variable on independent variables will also get weaken on generalising the area and species.

1.2 Description of Bamboo Species

Five species of bamboo (*Bambusa tulda*, *Dendrocalamus hamiltonii*, *Dendrocalamus longispathus*, *Melocanna baccifera* and *Schizostachyum dullooa*) from the state of Mizoram have been chosen for developing the predictive model for culm biomass estimation using DBH and height as explanatory variables. Descriptions of the five selected bamboo species in brief are given below:

1. *Bambusa tulda* Roxb.: It is an evergreen or deciduous, arboreous and gregarious bamboo. In Mizo, it is known as *Rawhling* and in Hindi it is known as *Pheka*. It is widely distributed in Orissa, West Bengal, Assam, Arunachal Pradesh, Meghalaya, Manipur, Nagaland, Tripura, Mizoram, Madhya Pradesh and Andhra Pradesh in India. Its altitudinal range varies from 50 to 1463 m above msl. It is frequent on flat alluvial land along stream in mixed deciduous forests along the banks of dry water courses.

Its young shoots are yellowish-green, sparsely pubescent with black hair, blades imbricating, powdery above, 5-10 cm in diameter which vary with the locality. Rhizomes are pachymorph or sympodial or clumping**.** Culm sheaths are deciduous and its height ranges from 15-32 cm, width from 25-34 cm at the base, smooth or covered with appressed white or brown hair. It is white powdery from inside and brown hair from outside. The culm sheath is slightly attenuated upwards and rounded or triangularly truncate at the top. Leaves are linear-oblong or lanceolate, rounded or cordate at the base, 6-35 cm length and 1.5-6 cm is wide.

It flowers sporadically or in small groups, while occasional gregarious flowering is also common. Its gregarious flowering in Mizoram was reported during 1924-28 (Parry, 1931), 1880, 1884, 1928 and 1976-79 (Mohan Ram and Gopal, 1981).

It is a very useful species for construction purposes for making basket works, mats, water and milk vessels, furniture haystack stabilisers, scaffolding, boat roofs, hat wall plates and wall hangers.

2. *Dendrocalamus hamiltonii* Nees & Arn. ex Munro: Locally in Mizo, it is known as Phiulrua. It is a large bamboo with caespitose culms, sometimes growing tall and erect but more often sending out its stems at an angle or curved downwards. Young shoots are conical, sheaths are yellowish-brown, covered with black hairs, blades stiff, pointed, yellowish green, velvety pubescent on dorsal surface, ciliate along the margins.

It is widely distributed in the states of Sikkim, Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland and Tripura at an altitudinal ranges from 50 to 1500 m above msl. It form patches to continuous brakes that are widely distributed in the sub-tropical and warm temperate climate of northern part of the sub-continent upto central Himalaya.

Its rhizomes are pachymorph or sympodial or clumping. Culm**s** are variable in height and vary from 12-25 m. And diameter at base vary from 10-18 cm. Culm sheath are long and stiff, deciduous at the time of branch emergence, variable in size, height varies from 34-45 cm and width is around 20 cm broad, glabrous, shining within, rough, glabrous or with scanty patches of stiff blackish-brown hairs without truncate at the top. The length of the culm sheath is third-fourth of the internode. The culm sheath blade is upright and present on the outer surface of the blade. Leaves are variable and rounded at the base into a short thick petiole, broadly lanceolate and 8-38 cm long.

It flowers usually sporadically almost every year, so that the clumps in flower may often be found and are collected. It also flowers gregariously sometimes. Its gregariously flowering cycle is 40±5 years. Gregarious flowering throughout the state of Mizoram was reported during 1997-98 and 2006-07 (Bisht and Naithani, 2010)

It is used for walling of huts, construction, basket making, mats, vessels, fuel, floats for timber rafts and shoots for food. It is grown in tea plantations as a protection against strong winds. The culms are good and cheap substitute for stuttering, scaffolding, fences, staircases and wooden nails. It is an ideal plant for checking soil erosion.

3. ***Dendrocalamus longispathus* (Kurz)*:*** It is a large handsome tufted bamboo. It is known *as Rawnal* in Mizo. It forms patches of vegetation in lower slopes and valleys near the water courses in the forests of Mizoram. In comparison to others, this species is comparatively thin walled and of small size. Young shoots are yellowish-green; blades are reflexed, covered with shining blackish hair, apex is erect, auricles are small and ligules are silvery.

Culm are usually 15-20 m tall, up to 10 cm in diameter, glaucous green when young, greyish-green or yellowish-green when old, nodes are slightly swollen are often fine rooted. Internodes are 25-60 cm long, 6-10 cm in diameter and are covered by long papery remnants of sheaths and dark- brown pubescence. Branch buds are semicircular and about 1 cm broad. Culm sheath are papery, green when young, brown when old, covered on the back with dense, stiff appressed brown or black hairs. Ligules are broad, serrated and often long fimbriate and auricles are usually absent. Leaves are 10-30 cm long, 2.5-4.5 cm width, oblong-lanceolate to linear–lanceolate, tapering gradually to the point, margins are rough and leaf sheath are smooth.

Its flowering cycle is estimated to be 30±5 years (Kaushik *et al*., 2015). Flowering has been reported from Mizoram in 1976-77 (Mohan Ram and Gopal, 1981)

It is used for thatching, construction, basket making, fuel chicks for doors, house posts, mat and furniture making. Shoots are used as food. Culm sheaths are used for irrigation and musical instruments. It is particularly suitable for the manufacture of kraft paper.

4. *Melocanna baccifera* Rozb. (Kurz): It is an evergreen arborescent bamboo and clumps are diffuse. It is known as *Mautak* in Mizo.

Rhizome is pachymorph or sympodial type with the neck usually elongated to 1 m but rarely upto 3.5 m. Culms are up to 10-20 m tall and diameter at base is about 4-8 cm. The colour is green when young and becomes yellowish-green to straw coloured when old. Nodes are marked with a thin ring. The internode length is 10-50 cm and 1.5-7.5 cm at the base. In this species, hair and pubescent both are absent.

Culm sheath is 10-15 cm × 15-30 cm, broader, brittle, parallel striped, covered with whitish closely pressed hairs. Leaves are 5-15 cm long with width of 2.5-5.0 cm, oblong-lanceolate or lanceolate, 1.25 cm long petiole, hairy when young, rough to touch on the margins and main vein is prominent.

Flowering is sporadic in initial stage and gradually becomes gregarious. Mohan Ram and Gopal (1981) reported that a survey of forest records indicates that gregarious flowering occurred in Mizoram during 1910-12 and 1958-59.

It is used as a principal material for building houses and is also an important source of superior paper pulp and fruits are edible. It is also used for making small bridges, thatching toys, screens, hats, umbrella sticks, baskets, food grain containers, chicken cages and wall plates.

5. *Schizostachyum dullooa* (Gamble) R.B. Majumdar: It is a medium sized bamboo, tufted sometimes more or less scandent. In Mizo, it is known as *Rawthlaw.* Culms are 4.9 m tall, whitish below, nodes are hardly prominent. Internodes are 0.4-1 m length and 2.5-8 cm broad. Culm sheath varies in size from 15-30 cm length and 10-25 cm broad, striate with scattered white hair prominent above, rounded at the top, concavely truncate and loosely fringed with stiff bristles.

Leaves are variable, oblong, narrow and tapering, acuminate, rounded often unequal at the base into a short petiole, terminating in a twisted, rough on the upper surface, minutely soft pubescent beneath or hairless, margins are rough, main vein is pale and not very prominent. Rao and Ramakrishnan (1988) have mentioned its gregarious flowering in Assam and Meghalaya respectively during 1967 and 1968.

It is used in making kites, *Mizo* looms, quivers, mats, baskets, umbrellas, small boxes to carry pan, carrying water, loading vessels and building construction purposes. They are used in sun grass rafting. *Buhban* or glutinous rice is also cooked in the joints. The young shoots are eaten and cooked as a vegetable.

2 Methodology

Site Description: Mamit is a fourth largest district of Mizoram state. It is situated between 23°15′21.25″-24 °15′16.80″ N latitude and 92 °15′44.54″-92 °40′39.63″ E longitude with an altitude ranging from 40 to 1485 m above msl. It is situated in the western part of Mizoram and located at a distance of 96 km from the state capital, Aizawl. Its geographical area is 3025 sq km. The district is bounded on the north by Hailakandi district of Assam state, on the west by North Tripura district of Tripura state and Bangladesh, on the south by Lunglei district and on the east by Kolasib and Aizawl districts. The important rivers flowing through the district are Tlwang, Tut, Langkaih, Teirei, Khawthlangtuipui and Mat. The location of the sample points laid out for sampling are given in Figure 1.

Climatic conditions: The relevant thermo-characteristics of Mamit district is that temperature do not fluctuate much throughout the year. Owing to its tropical condition, it enjoys the moderate climate. Less rainfall is found in North-east monsoon as compared to other seasons. The district receives annual rainfall between 2000-3100 mm from both North-east and South-west monsoons. The area receives an adequate amount of rainfall which is responsible for a humid tropical climate characterised by short winter and long summer and heavy rainfall.

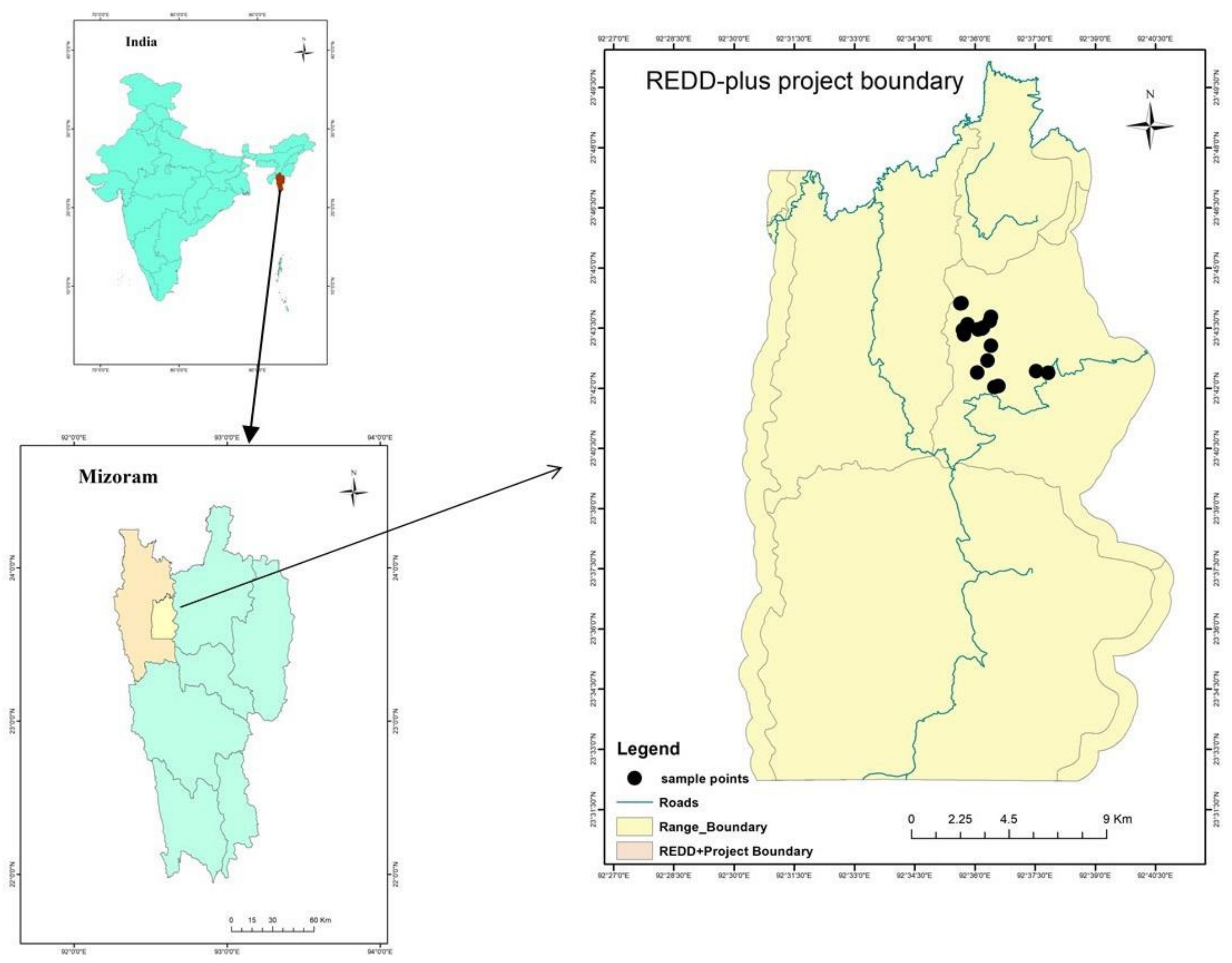

Figure 1. Map of study site (REDD+ project area) in Mizoram, India

Field equipment and materials: Field equipments and materials used for the collection of the data from the field and further laboratory analysis are GPS, silva compass, linear measurement tape, DBH measurement tape, saw, portable hanging spring scale up to 100 kg with 0.05 kg precision, drying oven, silica crucibles and other materials (poly bags, ropes, field data forms for record keeping etc).

Data collection: The methodology given by the Forest Survey of India was followed for collection of data (FSI, 2015). Thirty three plots of 0.1 ha (31.62 × 31.62 m) were laid out randomly in the study site for collection of relevant data for estimation of biomass and development of allometric equations. For bamboo clump analysis in terms of clump size distribution along with their diameters and height within the plots were studied. Latitude, longitude and altitude of each sample plots were also recorded. Data collected from the sample plots have been collected as per field description form (Annexure-I).

Selection of the sampling culms: All bamboo culms situated within the sample plot of 0.1 ha size in two age groups that is 1-2 years and over 2 years old were selected. All the five bamboo species were counted in the above mentioned two age groups and were categorised in three diameter classes namely <3cm, 3-5cm and >5 cm (lowest, middle, highest). The age of different culms in the clumps was determined on the basis of culm sheath, colour of culms, position of the culms, and growth and development of branches and leaves (Ming *et al*., 2010). Culms were marked and numbered moving from the north direction and working inwards to prevent accidental double counting. Along with the scientific and local names of bamboo species, number of clumps and total numbers of culms (species wise) in each quadrat were also recorded.

Field measurements and harvesting of bamboo culms: Bamboo culms were marked in accordance to their age categories and culms were harvested. Total number of culms in each range was recorded and three culms in each range were harvested using a diameter tape for categorising into diameter classes. Total fresh weight and total height of each harvested culm were recorded at field. Three portions of each harvested culm (base, middle and apex with a total sample of 200-300 gm) were collected for oven drying at 65-70 degree centigrade for determination of dry matter till the constant weight is achieved.

Sample preparation for the laboratory: After measuring the fresh weight, representative samples of 200-300 gm of each bamboo species along with the fresh sample weights in the respective categories were taken to laboratory to determine the dry weight.

Laboratory analysis: All the samples were analysed in the laboratory for determination of dry weight. The total dry weight of the culm of the samples is calculated based on the total fresh weight of culm under two age groups and three diameter classes measured in the field and ratio of the dry weight to fresh weight were calculated for the respective samples in the laboratory. The formula given below was used for calculation of dry mass of culms.

Culm dry weight= $W_{\text{sample dry weight}} / W_{\text{sample wet weight}} \times$ total fresh weight of culm

where,

Culm dry weight	=	biomass of each culm under each category and diameter class (kg)
$W_{\text{sample dry}}$	=	weight of the oven-dry sample of individual tree components taken to the laboratory to determine moisture content (kg)
$W_{\text{sample wet}}$	=	weight of the fresh sample of individual tree component taken to the laboratory to determine the moisture content (kg)
Total fresh weight of culm	=	Fresh weight of a culm immediately after harvesting (kg)

Regression analysis and development of equations: After the completion of the field work and laboratory analysis; data entry and statistical analysis were carried out for development of equations for biomass estimation of five bamboo species. Relevant data were entered in the MS Excel spreadsheet considering the quality assurance and control of the data. Data from 33 sample plots of three diameter classes with three replications were statistically computed. Statistical analysis was performed using STATISTICA release 7.0 software. The predictor variables used for formulating biomass equations were diameter at breast height and height. During the regression analysis, the constants also known as y-intercept is also included which explains the value at which the fitted line crosses the y-axis. After completion of the regression analysis, the best fit equation was assessed and the equations with the highest correlation index that were highly significant and with the smallest error (RMSE) for biomass estimation were selected.

Bamboo biomass and carbon stock measurement: The biomass of five species was estimated by using variables like diameter at breast height and height of the culm. The multiple linear equation (equation 1) was used in all the bamboo species except *Schizostachyum dullooa.* In this species non-linear equation (equation 2) was used. Both the equations were based on two independent variables (DBH and height):

$Y = \alpha + \beta_1 X_1 + \beta_2 X_2$ (Linear) *equation 1*

where,

Y = Biomass of culms of different diameter categories (kg)

α = Intercept

β_1 and β_2 = Partial regression coefficients in the population

X_1 and X_2 = DBH and height both

$Y= \alpha / [(\beta_1 / X_1) + (\beta_2 + X_2)]$ (non-linear) *equation 2*

In equation 1, β_1 and β_2 are called partial regression coefficients because each expresses only part of the dependence relationship. The Y intercept, α (sometimes designated β_0) is the value of Y when both X_1 and X_2 are zero.

The equation 2 includes includes the reciprocal one or more predictor variables. It is used when the slope is a function of 1/X, the slope gets flatter as X increases. For this type of model, X can never equal to zero because it can't divided by zero.

In a linear regression model, R^2 (coefficient of determination) is a measure of strength of prediction. It will increase if the independent variables results in an improved fit of the regression equation to the data. It is the ratio of explained variation to total variation, this indicates the larger the explained variation, the better the model is at prediction. This means it measures the percent variation in the dependent (response) variable that is explained by the model (Zar, 2007). Not only this, standard error also proves to be a good indicator of the goodness of fit. It is reported for the intercept and for partial regression coefficients of the independent variables. The effect of species on biomass and carbon capture was seen by one way analysis of variance.

The biomass value in kg per hectare for each culm was then converted first into Mega gram per hectare. Thereafter, the biomass values were converted into carbon by multiplying them with the default carbon fraction of 0.47 recommended by IPCC (2006). Thus, the calculated tonnes of carbon were converted into carbon dioxide equivalent ($tCO_2eq.$) by multiplying the carbon value by 3.67, as suggested by Pearson *et al*. (2007).

3 Results

Choice of models for biomass estimation is considered very important in quantifying biomass and carbon fluxes (Gao *et al*., 2016). In this study, for *Bambusa tulda*, *Dendrcalamus hamiltonii*, *Dendracalmus longispathus* and *Melocanna baccifera*, multiple linear regression equations were found to be best fit and for *Schizostachyum dullooa* showed non-linear equation was found to be best fit. Therefore, both the linear and non-linear model was considered taking DBH and height as independent variables to predict biomass. For all the species, the developed multiple linear and non-linear equations among different species fitted showed significant results at $p<0.05$ level. The suitability of the model was based on R^2 and RMSE. The higher the value of R^2 and the lower the value of RMSE proves the reliability of the predictive model. The results of bamboo species in the form of standard statistics are mentioned in Annexure II and summary output of all bamboo species are mentioned in Annexure III.

In relation to the summary statistics the tables of each bamboo species compared the p-value for the F-test at 0.05 significance level for all the bamboo species. It was found that p-value is less than the significance level which proved that the regression model fits the data better than the model with no independent variables. The significant p-value is a meaningful addition to the model because changes in the predictor's value are related to changes in the response variable.

3.1 Biomass and carbon stock of *Bambusa tulda*

Biomass was estimated under three category of diameter classes (<3cm, 3-5cm, >5cm), maximum biomass was estimated in >5cm diameter class (10.89 Mg/ha) and carbon stock (5.12 t/ha) too and minimum biomass (3.54 Mg/ha) and carbon stock (1.66t/ha) was found in <3cm diameter class. The total biomass for the whole culm was estimated as 21.14 Mg/ha and carbon stock as 9.93t/ha and 36.47 tCO_2eq/ha as carbon dioxide emission reduction.

In model generation for biomass estimation based on DBH and height of the culm, the linear equation showed 0.82 R^2 and 0.56 RMSE. The equation developed is shown in Table 1 and the intercept (α) was found to be -2.62 and partial regression coefficients (to be 0.91, 0.25 as presented in Table 1 and 2.

Table 1. Linear equation for *Bambusa tulda*

Intercept (α)	Partial regression coefficients (β_1,β_2)	R^2	RMSE	Biomass equation
-2.62	0.91,0.25	0.82	0.56	Y=-2.62+0.91*DBH+0.25*ht

Table 2. Summary statistics (Mean ± standard error) of *Bambusa tulda* in three diameter classes

Diameter class	DBH (cm)	Height (m)	Biomass (Mg/ha)	Carbon stock (t/ha)	Carbon dioxide emission reduction (tCO_2eq/ha)
<3cm	2.43±0.20	6.61±1.41	3.54±1.14	1.66±0.93	6.11±2.13
3-5 cm	4.24±0.37	10.89±1.40	6.71±5.39	3.15±2.53	11.57±9.31
>5cm	6.57±0.59	14.15±1.88	10.89±4.07	5.12±1.26	18.79±5.65

3.2 Biomass and carbon stock of *Dendrocalamus hamiltonii*

In >5 cm diameter class, the maximum biomass and carbon stock were estimated as 23.06 Mg/ha and 10.84 t/ha, respectively. In 3-5 cm diameter class, biomass estimation was found to be 13.92 Mg/ha and carbon stock to be 6.54 t/ha. *Dendrocalamus hamiltonii* showed total biomass of the culm as 40.12 Mg/ha, carbon stock to be 10.84 t/ha and 39.79 tCO_2eq/ha of carbon dioxide emission reduction.

Two independent variables (DBH and height) showed good predictor for biomass estimation. The R^2 for the linear relationship was found to be 0.68 and RMSE to be 1.68. The value of the intercept, partial linear regression coefficients and equation is mentioned in Table 3 and 4.

Table 3. Linear equation for *Dendrocalamus hamiltonii*

Intercept (α)	Partial regression coefficients (β_1,β_2)	R^2	RMSE	Biomass equation
-2.43	1.17,-0.70	0.68	1.87	Y=2.43+1.17*DBH-0.70*ht

Table 4. Summary statistics (Mean ± standard error) of *Dendrocalamus hamilonii* in three diameter classes

Diameter class	DBH (cm)	Height (m)	Biomass (Mg/ha)	Carbon stock (t/ha)	Carbon dioxide emission reduction (tCO_2eq/ha)
<3cm	2.27±0.22	7.72±1.50	3.14±0.98	1.47±0.46	5.42±1.69
3-5 cm	4.21±0.40	11.82±1.11	13.92±4.02	6.54±1.64	24.02±4.07
>5cm	6.37±0.41	14.49±2.17	23.06±13.01	10.84±6.15	39.79±22.59

3.3 Biomass and carbon stock of *Dendrocalamus longispathus*

For biomass estimation, significant relationship was found in 3-5 cm diameter class. The total culm biomass was observed as 48.34 Mg/ha, carbon stock was to be 22.71 t/ha and carbon dioxide emission reduction of 83.4 tCO_2eq/ha. Maximum biomass, carbon stock and carbon dioxide emission reduction was maximum in >5cm diameter class and shown in Table 6.

Linear relationship was found between DBH and height with biomass, high R^2 (0.87) and minimum RMSE (0.29) was observed. This explains that 87 per cent variability in biomass estimation is explained by the explanatory variables (DBH and height) in prediction model. The equation developed along with other critical parameters generated is presented in Table 5.

Table 5. Linear equation for *Dendrocalamus longispathus*

Intercept (α)	Partial regression coefficients (β_1,β_2)	R^2	RMSE	Equation
-3.53	0.71,0.33	0.85	0.33	Y=-3.53+0.71*DBH+0.33*ht

Table 6. Summary statistics (Mean ± standard error) of *Dendrocalamus longispathus* in three diameter classes

Diameter class	DBH (cm)	Height (m)	Biomass (Mg/ha)	Carbon stock (t/ha)	Carbon dioxide emission reduction (tCO_2eq/ha)
<3cm	2.25±0.48	8.12±1.23	4.65±3.25	2.18±1.53	8.02±5.61
3-5 cm	4.29±0.23	11.13±0.74	20.90±11.04	9.82±5.19	36.06±19.04
>5cm	7.51±0.51	12.15±1.60	22.79±13.98	10.71±6.57	39.32±24.12

3.4 Biomass and carbon stock of *Melocanna baccifera*

The biomass of *Melocanna baccifera* for the whole culm was observed as 40.73 Mg/ha and carbon stock to be 19.13 t/ha and carbon dioxide emission reduction to be 70.27 tCO_2eq/ha. The maximum biomass and carbon stock was observed in >5cm diameter class and significant changes in biomass among the species was reported in 3-5 cm diameter class.

Good performance was shown in the form of R^2 (0.70) and RMSE (0.83) for the linear equation developed between DBH and height with biomass of the culm. The equation is given in the Table 7 along with other important parameters on which the equations is dependent upon. The details of statistical attributes for *Melocanna baccifera* are given in Table 8.

Table 7. Linear equation for *Melocanna baccifera*

Intercept (α)	Partial regression coefficients (β_1,β_2)	R^2	RMSE	Equation
-1.09	0.60, 0.07	0.70	0.83	Y=-1.09+0.60*DBH+0.07*ht

Table 8. Summary statistics (Mean ± standard error) of *Melocanna baccifera* in three diameter classes

Diameter class	DBH (cm)	Height (m)	Biomass (Mg/ha)	Carbon stock (t/ha)	Carbon dioxide emission reduction (tCO_2eq/ha)
<3cm	2.05±0.28	6.50±1.45	2.65±1.71	1.24±0.80	4.57±2.95
3-5 cm	3.86±0.62	9.68±0.21	14.35±8.10	6.74±3.81	24.76±13.98
>5cm	6.10±0.87	12.33±2.11	23.73±18.43	11.15±8.66	40.94±13.79

3.5 Biomass and carbon stock of *Schizostachyum dullooa*

The biomass of *Schizostachyum dullooa* in three different diameter class ranged from 2.75 to 5.67 Mg/ha, carbon stock from 1.29 to 2.66 t/ha and emission reduction from 4.75 to 9.78 tCO_2eq/ha. Cumulative biomass, carbon stock and carbon dioxide emission reduction of the whole culm was observed to be 13.27 Mg/ha, 6.22 t/ha and 22.89 tCO_2eq/ha, respectively.

The non-linear equation developed using DBH and height as predictor variables for biomass estimation showed a good performance. The equation showed the reliability based on the parameters such as R^2 and RMSE and they were 0.70 and 0.80, respectively. Other important parameters along with the equation are given in Table 9 and 10.

Table 9. Linear equation for *Schizostachyum dullooa*

Intercept (α)	Partial regression coefficients (β_1,β_2)	R^2	RMSE	Equation
-0.32	1.85,6.46	0.70	0.80	Y=-0.32+1/1.85*DBH+1/6.46*ht

Table 10. Summary statistics (Mean ± standard error) of *Melocanna baccifera* in three diameter classes

Diameter class	DBH (cm)	Height (m)	Biomass (Mg/ha)	Carbon stock (t/ha)	Carbon dioxide emission reduction (tCO_2eq/ha)
<3cm	1.95±0.79	8.01±0.77	2.75±0.95	1.29±0.45	4.75±1.65
3-5 cm	3.31±0.21	11.27±1.14	4.85±1.74	2.27±0.82	8.36±3.01
>5cm	4.94±0.89	27.83±2.56	5.67±1.25	2.66±0.99	9.78±4.33

4 Discussion

The present study included both the independent variables (DBH and height) to estimate culm biomass in five bamboo species (*Bambusa tulda*, *Dendrocalamus hamiltonii*, *Dendrocalamus longispathus*, *Melocanna baccifera* and *Schizostachyum dullooa*) which are dominantly distributed in Mizoram especially *Melocanna baccifera*. Nearly two-third of the growing stock of bamboo in the country is available in the North-Eastern states of India (Pandey *et al*., 2008).

In Mizoram, bamboo harvested in last five years is 1,43,756 MT (https://nbm.nic.in/StateMission.aspx; accessed on 18-11-2018). The biomass density obtained in this study is in the range of the reported value of 2.65-23.73Mg/ha where maximum and minimum value was observed in same species *Melocanna baccifera* in three different DBH classes. Similarly, the carbon stock assessment ranged from 1.24 t/ha-11.15 t/ha in different diameter categories and emission reduction also followed the similar pattern. For the whole culm, the carbon stock in different species varied from 6.22-22.71 t/ha.

An assessment in dry tropical region was done by Singh and Singh (1999) and reported that the values of young plantation was found to be lower than 3–5 year old *Dendrocalamus strictus* plantation ranging from 30–49 Mg/ha. Singnar *et al*., 2017 studied 15-18 years aged forest of Assam and observed the biomass density in the range of 43–45 Mg/ha in *Schizostachyum dullooa* and *S. ploymorphum* bamboo species. In this study, the biomass density of the whole culm varied from 13.27-48.34 Mg/ha. The differences in the biomass density may be attributed to the differences in the culm size, culm height, culm and clump density, culm behaviour and further the taper rate of the bamboo species.

Carbon stock in bamboos represents a permanent stock, as carbon export through harvesting of mature culms is balanced by carbon gain from new culms produced in the clump (Nath and Das, 2011).The maximum carbon storage was found in >5 cm diameter class in *Melocanna baccifera* (40.94 tCO_2eq/ha). Carbon mitigation potential of plantations is dependent on tree density, age, structure and carbon concentration in different components (Kanime *et al*., 2013).

Considering the multiple and wide use of bamboos, predictive models (high R^2 value and low RMSE) developed in this study can provide a useful information especially for forestry practitioners, private bamboo growers and state forest department groups, bamboo growers and farmers etc. particularly for North-East India.

5 Conclusion

To combat climate change related threats, bamboo is a core development resource for providing practical solutions. Bamboo could be a useful species for the Mitigation, Adaptation and Development (MAD) challenge in the face of climate change (INBAR, 2010). The biomass of the plant can be attributed by the size of the morphological features of the plant. Morphological characteristics/ variables like height and diameter at breast height of the species are easy to measure in comparison to dry weight of the aboveground components of the species. A range of the variables are examined to form accurate and reliable equations to predict the biomass in an easy way.

Development of predictive models for biomass estimation in bamboo is an essential dimension in the current scenario, especially by lessening the potential debilitating effect on the efficiency of forest, to act as a carbon sink. Further, it supports the approach followed by REDD+ to achieve the sustainable management of forests and provide climate smart solutions. It economic role in national and international trading of products has accelerated and needs to be strategically harnessed to lessen the impact on forest based resources.

Carbon stocks of plant around the world is site specific and depends on the stand composition, age, soil properties along with the management of forest. To estimate the precise accurate carbon stock by indirect method such as allometric equations proves to be helpful. These equations are site and species specific due to the biological variability, geographical and environmental conditions and their management practices.

This study has developed allometric equations for five bamboo species (*Bambusa tulda, Dendrocalamus hamiltonii*, *Dendrocalamus longispathus, Melocanna baccifera* and *Schizostachyum dullooa*) for the whole culm using both the independent variables (DBH, height) for estimation of biomass and carbon stock. The equations developed in this study can be used to estimate biomass and carbon stock of five bamboo species in similar biotic, edaphic and climatic factors along with the clump and culm behaviour and its taper rate.

Development of allometric equations for bamboo species will help in adopting IPCC Tier 3 approach (higher order approach is followed which includes detailed mensurational measurements like species specific allometric equations) for estimation of carbon stocks.

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Field Description Form

Name of Village: ....
District: ....
State: ....

Date: ....
Time: ....
Team Leader: ....
Othermembers:...........................

Plot Number

Number of bamboo species

GPS coordinates (degree decimal) of plot

- Latitude
- Longitude
- Altitude

Name of bamboo species (scientific name)

Vernacular name of the bamboo species

Number of clumps per hectare

Age class

- 1-2 years
- >2 years

Any additional information

Details of culm within the plot for each sample with three replications

Number of culms (DBH wise)	DBH (cm)	Height (m)	Total culms /hectare	Total fresh weight of culm (kg/culm)	Weight of fresh sample (kg)	Weight of dried sample (kg)	Total biomass (kg)
Lowest range (<3cm)							
Middle range (3-5 cm)							
Highest range (>5cm)							

Data record of oven dry mass of culm in each diameter class

Name of Laboratory: ....
Date of each data for each sample point: ....
Name of person in-charge: ....

Sample ID	Plot number	Name of the species	DBH class	Total fresh weight of culm (kg)	Sample fresh weight (kg)	Sample dry weight (kg)	Total biomass (kg)

Annexure-II

Basic statistics (mean ± standard deviation) of bamboo species

S. No.	Name of bamboo species	Diameter categories	DBH (cm)	Height (m)	Biomass (kg/culm)
1.	*Bambusa tulda*	<3cm	2.43±0.29	6.61±1.35	1.41±0.89
		3-5 cm	6.57±0.58	14.15±1.79	3.59±0.78
		>5cm	4.94±0.80	13.34±0.57	7.29±1.44
		Whole culm	4.41±1.76	10.55±3.44	3.53±2.50
2.	*Dendrocalamus hamiltonii*	<3cm	2.27±0.30	7.71±1.49	1.10±0.56
		3-5 cm	4.21±0.40	11.82±1.08	3.28±2.58
		>5cm	6.37±0.44	14.49±2.46	7.56±1.92
		Whole culm	4.29±1.73	11.34±3.31	4.01±1.31
3.	*Dendrocalamus longispathus*	<3cm	2.26±2.47	8.11±1.35	0.83±0.44
		3-5 cm	4.29±0.34	11.13±0.73	3.25±1.35
		>5cm	7.51±0.53	12.15±1.52	5.91±1.29
		Whole culm	4.69±2.23	10.26±2.47	3.33±2.36
4.	*Melocanna baccifera*	<3cm	2.05±0.33	6.49±1.43	0.48±0.25
		3-5 cm	3.86±0.63	9.68±2.11	2.11±0.69
		>5cm	6.10±0.99	12.33±2.05	3.46±1.38
		Whole culm	4.00±1.80	9.50±3.04	2.01±1.51
5.	*Schizostachyum dullooa*	<3cm	1.95±0.70	8.01±0.69	0.66±0.20
		3-5 cm	3.31±0.21	11.26±1.02	1.59±0.19
		>5cm	4.94±0.80	11.34±3.31	2.72±2.10
		Whole culm	3.40±1.38	15.70±2.59	1.65±1.45

Summary output of bamboo species

S. No.	Scientific name	Multiple R^2	Adjusted R^2	Standard error	Intercept (α)	t- value	F- statistic	p-value
1.	*Bambusa tulda*	0.82	0.81	0.46	-2.62	-5.58	139.52	<0.05*
2.	*Dendrocalamus hamiltonii*	0.68	0.67	0.86	-2.43	-2.82	66.72	<0.05*
3.	*Dendrocalamus longispathus*	0.85	0.84	0.29	-3.53	-5.35	176.61	<0.05*
4.	*Melocanna baccifera*	0.70	0.69	0.65	-1.09	-3.73	104.49	<0.05*
5.	*Schizostachyum dullooa*	0.70	0.67	0.64	-0.32	-1.35	28.44	<0.05*

*significant at 0.05 level